PROCEEDINGS OF THE 1ST SCHOOL OF ENGINEERING (SoE) CONFERENCE

9th to 10th May 2024

at Malawi University of Business and Applied Sciences, Blantyre, Malawi

THEME: MALAWI 2063 - UNLOCKING DEVELOPMENT THROUGH ENGINEERING AND INNOVATIONS

https://mubas.ac.mw/page/SoEConference

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CONFERENCE ORGANISING COMMITTEE

The conference was organised by the School of Engineering Conference Organising Committee comprised the following:

1. Eng. Assoc. Prof. Ignasio Ngoma, Committee Chairperson, Civil Engineering Department, +265888841947, ingoma@mubas.ac.mw
2. Assoc. Prof. Innocent Kafodya, Head of Civil Engineering Department
3. Assoc. Prof. Faides Mwale, Civil Engineering Department
4. Dr. Joshua Chisambi, Head of Mining Engineering Department
5. Dr. Kenneth Gondwe, Mechanical Engineering Department
6. Dr. Alick Vweza, Electrical Engineering Department
7. Mr. Waheed Mia, Mechanical Engineering Department
8. Ms. Tadala Namaona, Electrical Engineering Department
9. Dr. Rodwell Bakolo, Head of Electrical Engineering Department
10. Dr. Timothy Chadza, Head of Mechanical Engineering Department
11. Mrs. Alice Kayange, Civil Engineering Department
12. Mr. Peter Bwanali, Marketing Section
13. Ms. Lucy Isaac, Marketing Section
14. Mr Akuzike Namutwa, Marketing Section
15. Ms. Jenala Misomali, School of Engineering

OPENING ADDRESS

Assoc. Prof. Chomora Mikeka, Director of Science, Technology and Innovation, Ministry of Education.

Inaugural Engineering Conference Organizing Chairperson, Assoc. Prof. Ignasio Ngoma: You taught us in Year 2 (1998) Civil Technology (Bending Moment Diagrams) vs. Sim.

That said, I give respect to all engineers in the room and those aspiring to join the problem-solving profession. Media, please reach out to all, far and wide.

Riding on all the Protocols listed,

I stand before you, fully aware of what we are grappling with as engineers and as researchers. The National Science, Technology and Innovation Policy (NSTIP) to address this infrastructure for Science Technology and Innovation (STI) and STI for infrastructure development. Engineering the Sciences ==>> To make them practical, beneficial to society, exciting/innovative and industrial. New curriculum to address this, already piloted through machines in schools as outdoor workshops and commercialization portals! The dots will all be connected someday! We have 6,954 Primary Schools and 1,774 Secondary Schools. We build a machine and plant it at a school for commercial gain to the school, service to the community around achieving experiential problem-project based learning and research and development (R&D). If we combine and resolve our forces, we can impact 5.285 million learners in primary, 0.485 million in secondary, including their 103,700 teachers and millions of community members (the citizens). By 2030, someone would tell this story better following its impact. By 2063, we would be glad to see the Malawi we want.

The theme for this inaugural School of Engineering Conference: Road to 2063: Unlocking Development Through Engineering and Innovations leads to the following observations:

A) What Development or Development of what? Economy! Productive and Real Economy!

B) Engineering and Innovation beyond the textbook! Fundamentals, Handbook, Theory and Practice; Statics and Dynamics ==>> Robotics ==>> UNIPOD ==>> Construction Equipment: dig, lift, measure!

Am I lost?

Now, about MUBAS: MUBEAS, MUBASE: Somehow, trying to locate the E in the Acronym. Matthews (CEO & FOUNDER OF WEAGLE HOLDINGS) will recount how during our time: 23rd August 1997 to 19th June 2002 we thought this place was the home of engineers. We walked with pomp. We somehow felt like if released to the world and challenged to solve any problem, then we would solve it really quick as we did in examinations or class work and tutorials. Unfortunately, the world, our nation problems are not question papers. We need to rethink and re-imagine how we engineer the engineering programmes.

1) MUBAS is a research-oriented university. It's Vision: to be an inclusive, engaged, entrepreneurial, innovative, and research-oriented university. The conference is in tandem with the Vision: research orientation is Edu 2.0, rise above the waters. Engage the communities, society, and nation (be deliberate; I am troubled right now by many universities outside Malawi seeking guidance; even in the course of their research meetings. Be inclusive in your engineering design and solutions. Sale your ideas, designs, products, processes and services. The government of Malawi has 20 sectors and of these 13 are service sectors. But they lack engineering flavour. Work for your government. Volunteer and apply yourself at Capital Hill through the MDAs. No MDA should resist an engineer who has solutions for the nation's challenges.

2) Research to generate evidence can be used as a vector to carry or propagate the MW2063. The true accelerator for SDGs, MIP-1, Agenda 2063, and Malawi is 2063 is STI. Yet in terms of numbers, STI is only 2.5%, ICT is 8.8%, STEM is 30.1% and HASS (Humanities, Arts and Social Sciences) is 58.6%.

3) Research Agenda: Download and study the preliminary issues that the sectors or MDAs are grappling with or desire solved by experts like ourselves. Offer yourself as a lamb without blemish. You will make the difference!

Finally, the secret and the painful truth: Engineering papers from the West vs. those from the East: Assess/Evaluate/Review vs Design/Simulation/Development/Fabrication/Technique/Mechanism....

East takes a posture for Economic Development through leapfrogging while West takes the academic posture.

You can assess, evaluate, review, give an overview of, but then, to develop Malawi economically, to self-excite or separately-excite the PRODUCTIVE AND REAL SECTOR ECONOMIC GROWTH, the West approach must come into the preliminary works and introduction. The core should be the process, product, or service to the citizen.

EXAMPLES:

1. "Performance evaluation of a carrot or single stroke engine!" vs "Fabrication of a single piston engine for fertilizer application in anchor or mega farms"

2. "Testing of a robotic machine to lift at least 1 tonne of debris is critical for construction industry."

Come to schools, with official clearance from the Ministry of Education, to fabricate, test your designed, simulated, analysed machines useful for all 13 sectors. The school in your village is the hub for engineering-led community development.

WITH THESE REMARKS, I DECLARE THAT THIS 1ST ANNUAL SCHOOL OF ENGINEERING CONFERENCE, OFFICIALLY OPEN!

CONFERENCE AGENDA

Eng. Assoc. Prof. Burnet O'Brien Mkandawire, Executive Dean, School of Engineering

- The Keynote Speaker, Eng. Prof. Evans Nkhalambayausi Chirwa
- The Conference Chairperson, Eng. Assoc. Prof. Dr. Ignasio Ngoma
- Distinguished invited guests
- Executive Deans of Schools
- MUBAS Heads of Academic Departments
- Heads of Non-academic Departments
- MUBAS Academic members of staff
- Sponsors
- Members of the Press
- Ladies and Gentlemen

Good morning and a warm welcome to you all. It is an honour and privilege for me to stand before you as we gather for this special moment, the Inaugural School of Engineering (SoE) Conference.

The Vision of Malawi University of Business and Applied Sciences (MUBAS) is to be an inclusive, engaged, entrepreneurial, innovative, and research-intensive university; and this inaugural SoE conference**,** under the theme, **"The Road to 2063: Unlocking Development Through Engineering and Innovation"**, aligns very well with the Vision as well as the Strategic Plan (SP). The Conference is a great milestone for the School, and it will go into the annals of our history not only as the first in the SoE, but also as the first since MUBAS was established following the delinking of colleges that formed University of Malawi (UNIMA). Being aligned with the SP also means that it is aligned with Malawi 2063 because MUBAS draws its strategies and inspirations from it.

I would like to thank the Conference Chairperson and his committee for working hard and exceptionally well to put up such a great conference. Please let us give them a round of applause.

The SoE has expanded tremendously over the past decade following reviews that have been taking place in consultation with various stakeholders from the industry. The School has four departments (Civil, Mechanical, Electrical, and Mining Engineering). These departments host over 41 degrees and diplomas, 13 of which are postgraduate ones (MSc, MPhil, PhD). The School also supports a number of MUBAS-wide projects and units such as Agricultural Mechanization and Industrial Park.

The conference programme is loaded with very good and captivating paper titles that speak to the theme, tackling issues relevant to the development of our nation, and the engineering discipline and profession.

Ladies and gentlemen, it is worth mentioning that the SoE submitted a proposal to establish a Journal, *Journal of Advancements in Engineering, Science, Innovation and Technology (JAEST*), which is undergoing approval processes at Senate level. It is envisioned that good papers from this conference, and going forward, will be published in the journal.

To all presenters, thank you for submitting papers, which will keep the conference alive as they will provide a platform for constructive discussions. I would like to request all delegates to participate fully and to actively engage with the presenters in the discourse.

I believe the journey that we have embarked on shall be sustained, and the Conference shall be a remarkable annual event.

Furthermore, I would like to thank all the sponsors, who include our own University Management, through the Vice Chancellor.

Finally, I would like to thank you all for your attention. God bless us all, MUBAS, and Malawi.

MAIN KEYNOTE ADDRESS

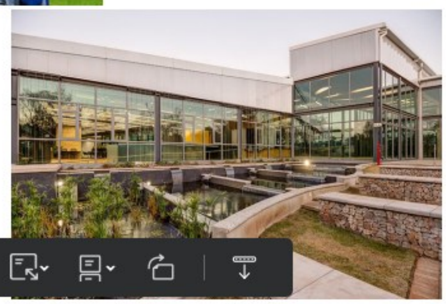
Eng. Prof. Evans Martin Nkhalambayausi Chirwa, Rand Water Chair in Water Utilisation, Department of Chemical Engineering, University of Pretoria (UP).

We are based in Pretoria (Tshwane), South Africa – Famously known as "The Jacaranda City"

University of Pretoria

- Is the Largest Residential University in South Africa, currently at ≈ 65,000 student/yr
- Has the largest enrollment of Engineering students in the continent of Africa

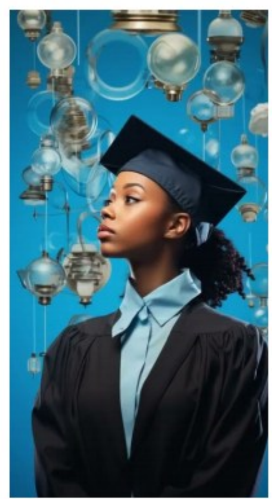
← OLD ARTS BUILDING IS LISTED AS NATIONAL HERITAGE SITE



THE NEW ENGINEER
ART WATER LABORA

Chemical Engineering Department at University of Pretoria

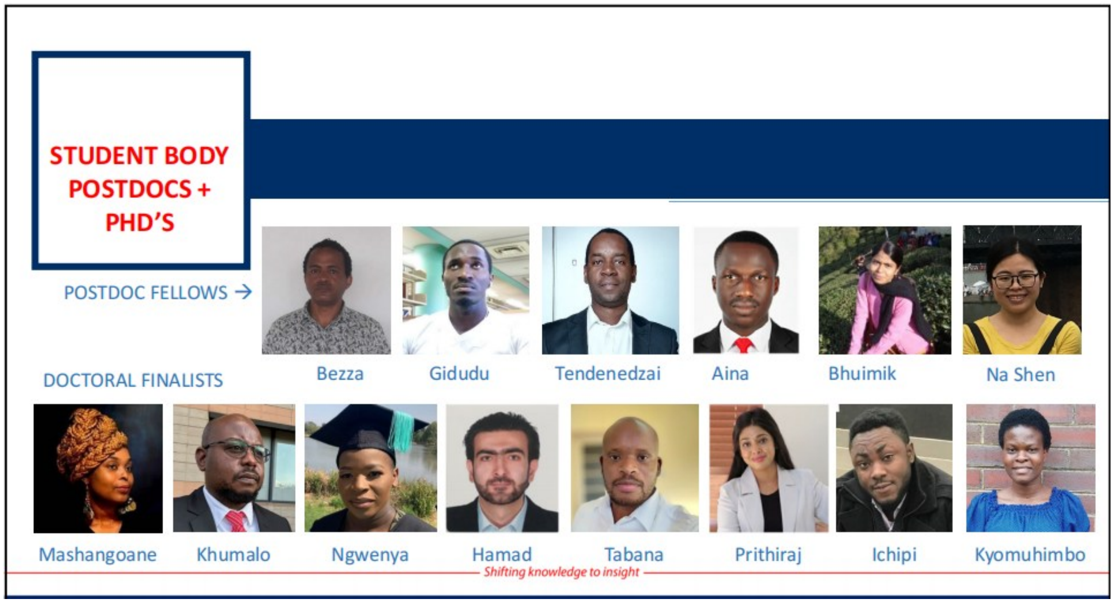
- Is housed in Level 8 of the Engineering Building 1 of the Faculty of Engineering, Built Environment and Information Technology (EBIT), HOD is **Prof Michael Daramola**, NRF Rated C2.
- The Department Achieved 1st position (Highest Research Outputs) in the University of Pretoria in 2023

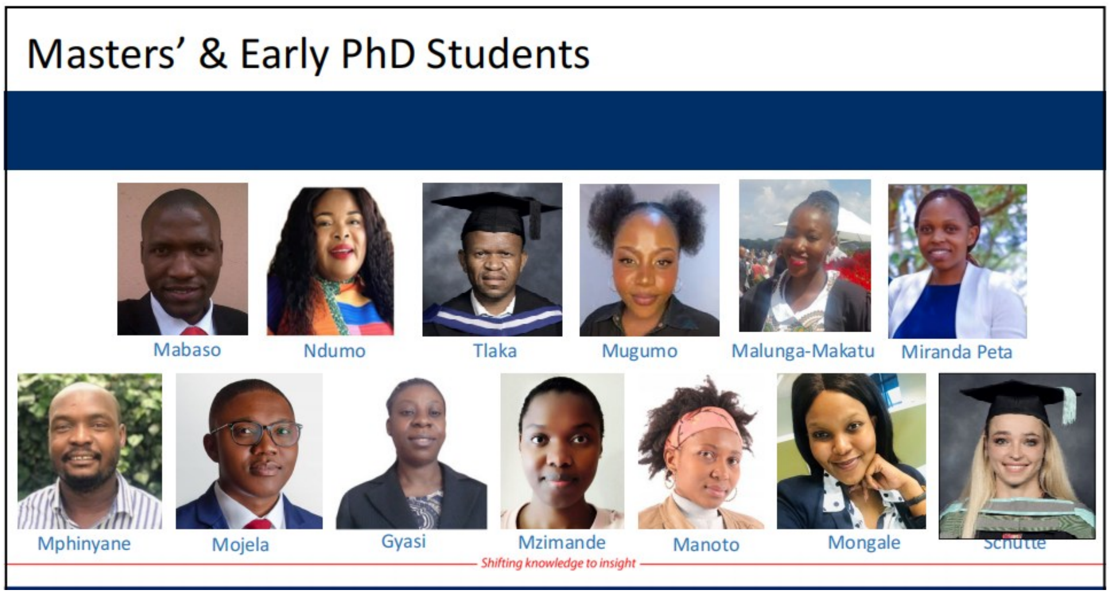


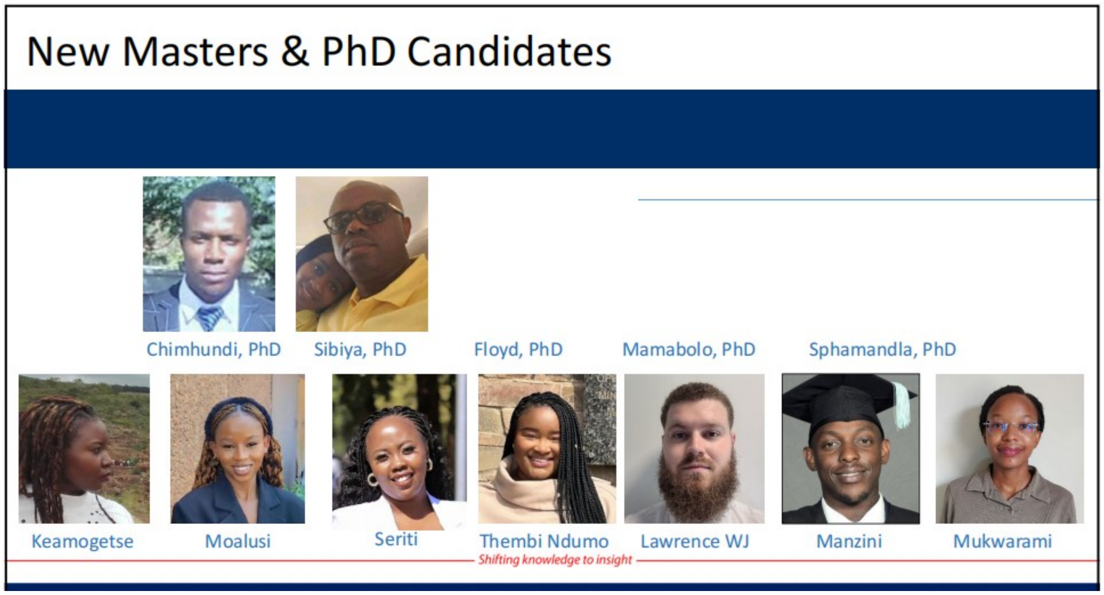
OVERVIEW

- UP Water Utilisation & Water Resources Division – Human Capacity
- SDG's and Research Focus
- Research Network's & Collaborations
  - World Universities Networks (WUN)
  - Africa University Twinning Programme (WUN)
  - Water4All'2025
  - MUBAS, LUANAR Water Programme
- Other Funding Opportunities
- Curriculum Development and Proposed MOU's
- Short Learning and Continuous Professional Development
- Africa Positioning in AI, Economies and Technologies

Shifting knowledge to insight


STUDENT BODY
POSTDOCS +
PHD'S
POSTDOC FELLOWS →
DOCTORAL FINALISTS
Bezza
Gidudu
Tendenedzai
Aina
Bhuimik
Na Shen
Mashangoane
Khumalo
Ngwenya
Hamad
Tabana
Prithiraj
Ichipi
Kyomuhimbo
Shifting knowledge to insight


Masters' & Early PhD Students
Mabaso
Ndumo
Tlaka
Mugumo
Malunga-Makatu
Miranda Peta
Mphinyane
Mojela
Gyasi
Mzimande
Manoto
Mongale
Schutte
Shifting knowledge to insight



Lead Researchers & Students – Official List

Lead Researchers

Prof HG Brink (Lead), Prof SM Tichapondwa, Dr Samuel Iwarere, Prof EMN Chirwa, Dr Lusani Mulaudzi, Dr Gerrit Kornelius, Prof MO Daramola, Dr Randal Albertus, Dr Zakhele Khuzwayo

Current Student Assistants

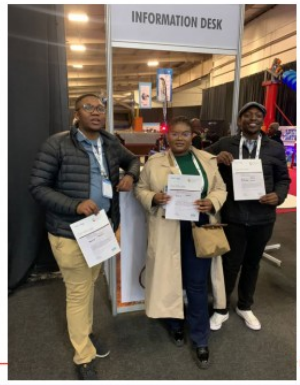
Dr Brian Gidudu, PostDoc
Dr Job Tendenedzai, PostDoc
Dr Fisseha Bezza, Postdoc
Dr Samuel Aina, Postdoc
Dr Madhumita Bhaumik, Postdoc
Dr Na Shen, Postdoc (Tsinghua University, Beijing)
Miss Khanyisile Malunga-Matatu, PhD
Miss Boitumelo Mashangoane. PhD
Mr Shane Tabana, PhD
Ms Khathutshelo Muedi, PhD
Mr Kenneth Maseko, PhD
Mr George Tlaka, PhD
Mr Andani Mphinyane, PhD

6 Postdocs

24 PhD students

20 Masters students

STUDENT COMPETITION AWARD



A group of students lead by Prof Deon Brink won the 1st Price in the 3rd University Challenge Africa of the IFAT Trade Fair, 6 June 2023, Johannesburg. The winning Team will compete in Munich Germany in May 2024 with all costs covered by DAAD.

Winners: Sentle Mojela, Carol Luposo, Mthobisi Manzini

to insight

SUMMARY OF ACHIEVEMENTS - PUBLICATIONS

PUBLICATIONS AND RESEARCH PROFILE

- Published a total of 45 journal articles in 2023.
- Published a total of 2 Book Chapters in 2023
- Published a total of 28 conference papers in 2023

Notable Achievements

- 82 % of the 2023 research credits for the Department of Chemical Engineering came from the Water Utilisation & Environmental Engineering Group.

Shifting knowledge to insight

ALIGNMENT TO SDG's

- **SDG 6.0:** Ensure availability and sustainable management of water and sanitation for all.
- **SDG 7.0:** Ensure access to affordable, reliable, sustainable and modern energy for all.
- **SDG 11.0:** Make cities and human settlements inclusive, safe, resilient and sustainable.

Shifting knowledge to insight

LATEST PROJECT AWARD - 2024 INTERNATIONAL NETWORK

World University Networks (WUN) Project on "*Sustainable Interventions for Recalcitrant Invasive Species Affecting Water Quality in North America, South East Asia and Southern Africa – the Case of the Hyacinth Plant.*"

Members (7 Universities Collaboration):

University of Pretoria (Lead Team), University of Leeds
University of Technology Sydney
Tecnológico de Monterrey
Makerere University, Guru University (Uganda)
University of Venda, Universiti Teknologi Malaysia

Shifting knowledge to insight

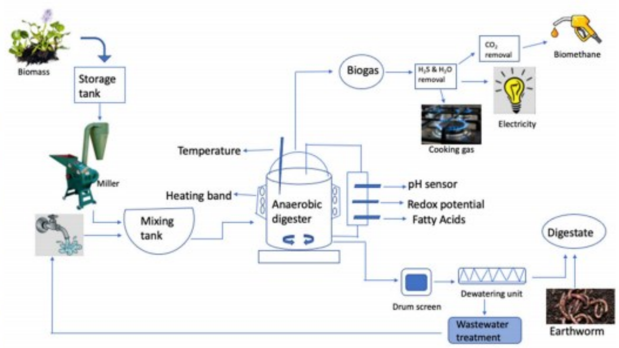
Water Hyacinth Infestation Problems

Hartbeespoort Dam, South Africa

Lake Victoria North West, Uganda

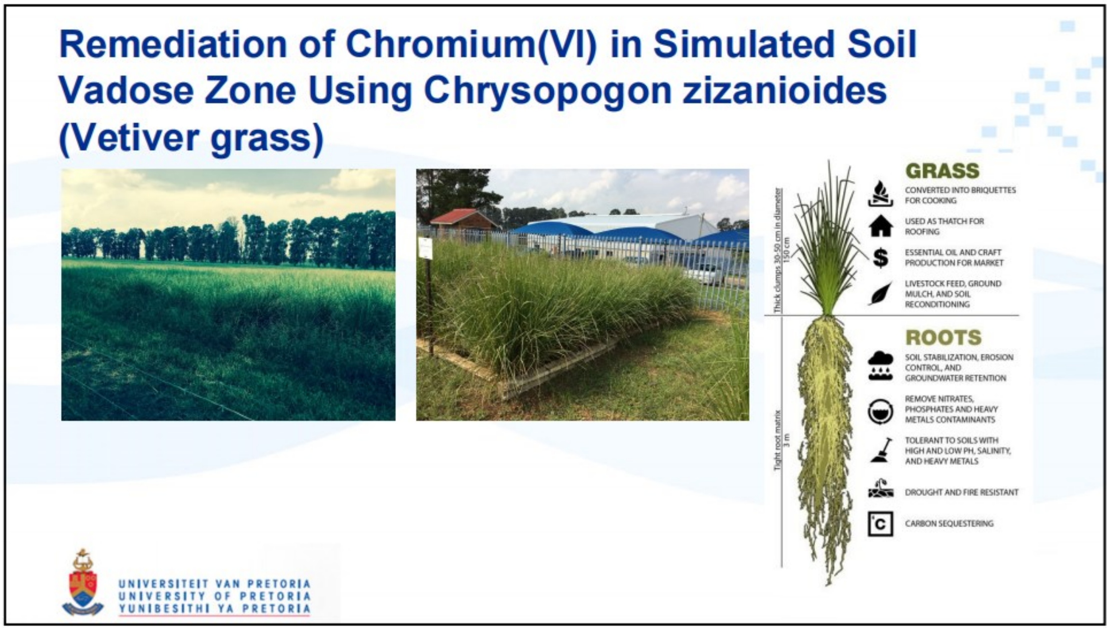
Volarisation of Water Hyacinth – Bioenergy Generation and Hydrogen Economy

Harvesting

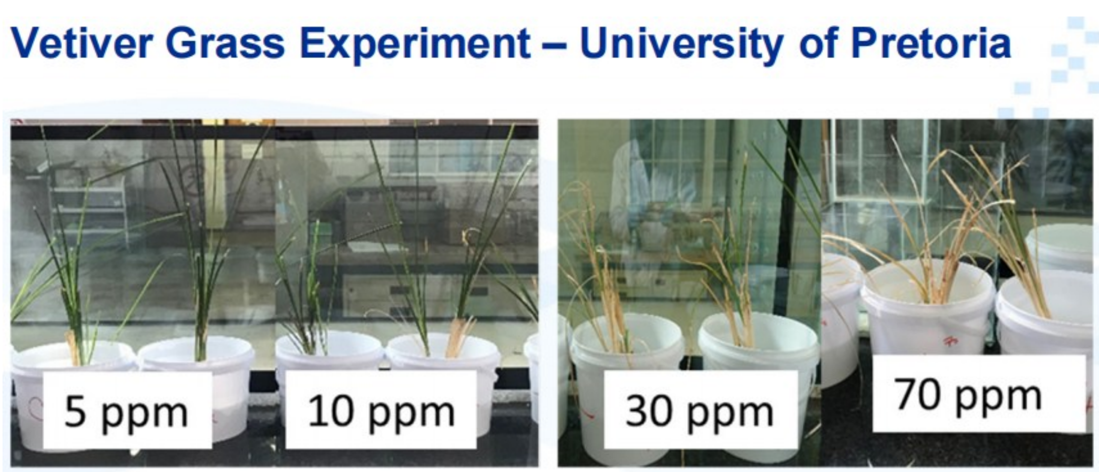


Conversion to Bioenergy

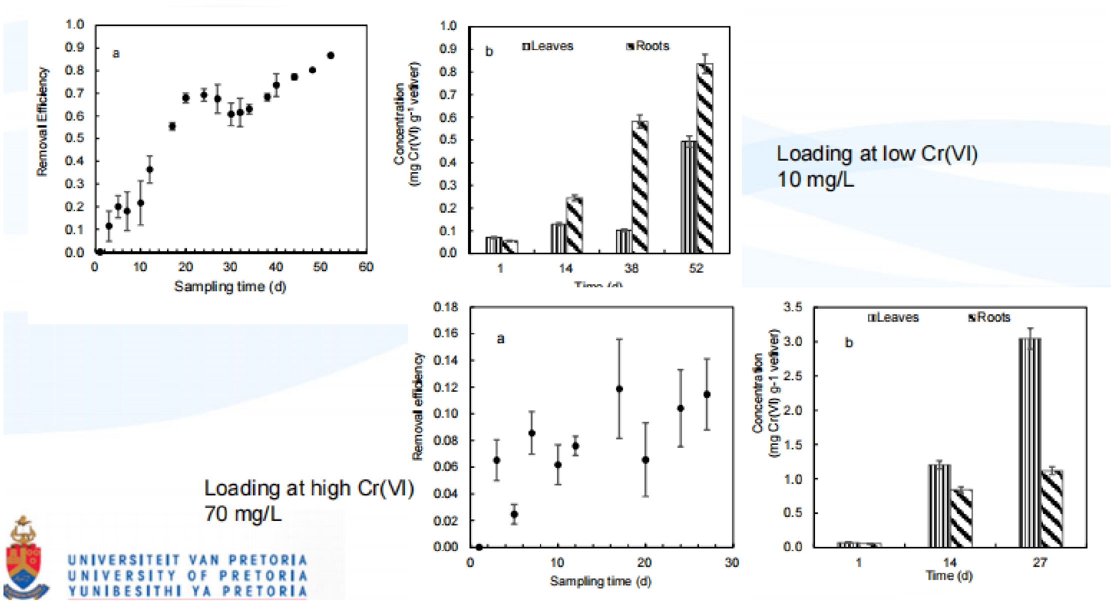
Other Biomass Based Technologies


Remediation of Chromium(VI) in Simulated Soil Vadose Zone Using Chrysopogon zizanioides (Vetiver grass)
Thick clumps 30-50 cm in diameter
150 cm
Tight root matrix
3 m
GRASS
CONVERTED INTO BRIQUETTES FOR COOKING
USED AS THATCH FOR ROOFING
ESSENTIAL OIL AND CRAFT PRODUCTION FOR MARKET
LIVESTOCK FEED, GROUND MULCH, AND SOIL RECONDITIONING
ROOTS
SOIL STABILIZATION, EROSION CONTROL, AND GROUNDWATER RETENTION
REMOVE NITRATES, PHOSPHATES AND HEAVY METALS CONTAMINANTS
TOLERANT TO SOILS WITH HIGH AND LOW PH, SALINITY, AND HEAVY METALS
DROUGHT AND FIRE RESISTANT
CARBON SEQUESTERING
UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

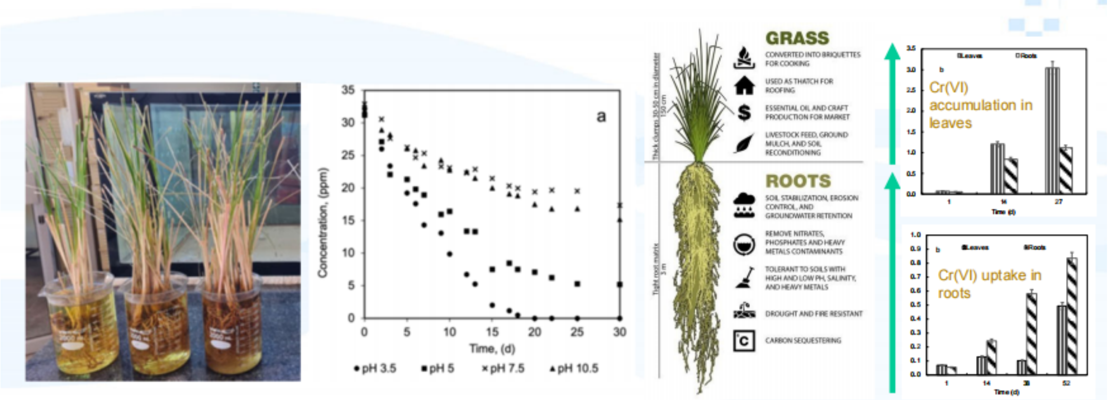

Vetiver Grass Growth in Controlled Environments


Vetiver Grass Experiment – University of Pretoria
5 ppm
10 ppm
30 ppm
70 ppm

Vetiver Grass Results

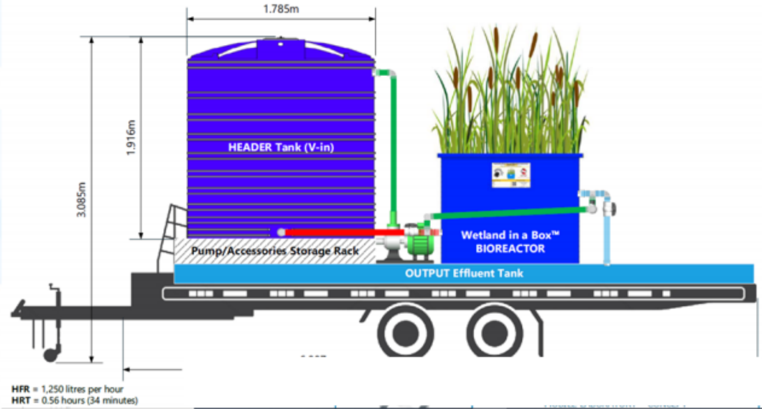


Summary of Findings



Project 2 on Biomass: Up-Flow Modular Wetlands (Kenneth Mabaso, PhD student)

Modular wetland unit



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Mobile test unit with feed tank for up-flow submerged wetland system.

Other Collaborations

- World University Networks Project for Water Hyacinth Remediation Project by (UP, U Leeds, Tec Monterrey, U Tec Sydney, U Tek Malaysia, U Makerere, University of Venda)
- Lilongwe University of Agriculture and Natural Resources (LUANAR)
- Malawi University of Business and Applied Sciences (MUBAS)
- Malawi University of Science and Technology (MUST, Thyolo)
- University of Venda (UniVen, Thohoyandou, SA)
- City of Cape Town (Cape Town, SA)
- UP, uMngeni-uThukela Water Networking Collaboration (Durban. SA)

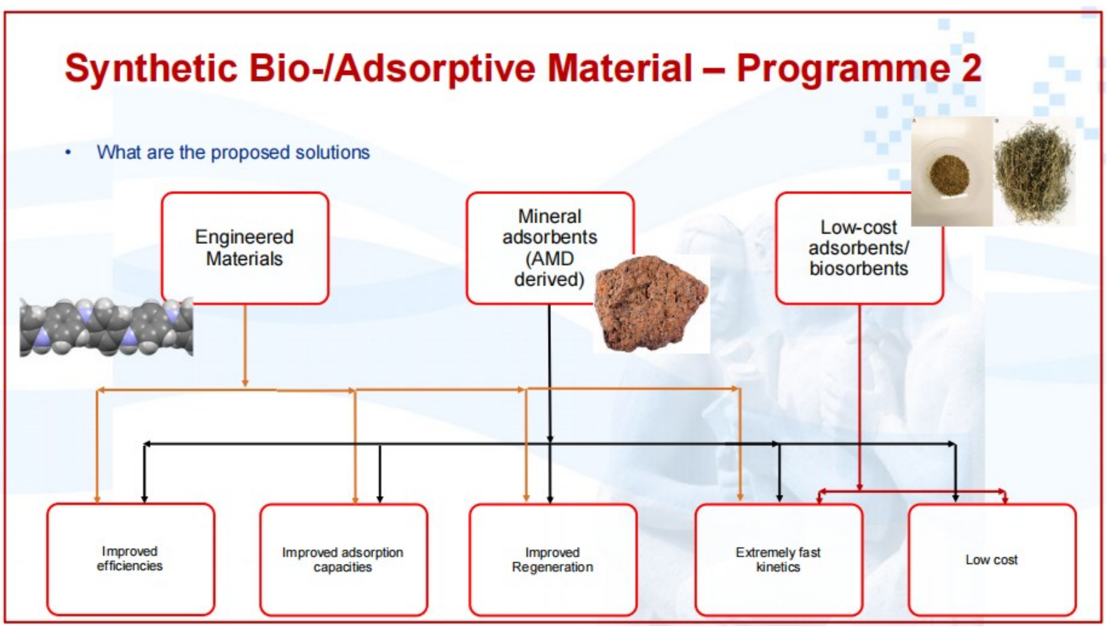
RESEARCH PROGRAMMES OVERVIEW OVER A FIVE YEAR PERIOD

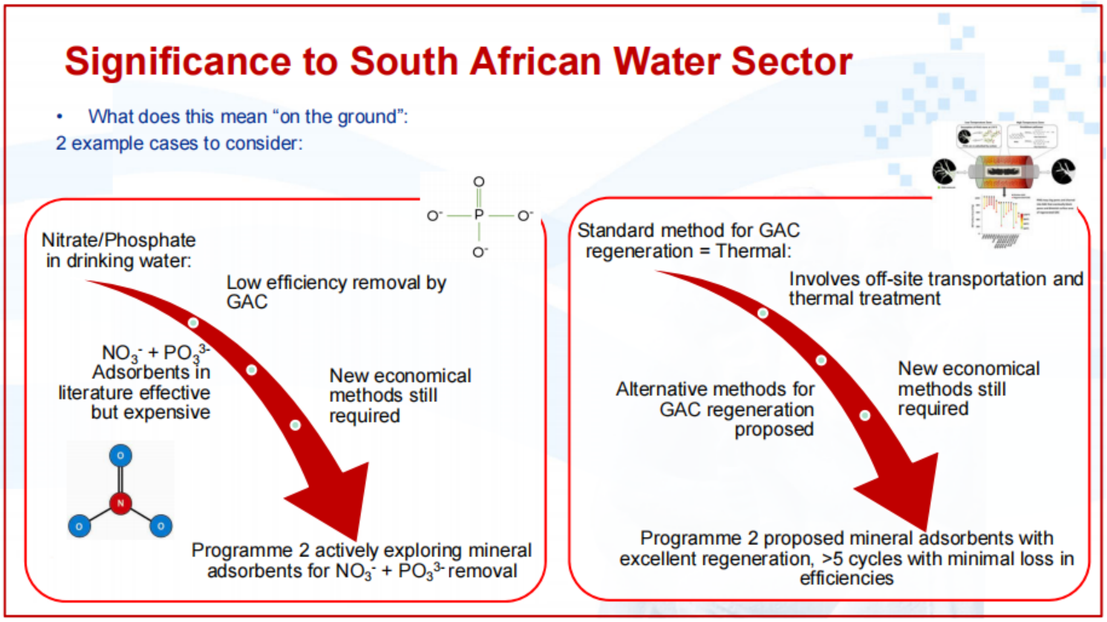
FOCUS TOPIC	Programme Name	Year 1	Year 2	Year 3	Year 4	Year 5
Thrust 1	Surface chemical technologies for treatment of water and wastewater including valorisation of materials for this purpose (Revised title in 2022).		Sorption Processes and Value Chain Analysis.	Sorption Processes and Value Chain Analysis.	Sorption Processes and Value Chain Analysis	Planning of Pilot studies for biosorbents derieved from AMD and Biochar
Thrust 2	Application of established and novel membrane-based technologies for water Treatment and non-conventional water desalination processes.	1. Literature review 2. Procurement and testing of different commercially membranes WRC Project on Solar Desalination: R 500 000.00 p/a	1. Development of FO membranes 2. Solar desalination via 3D Printed graphene. 3. Energy saving processes including microbial fuel cells, .	1. Development of FO membranes 2. Solar desalination via 3D Printed graphene. 3. Energy saving processes including microbial fuel cells, NRF CPRR Funds: R 1 100 000.00 p/a	1. Development of FO membranes 2. Solar desalination via 3D Printed graphene. 3. Energy saving processes including microbial fuel cells,	1. Planning of Pilot studies for desalination processes 2. Applications for doped 3D Printed graphene for solar desalination 3. Energy saving processes including microbial fuel cells,
Thrust 3	Evaluation of conventional and advanced oxidation processes to address both biological challenges and undesirable organic compounds in water.	1. Literature review 2. Synthesis and characterize visible light photocatalysts	3. Optimization of batch reactor parameters using simulated water	4. Explore possible catalyst recovery 5. Conduct pilot studies existing plant	1. Explore possible catalyst recovery 2. Conduct pilot studies existing plant	1. Explore possible catalyst recovery 2. Conduct pilot studies existing plant
Thrust 4	Assessment of appropriate technologies for the treatment of wastewater and other polluted water sources to industrial and potable standards. (Manoko and Assis, Biochar Application; Bezza WRC, Graphene 3D Printing Nanotechnology for desalination)		1. Literature review 2. Experimental Development for Hydrothermal Carbonisation, Low Temp Carb, Graphene 3D Pronting	3. Experimental Trials	Planning for pilot studies – development for piloting, Brink: TIA Project – R 500 000.00 p/a WUN 2023, R 458 000.00 p/a on Hyacinth Research	1. Field evaluations of the sustainable remediation of nuisance invasive species 2. Modular wetland development 3. Piloting metal bioremediation

Shifting knowledge to insight

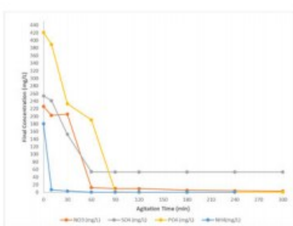
Current Research Programmes Expanded

– Adsorption & Biosorption Technologies

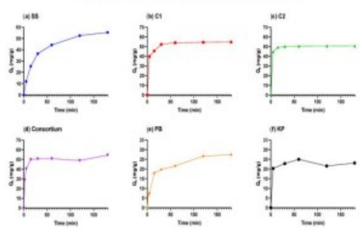




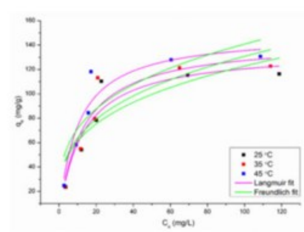
Nutrient Removal – AMD Recover Material



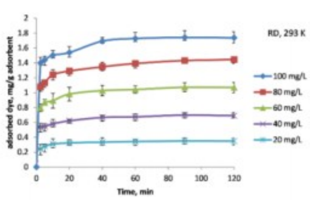
Lead Removal – Biosorption



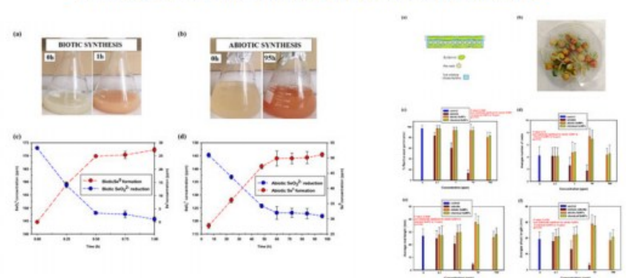
Copper Removal – Burnt Tyre Waste

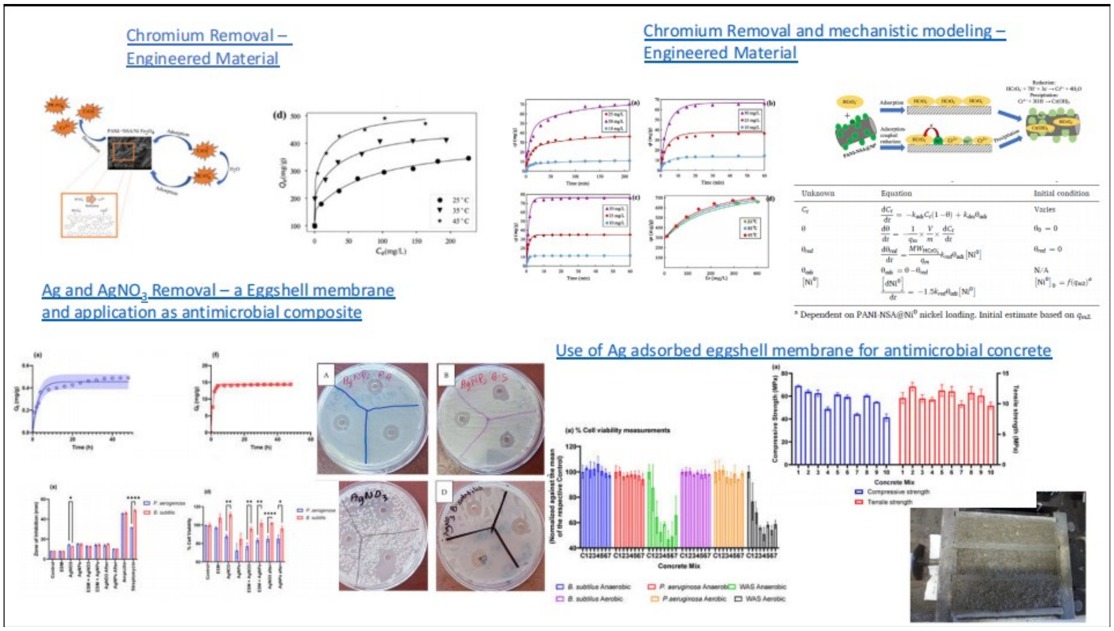


Dye Removal – Biosorption

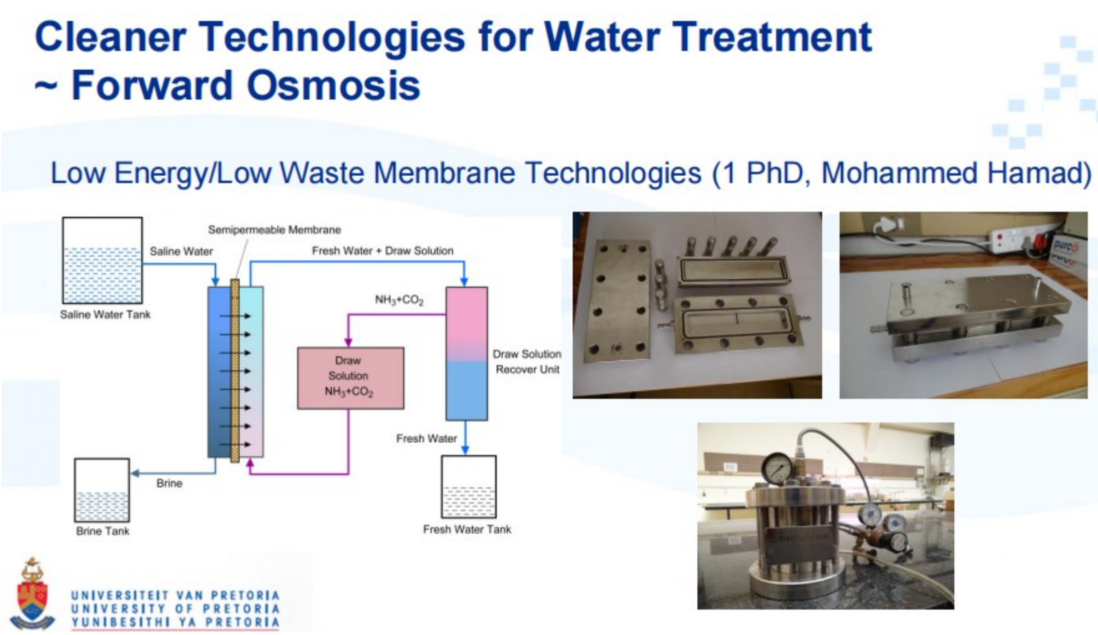


Biosynthesis and application of SeNPs in plant germination





Membrane Technologies & Desalination



Summary of Results

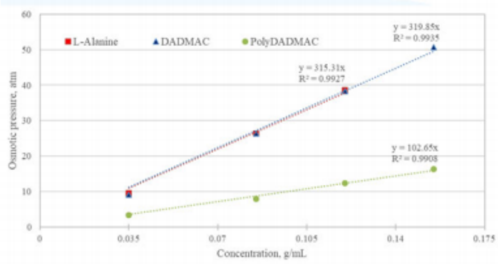
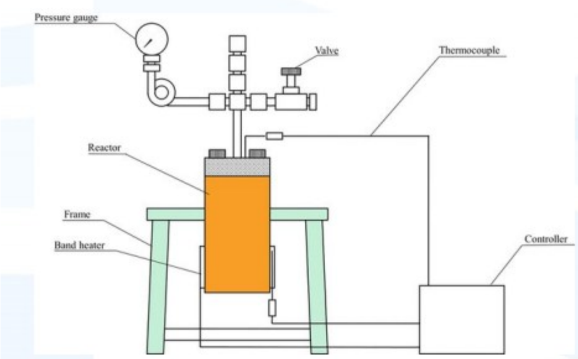


Table 4.1: Osmotic pressure and pH values of the Draw Solutions concentration.

Draw Solution		Concentrations			
		0.035 g/mL	0.085 g/mL	0.120 g/mL	0.155 g/m
L-Alanine	OP	09.54 atm	26.31 atm	38.63 atm	------
	pH	6.53	6.96	6.24	------
DADMAC	OP	9.10 atm	26.41 atm	38.22 atm	50.60 atm
	pH	7.22	7.44	7.73	7.65
PolyDADMAC	OP	03.39 atm	07.95 atm	12.32 atm	16.38 atm
	pH	6.28	6.15	6.41	6.55

The dynamic viscosity results were measured by the Rheoplus 3.0X software as explained in

Hydrothermal Carbonisation of Biomass for Application in Solar Energy Absorber for Solar Desalination of Sea Water (Englatina Assis, UP, Prof Leonard Tijing, UTS)



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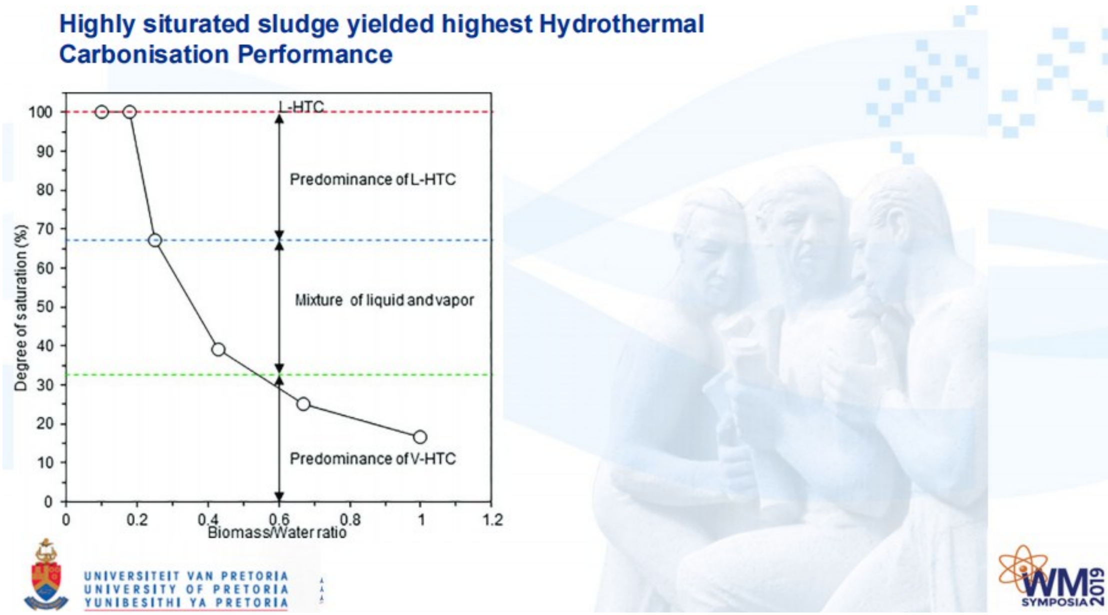
Highly siturated sludge yielded highest Hydrothermal Carbonisation Performance
L-HTC
Predominance of L-HTC
Mixture of liquid and vapor
Predominance of V-HTC
Degree of saturation (%)
Biomass/Water ratio
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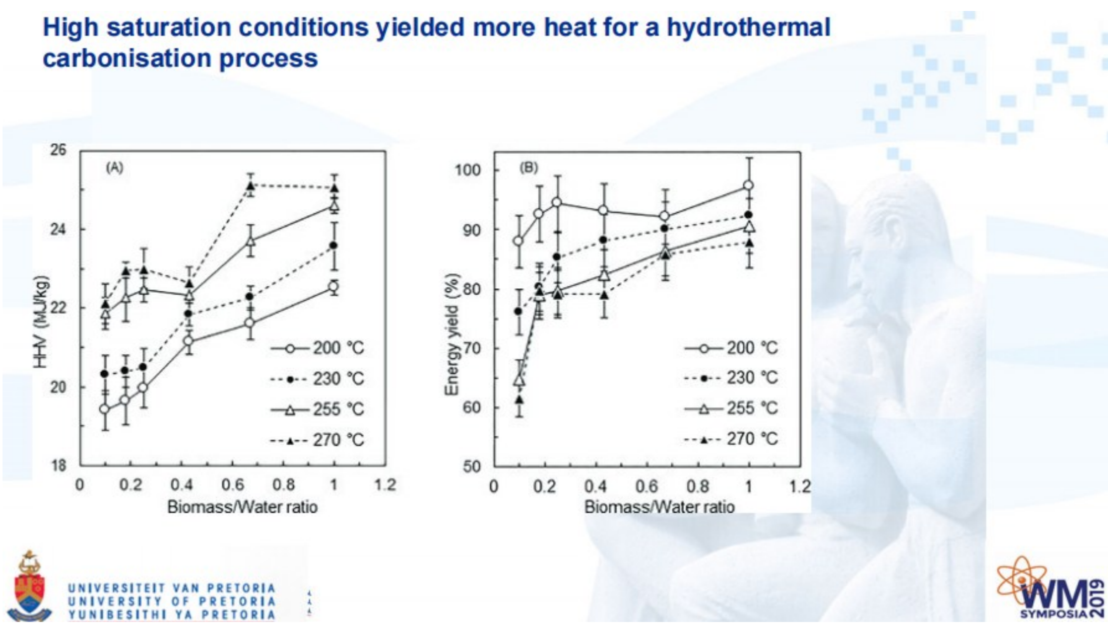
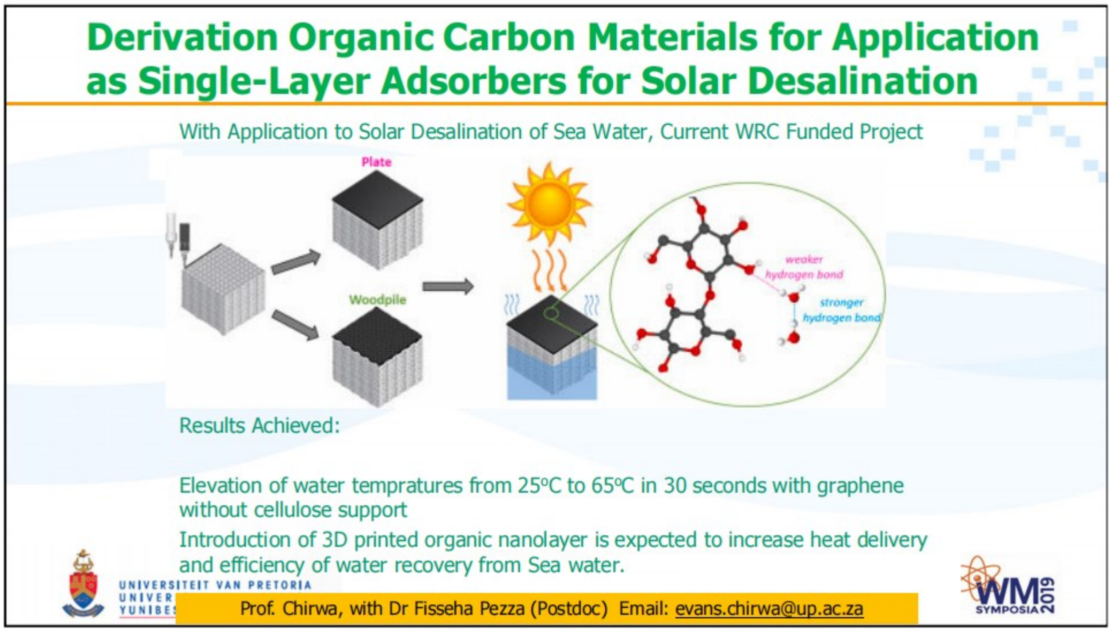
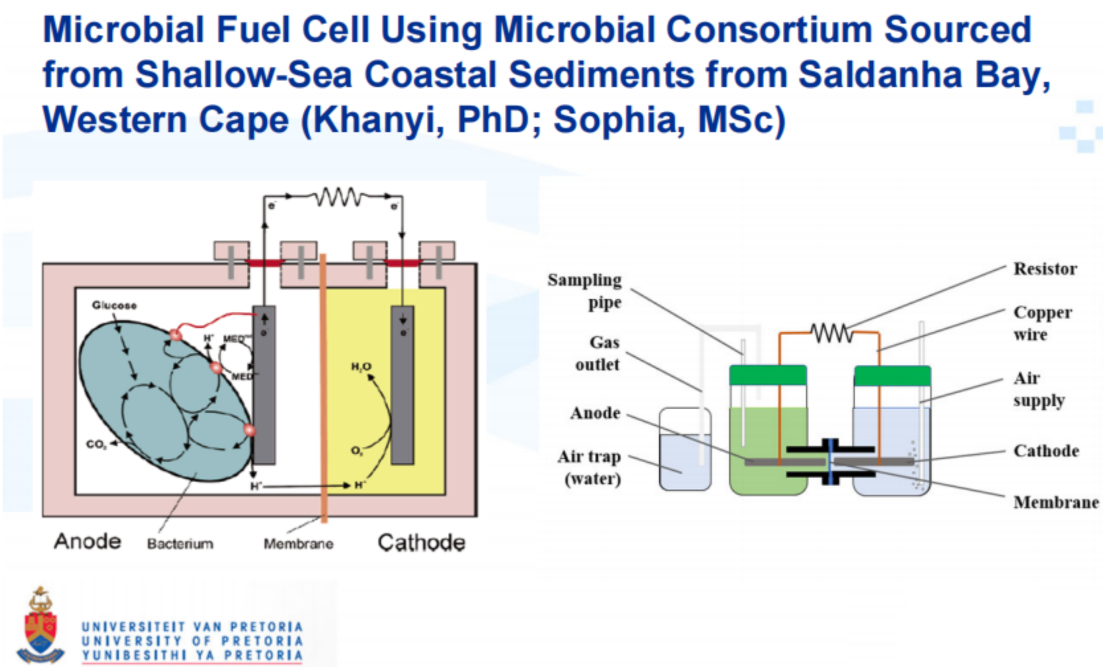
WM SYMPOSIA 2019


High saturation conditions yielded more heat for a hydrothermal carbonisation process
(A)
HHV (MJ/kg)
Biomass/Water ratio
200 °C
230 °C
255 °C
270 °C
(B)
Energy yield (%)
Biomass/Water ratio
UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
WM SYMPOSIA 2019


Derivation Organic Carbon Materials for Application as Single-Layer Adsorbers for Solar Desalination
With Application to Solar Desalination of Sea Water, Current WRC Funded Project
Plate
Woodpile
weaker hydrogen bond
stronger hydrogen bond
Results Achieved:
Elevation of water tempratures from 25ºC to 65ºC in 30 seconds with graphene without cellulose support
Introduction of 3D printed organic nanolayer is expected to increase heat delivery and efficiency of water recovery from Sea water.
UNIVERSITEIT VAN PRETORIA
Prof. Chirwa, with Dr Fisseha Pezza (Postdoc) Email: evans.chirwa@up.ac.za
WM SYMPOSIA 2019


Microbial Fuel Cell Using Microbial Consortium Sourced from Shallow-Sea Coastal Sediments from Saldanha Bay, Western Cape (Khanyi, PhD; Sophia, MSc)
Glucose
H_2O
O_2
CO_2
Anode
Bacterium
Membrane
Cathode
Sampling pipe
Gas outlet
Anode
Air trap (water)
Resistor
Copper wire
Air supply
Cathode
Membrane
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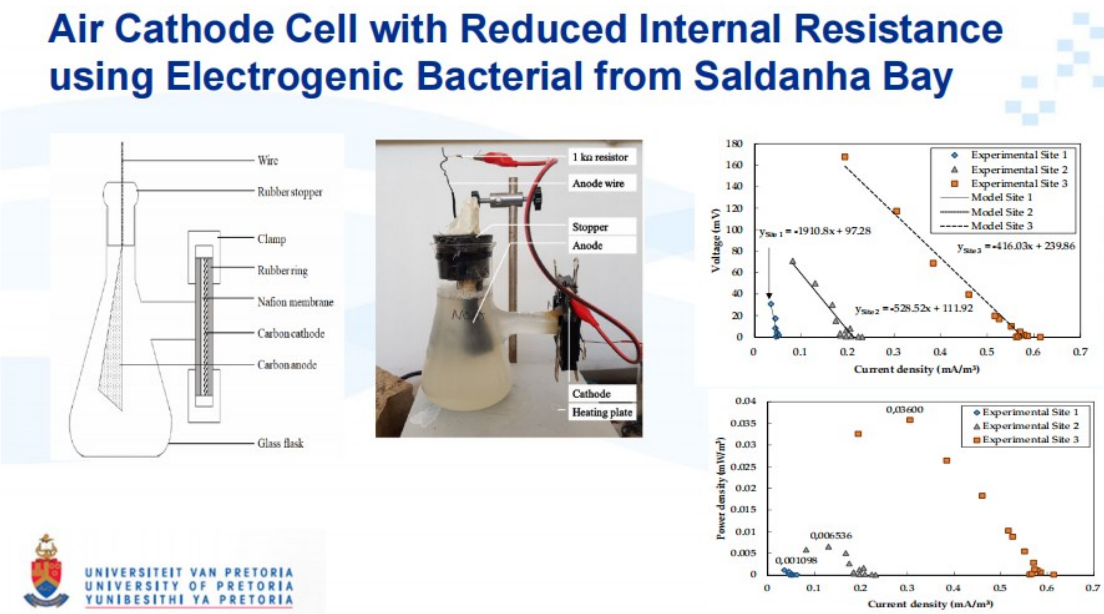
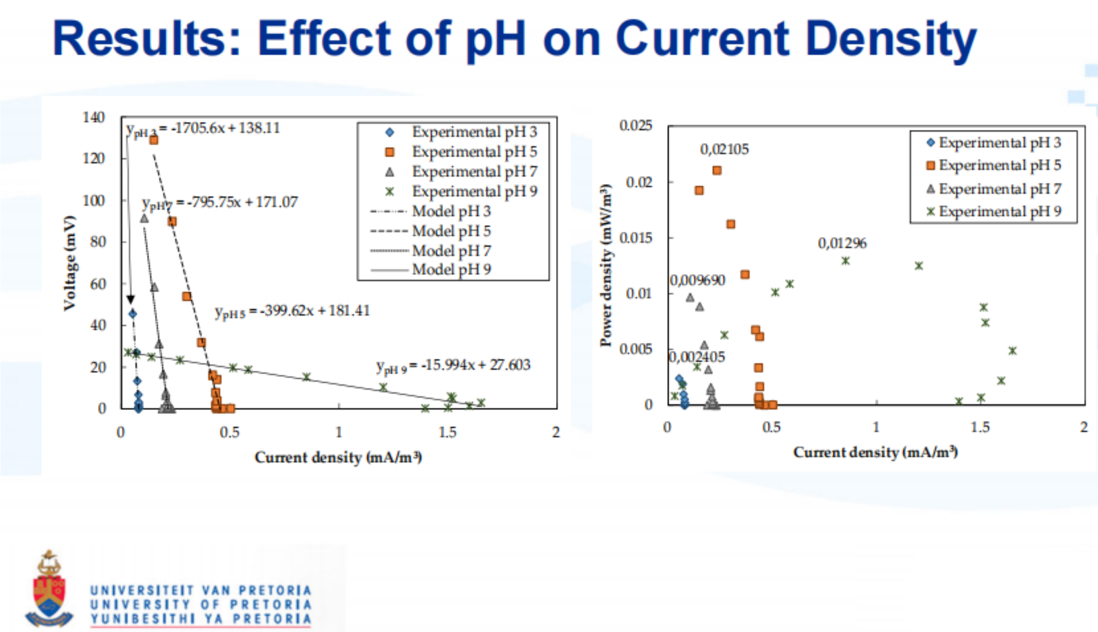
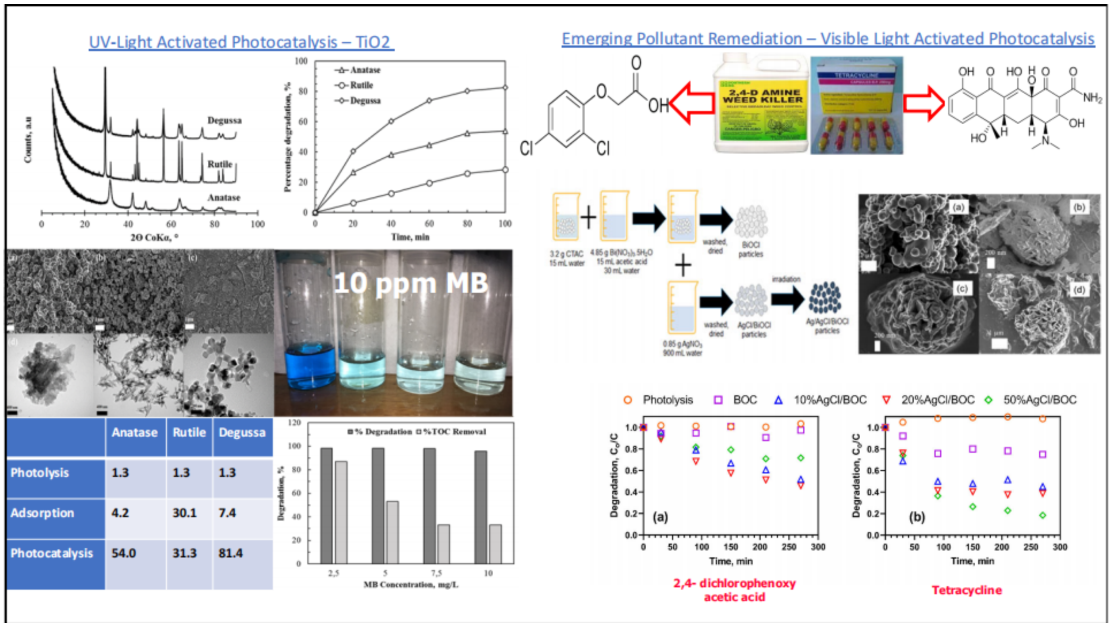
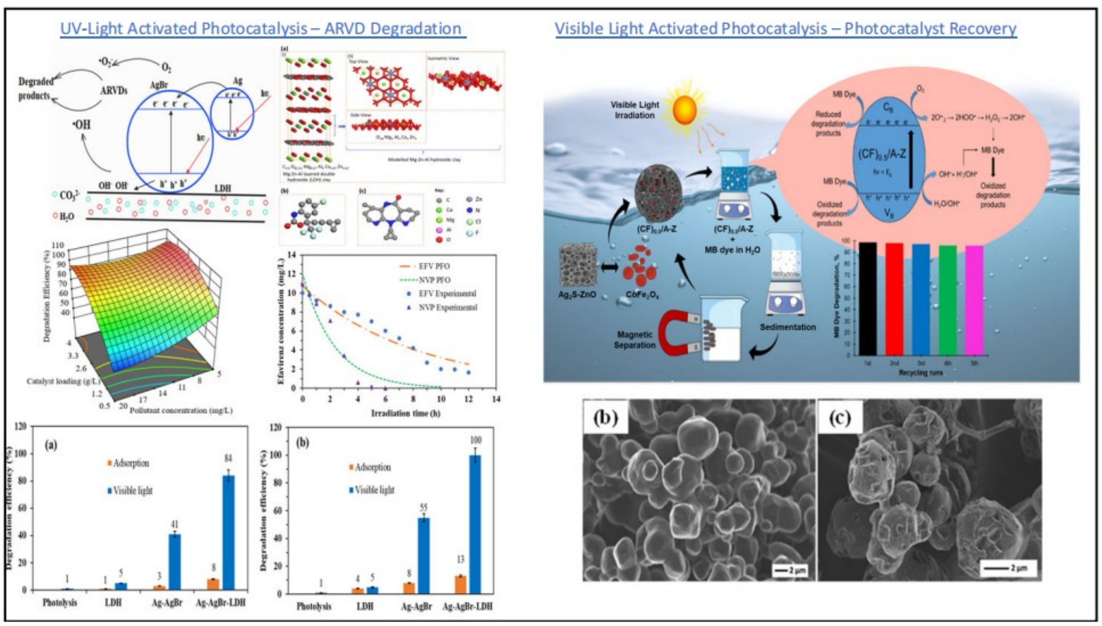
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA





Advanced Oxidation and Photocatalytic Processes


UV-Light Activated Photocatalysis – TiO2
Emerging Pollutant Remediation – Visible Light Activated Photocatalysis
Degussa
Rutile
Anatase
Counts, a.u
2Θ CoKα, °
Percentage degradation, %
Time, min
10 ppm MB
Anatase
Rutile
Degussa
Photolysis 1.3 1.3 1.3
Adsorption 4.2 30.1 7.4
Photocatalysis 54.0 31.3 81.4
% Degradation
%TOC Removal
Degradation, %
MB Concentration, mg/L
Photolysis
BOC
10%AgCl/BOC
20%AgCl/BOC
50%AgCl/BOC
Degradation, C_0/C
Time, min
2,4- dichlorophenoxy acetic acid
Tetracycline


UV-Light Activated Photocatalysis – ARVD Degradation
Visible Light Activated Photocatalysis – Photocatalyst Recovery
Degraded products
ARVDs
AgBr
Ag
•OH
LDH
CO_3^{2-}
H_2O
Degradation Efficiency (%)
Catalyst loading (g/L)
Pollutant concentration (mg/L)
EFV PFO
NVP PFO
EFV Experimental
NVP Experimental
Efavirenz concentration (mg/L)
Irradiation time (h)
Adsorption
Visible light
Degradation efficiency (%)
Photolysis
LDH
Ag-AgBr
Ag-AgBr-LDH
Visible Light Irradiation
MB Dye
Magnetic Separation
Sedimentation
MB Dye Degradation, %
Recycling runs
(b)
(c)

UNIVERSITY OF PRETORIA MASTER'S & PHD PROGRAMME

Water Utilization (Research Degrees)

- MSc Water Utilisation Engineering (CVD 800)
- MSc Water Utilisation Appl. Sci. (CVD 807)
- PhD Chemical Engineering(CIR 990)
- PhD Chemical Technology (CCT 990)

Environmental Engineering (Research Degrees)

- MSc Environmental Engineering (CVD 800)
- MSc Environmental Technology(CVD 807)
- PhD Chemical Engineering (CIR 990)
- PhD Chemical Technology (CCT 990)

TRAINING PROGRAMMES THAT CAN BE EXPANDED TO MUBAS

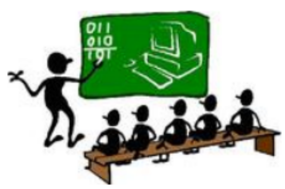
MSc. MEng - Water Resources Engineering (2 years)
PhD – Water Resources Engineering (3 years)

BSc - Environmental Engineering/Technology (4 year)
MSc. MEng - Environmental Engineering (2 years)
PhD - Environmental Engineering (3 years)

COURSES ALREADY IN PLACE THAT CAN BE ADOPTED

Water Utilization (Honours)

- Chemical Water Treatment (WCW 780/787)
- Biological Water Treatment (WBW 780/787)
- Water Quality Management (WQB 780/787)
- Industrial Waste Engineering (WAI 780/787)
- Separation Technology (CKY 780/787)
- Principles of Environmental Engineering (CEM 780/787)
- Water Supply and Sanitation (EWM 822)



Short Courses Presented

- Water Quality Management and Effluent Treatment
- Advanced Water Treatment Processes
- Environmental Management and Regulation
- Operational of Water and Wastewater Treatment Plants
- Waste Minimisation and Remediation
- Modelling and Simulation of Wastewater Treatment Processes
- Water Analysis and Monitoring

Shifting knowledge to insight

AFRICA POSITIONING AS FUTURE LEADER IN 4IR, AI, TECH & ECONOMY

The youngest continent based on average age
The fast growing economies
The largest reserves of natural resources
Most isolated regarding world war affairs

The late Prof Jiří Jaromír Klemeš, Brno University of Technology, Czech Repoblic

Shifting knowledge to insight

THANK YOU

South Campus, Building 2, Room 1-27, Hatfield
Tel: +27 (0) 12 420 5894 | Email: evans.chirwa@up.ac.za | Web: https://www.up.ac.za/chemical-engineering

KEYNOTE SPEAKER 2: Construction and Transport

Eng. Prof. Grant Keelebe Kululanga, Former Principal, The Polytechnic, UNIMA

Distinguished Guests, Esteemed Scholars, Industry Experts, and Fellow Engineers, it is a great honor and privilege to stand before you today at this prestigious annual conference of the School of Engineering, where we gather to discuss and explore the latest research in construction, materials, and transport. As we step into a future shaped by rapid technological advancements and global challenges, it is imperative that we focus on sustainable and cutting-edge engineering solutions that will define the next generation of infrastructure and mobility.

Innovations in Construction

The construction industry is at the forefront of technological transformation. Recent innovations have revolutionized how we design, build, and maintain infrastructure. The adoption of Building Information Modeling (BIM) has enhanced project visualization, improved coordination among stakeholders, and reduced waste (Eastman et al., 2020). Moreover, 3D printing technology is emerging as a game-changer, enabling cost-effective and sustainable construction with minimal material wastage (Shakor et al., 2021). Another transformative development is the use of modular and prefabricated construction, which significantly reduces construction time, labor costs, and environmental impact (Lawson, Ogden, & Goodier, 2022). This approach has been particularly effective in addressing housing shortages and emergency shelter needs.

Furthermore, the integration of robotics and artificial intelligence (AI) is improving efficiency in construction sites. AI-driven project management tools are optimizing resource allocation, while autonomous equipment is enhancing safety and productivity (Zhou et al., 2023).

Innovations in Materials

Material science is a cornerstone of engineering innovation. The need for sustainable and resilient materials has led to significant breakthroughs in this field. The development of self-healing concrete, which can autonomously repair cracks, is extending the lifespan of structures and reducing maintenance costs (De Belie et al., 2021). Similarly, graphene-enhanced materials are offering superior strength and durability while maintaining lightweight properties (Bissett et al., 2022).

Recycled materials are also playing a crucial role in sustainable construction. The use of recycled plastic aggregates and fly ash-based geopolymer concrete is reducing reliance on virgin resources while lowering carbon emissions (Rashid et al., 2023). In addition, biodegradable construction materials, such as mycelium-based insulation and bamboo composites, are paving the way for eco-friendly infrastructure (Jones et al., 2024).

Innovations in Transport

The transport sector is undergoing a paradigm shift towards sustainability, efficiency, and connectivity. The development of smart transportation systems powered by the Internet of Things (IoT) is optimizing traffic flow, reducing congestion, and enhancing road safety (Litman, 2023). Autonomous and electric vehicles (EVs) are revolutionizing urban mobility, reducing emissions, and lowering transportation costs (Gehrke et al., 2022).

One of the most groundbreaking advancements in transport infrastructure is the concept of hyperloop technology, which aims to achieve ultra-high-speed travel with minimal environmental impact (Elbanhawi et al., 2023). Similarly, the rise of drone-based logistics and air taxis is reshaping last-mile delivery and urban mobility, providing faster and more efficient transportation solutions (Goyal & Reiche, 2024).

Another significant trend is the emphasis on green transportation, including the use of hydrogen-powered trains and electric buses. Cities worldwide are investing in smart public transit systems, integrating real-time data analytics to enhance commuter experiences and reduce energy consumption (Scholz et al., 2024).

Conclusion

As we embrace the future, it is imperative for engineers, researchers, and policymakers to collaborate in fostering sustainable, innovative, and resilient solutions in construction, materials, and transport. By leveraging cutting-edge technologies, embracing sustainable practices, and prioritizing efficiency, we can build a smarter and more sustainable world. Let this conference serve as a platform to inspire groundbreaking ideas, forge meaningful partnerships, and drive progress in engineering. Together, we have the power to shape the future of infrastructure and mobility for generations to come.

KEYNOTE SPEAKER 3: Water, Sanitation and Environment

Bryson Mkomaanthu, CEO, PressCane Limited

Title: Engineering Hope: Transforming Water, Sanitation, and Environmental Challenges into Sustainable Solutions"

Key Issues raised:

1. Water and Sanitation Crisis: Millions lack access to safe water and sanitation, increasing vulnerability to diseases and affecting education outcomes.

2. Environmental Degradation: Land degradation, deforestation, and pollution are escalating natural disasters and threatening ecosystems.

3. Insufficient Infrastructure and Policy Implementation: Existing policies are often not matched with adequate infrastructure and enforcement, limiting sustainable impact.

Way forward to attain conference agenda:

1. Promote Context-Based Engineering Solutions: Encourage the adoption of technologies that promote recycling or reuse of effluent, renewable energy and water-saving sanitation systems.

2. Enhance Policy and Planning Capacity: Strengthen policy enforcement and ensure infrastructure anticipates future environmental and demographic changes.

3. Foster Research, Education, and Collaboration: Support innovation through academia-industry partnerships and embed environmental themes into education and public outreach.

KEYNOTE SPEAKER 4: ICT, AI and Water

Eng. Dr Mathews Mtumbuka, CEO & Founder WEAGLE Holdings

Topic: Trends in ICT, AI AND WATER

INTRODUCTION

The world has been governed by a series of industrial revolutions. From the invention of steam engine through the discovery of vehicles and aeroplanes and remarkably telephony including the landmark wireless mobile communication systems, we see the world ever changing. Now we have the advent of Artificial intelligence that influences all facets of modern life. This paper reviews the past, present and future of industrial and technological revolutions in the context of Global as well as Malawian trends.

INDUSTRIAL REVOLUTIONS

1. **First Industrial Revolution 1765**: Steam power and mechanization enabling industry to replace agriculture as backbone of economy.
2. **Second Industrial Revolution 1870**: New forms of energy: electricity, gas & Oil. Electrical Assembly Line. Invention of vehicles and aero planes. Most important revolution.
3. **Third Industrial Revolution 1969:** Emergence of Nuclear energy. Advances in semiconductors, electronics, telecoms and computers, PLCs & Robots.
4. **Fourth Industrial Revolution 2000:** Internet. Robotics and Artificial Intelligence. Machine Learning. Big Data. Internet of Things.

Specifically, the 4th Industrial Revolution which is the current regime is a fusion of advances in the following:

1. Artificial Intelligence (AI)
2. Machine Learning
3. robotics
4. the Internet of Things (IoT)
5. Web3
6. Blockchain
7. 3D printing
8. genetic engineering
9. quantum computing
10. Virtual Reality

ICT and Malawi Vision 2063

The overarching long term vision for Malawi is contained in the Malawi 2063 document which alludes also to the importance of Information and Communication Technology as an enabler of development. Specifically, this is contained under Enabler number 6 which is Economic Infrastructure.

- We shall have robust ICT infrastructure with cross-country coverage of reliable and affordable services fostering technological adoption and digital access
- As a country, we shall have a world-class digital economy that is globally competitive
- We shall promote investment in ICT infrastructure to increase digital access and technological adoption.

Artificial Intelligence (AI)

Artificial intelligence (AI) is the simulation of human intelligence processes by machines, especially computer systems. Specific applications of AI include expert systems, natural language processing, speech recognition and machine vision.

Artificial Intelligence (AI) has a wide range of areas of application. One of the key areas where AI has already demonstrated big impact is the field of business leadership. Leadership is all about making informed decisions in a world where data is abundant and complex. AI helps leaders to decipher complex data landscapes, extracting valuable insights and offering a clear road map for the future. This clarity empowers leaders to make quick, accurate decisions during time-sensitive situations.

Big Data and AI

Big data refers to the volume, velocity, and variety of data that artificial intelligence technologies are using to discover patterns and correlations hidden in massive collections of data

Companies like Netflix or Procter & Gamble leverage big data to anticipate market demand.

Predictive models are built for new products and services by classifying key attributes of past products then modeling the commercial success of those offerings.

Big data enables companies to gather data from website visits, social media interactions, and ads you click on. The data is then used to make improvements to the customer experience in ways such as delivering personalized offerings in hopes to reduce customer churn.

IMPACT OF AI ON JOBS

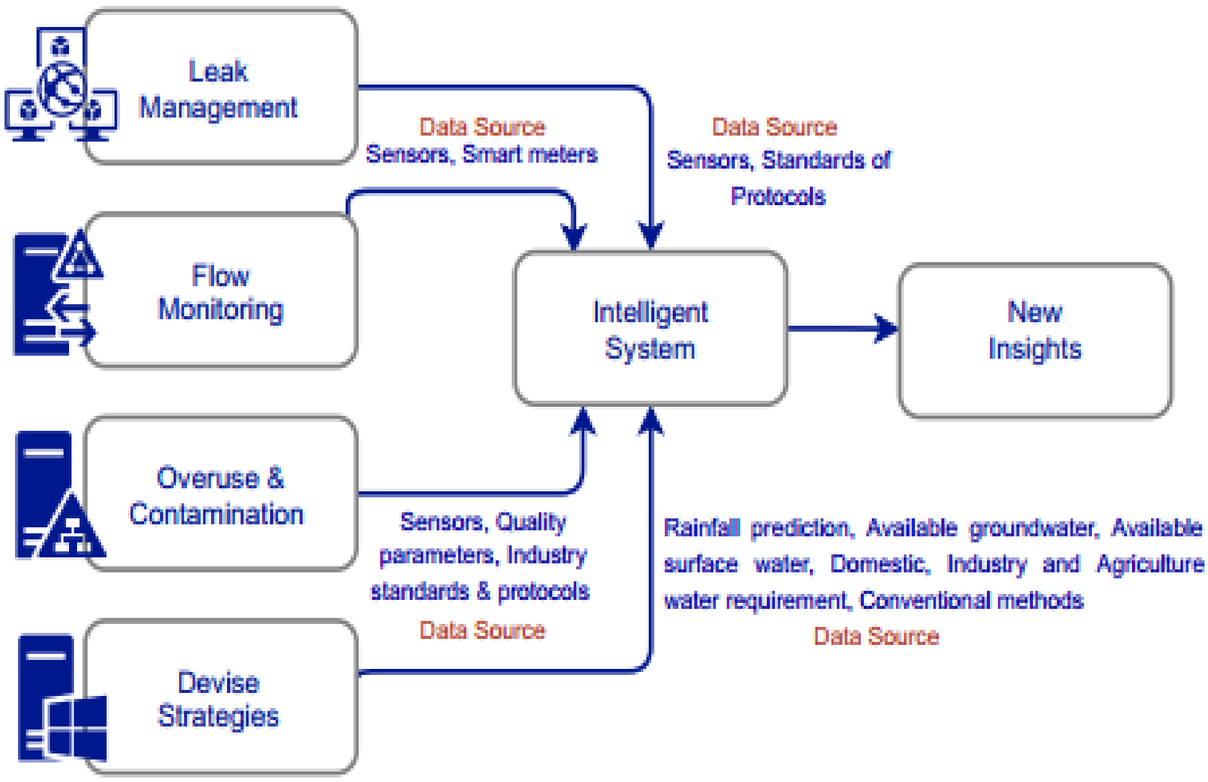
Like any other new development, the advent of AI brings with it also some adverse impacts especially on the job market. Due to its automation nature, some industries will lose jobs. Some of the employment sectors likely to be impacted by AI are as follows:
1- Data Entry Clerk
2- Telemarketer
3- Factory Worker
4- Cashier
5- Driver
6- Travel Agent
7- Bank Teller

Water Management

The deployment of ICT has been amerced in every domain and has found its way into the water management sector as well. Intelligent data analysis can render an efficient water management for improvising the water distribution and to minimize operational costs. Artificial Intelligent (AI) techniques can be deployed for effective decision making for the usage of water for various purposes. The combination of ICT with AI would facilitate achieving the Sustainable Development of the water sector

Smart Water Management

Below is a diagrammatic illustration of how ICT/AI can be used in the operation of a smart water management system.



AI in Water Treatment Process

AI has also proved to be very useful in the water treatment process as demonstrated below:

Process control	Analysis and Forecasting system
❶ Optimum control of pump	Ⓐ Prediction of the Demand for Water Supply
❷ Optimal Control of Inlet Valve	Ⓑ Prediction of Water Supply Time
❸ Optimal Coagulant Control	Ⓒ Measurement and analysis of pump efficiency
❹ Optimal control of chlorine	Ⓓ Calculation and analysis of sludge generation
❺ Optimum control of sedimentary sludge	Ⓔ Prediction of Water quality
❻ Optimal control of filter	Ⓕ Process simulation program
❼ Optimum drain water control	Ⓖ Self-diagnosis of Equipment and failure prediction
❽ Equivalent control of reservoir	
❾ Pipe leak detection	

Advantages of AI in the Water Management

AI has a number of advantages when applied in the management of water systems. Some of the advantages are as follows:

- ❑ Feature extraction and dimensionality reduction of the huge attributes;
- ❑ Finding the solution to a complex problem through parallel processing capabilities;
- ❑ Prediction of the target variables with a desired level of accuracy;
- ❑ Working with multiple data points in certain applications;
- ❑ Algorithms like RNN is useful for time-series prediction and analysis;
- ❑ Algorithms like DNN offers faster prediction and training;

AI and Cybersecurity

The global Cyber Security terrain is very big and ever expanding. In fact, the cybersecurity market was worth $173.5 billion in 2022. The good news is that AI algorithms can analyze network traffic to identify patterns that indicate a potential cyber threat. AI can detect anomalies, unusual traffic patterns, or suspicious behaviors that may go unnoticed by human analysts by processing large volumes of network data. Unfortunately, hackers too use AI to do dirty work in the digital space.

SUMMARY

AI has come to stay and is already beginning to impact every sector and every facet of life. Every profession and every field, especially engineering sectors need to immediately embrace and embed AI in the daily operations for continuous improvement to maximize operational efficiency and effectiveness.

KEYNOTE ADDRESS 5: Energy, Mining and Industry

Mr. Fredrick Josiya, MEng. - Petroleum Eng.; BEng. Hons - Mining Eng.
CEO Mining Solutions Ltd

Title: An overview of Extractive Sector (With emphasis in Mining)

The extractive industry refers to the sector of the economy that involves the extraction, processing, and production of raw materials from the earth's underground. This industry plays a crucial role in providing essential resources for various sectors, including construction, manufacturing, energy, and more.

In Malawi currently priority sectors are denoted as ATM, meaning, Agriculture, Tourism and Mining. Mining in Malawi is at middle stage. Currently Mining Sector has 20 Reconnaissance Licence; 143 Exclusive Exploration Licence and 141 Mining Licence in addition to numerous small and medium licenses. On oil and gas, in 2012 Malawi demarcated 9 exploration blocks for petroleum and investors came to start exploration work for oil & gas. At the moment due to some other factors, the exploration for petroleum is yet to be re-demarcated and advertised again for interested investors. In Malawi we have 21 hot springs sites which are very potential for geothermal development as an alternative source of energy generation besides HEP. This mean Malawi is privileged to be encompassed with all the main players of extractive industry.

According to Malawi Economic Report of 2023, Mining and quarrying contributes 1.1% to government revenue; 0.6% to the entire exports and 0.2% to the national GDP. From 2019 to 2022 there was constant growth of the mining sector and register slight increase in 2023. This means that more attention been to be put in mining sector to achieve the vision of Malawi 2063. Mining Sector have a tremendous potential to be a game change for the economy of Malawi as it does in other regional state in SADAC like Zambia, South Africa and Botswana. The government need to invest a lot in minerals exploration so that as a country we can specifically know our natural resources worth and plan properly for its extraction.

Major challenges of the extractive industry including the subset of mining sector among others are political will; financial resources; good governance ; human resources capacity and exploration limitations.

It takes political leadership to mobilize enough financial resources towards the mining sector in the national budget to enhance detailed minerals exploration and human capacity development that champions good governance to induce rapid mining growth.

Extractive industry in the education circles is growing very well and balanced in public universities with MUBAS offering Mining Engineering and MUST offering degree in Petroleum resources and geology being offered both by MUST and UNIMA.

It is very encouraging that our Head of State His Excellency Professor Lazarus McCarthy Chakwera throughout the past 5 years SONA, he has been including Mining as an outstanding sector of national interest. This is very commendable and encouraging.

What Malawi needs now is more action than talking. We have talked enough about mining. Our leaders now should make Malawi nation to walk the talk in mining development.

CONFERENCE PAPER PROCEEDINGS

SESSION 2A: Water, Sanitation and Environment

Paper 1: Exploring potential benefits that may accrue to the Government of Malawi by adopting the Water-Energy-Food (WEF) Nexus in project implementation

By

Geoffrey Chavula, Theresa Mkandawire, and Ignasio Ngoma.

Corresponding Author: gchavula@mubas.ac.mw

This paper explores potential benefits that the Government of Malawi stands to gain by adopting the Water-Energy-Food Nexus in the implementation of various projects related to water, energy and agriculture in the country. The discourse on food, water, and energy security is driven by the growing pressure on natural resources. The demand for food, water, and energy is increasing steadily, but the resources required to generate them are limited, and in many cases dwindling. Furthermore, the situation is exacerbated by the vagaries of climate change and climate variability. The inter-dependencies among water, energy, and food are numerous and multidimensional, and their relationship is often referred to as the Water, Energy, and Food (WEF) nexus. Rapid economic growth, expanding populations and increasing prosperity are driving up the demand for energy, water and food, especially in developing countries. It is envisaged that by 2050, the demand for energy will nearly double globally, with water and food demand estimated to increase by over 50%. However, the ability of existing water, energy and food systems to meet this growing demand is constrained by the competing needs for the limited resources. It is in light of the above that this paper investigates potential benefits that may accrue to the Government of Malawi by leveraging on the country's existing natural resources, namely: water resources potential (both surface water and groundwater); the potential of energy resources (i.e., water, wind and solar); land resources (hectarage of irrigable land); and ecosystems (i.e. size of forests and wetlands).

1.0 Background and country overview

Malawi is a small landlocked country located in sub–Saharan Africa (Figure 1) between latitudes 9° 22' and 17° 03' south of the equator, and longitudes 33° 40' and 35° 55' east of the Greenwich meridian. It is bordered by Tanzania to the north and northeast, Mozambique to the east, south and southwest and Zambia to the west and northwest. The country's total surface area is approximately 118,484 km², of which 28,000 km² is taken up by Lake Malawi (Chavula, 2008). It is 910 km long and varies in width from 60 to 161 km, with a total surface area of 11.8 million hectares. Of this, 9.4 million hectares (80%) is land and the remaining 2.4 million hectares (20%) is covered by water. In addition, 1.8 million hectares of the total 9.4 million hectares is public land, 1.2 million hectares is estate land, 0.3 million hectares is urban land, and 6.1 million hectares is customary land (GoM, 2021). Furthermore, arable land constitutes 39.8% of the total land area, with 1.4% of the land area under permanent cropland, 34.0% is covered by forests, and the remaining 24.8% is classified as other land.

According to the World Bank Atlas, Malawi's human population is estimated to be 19 million, with a population density of 203 people per square kilometer (World Bank, undated), the highest in the SADC region. Nearly 90% of the people live in rural areas. The main economic base of the country is agriculture, with subsistence and smallholder farming as main activities for the rural population.

Climate

Malawi experiences a tropical-continental climate with two distinct seasons, namely: a wet season from November to April and a dry season from May to October. The dry season is characterized by strong southeasterly trade winds (local known as *Mwera*) whereas during the wet season the winds are generally northeasterly and weaker (locally known as *Mpoto*). A cool, dry winter season prevails from May to August, with mean temperatures varying between 17 and 27 degrees Celsius while a hot dry season lasts from September to October, with average temperatures varying between 25 and 37 degrees Celsius. There is evidence suggesting the existence of variability in temperature and an increased intensity of floods and droughts (Chavula, 2008).

Three major synoptic systems bring rainfall to the country, namely: the Inter Tropical Convergence Zone (ITCZ), the Zaire Air Boundary (ZAB)/Congo Airmass, and tropical cyclones (Chavula, 2008). The Inter Tropical Convergence Zone is a broad zone in the equatorial low-pressure belt towards which the northeasterly and southeasterly trade winds of the two hemispheres converge. The ITCZ oscillates randomly across the country during the rainy season and produces widespread rainfall. The rains start in the southern part of the country and progress northwards. The Zaire Air Boundary is a re-curved south Atlantic southeast trade winds system, which after collecting moisture over the Atlantic and Congo (Zaire) rain forest, arrives in Malawi via Zambia as a moist northwesterly wind, bringing widespread rainfall in the country. Tropical Cyclones are intense low-pressure cells that originate in the Indian Ocean and move from east to west and bring widespread heavy rainfall in Malawi, mainly in the southern part of the country, depending on their position in the Mozambique Channel. These rains usually result in flooding. Malawi's annual average rainfall varies from approximately 700 mm in low altitude areas such as the Lower Shire Valley in the Southern Region, to over 2000 mm in highlands and lakeshore areas (Fig 2).

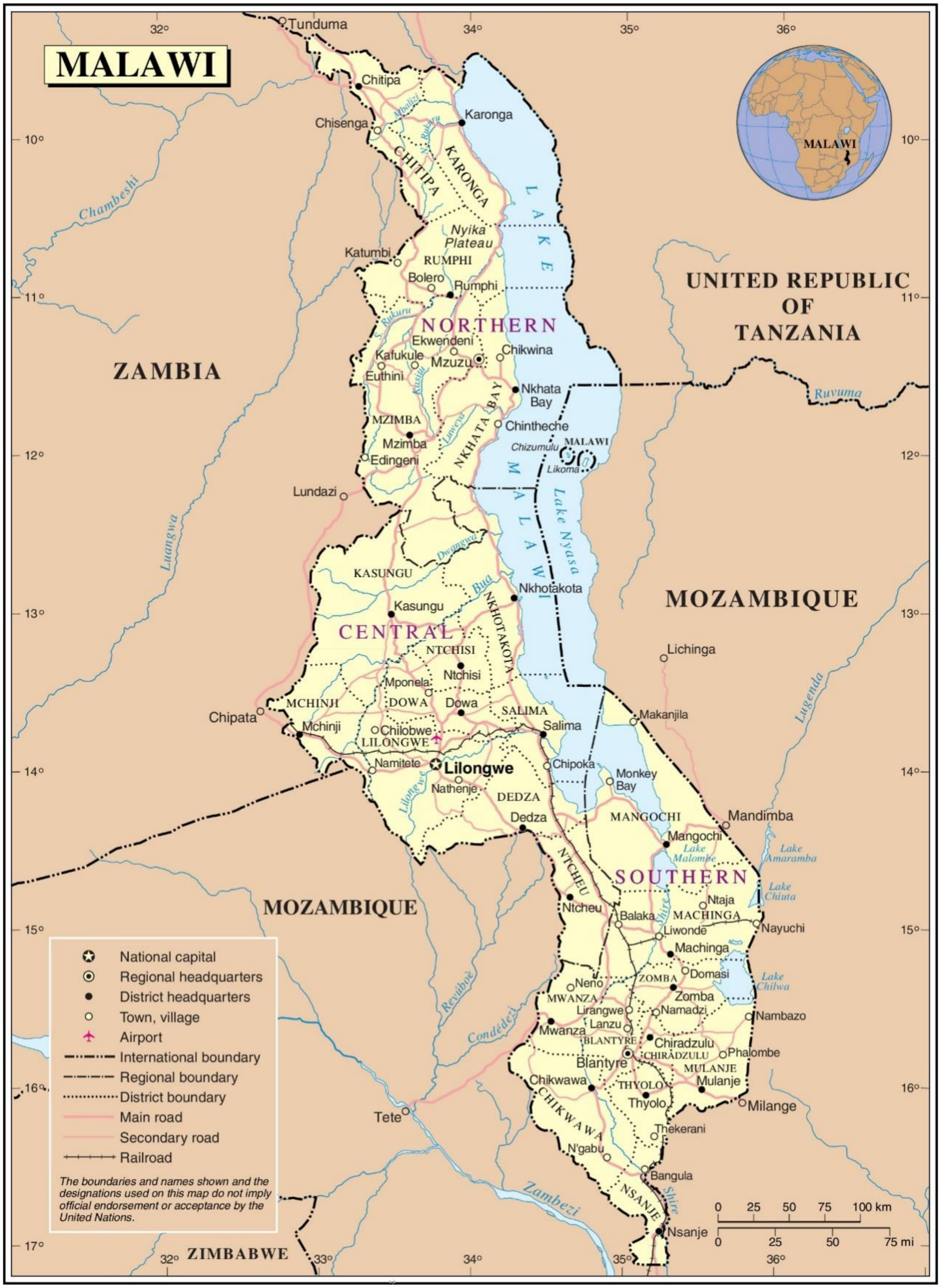


Figure 1: Map of Malawi

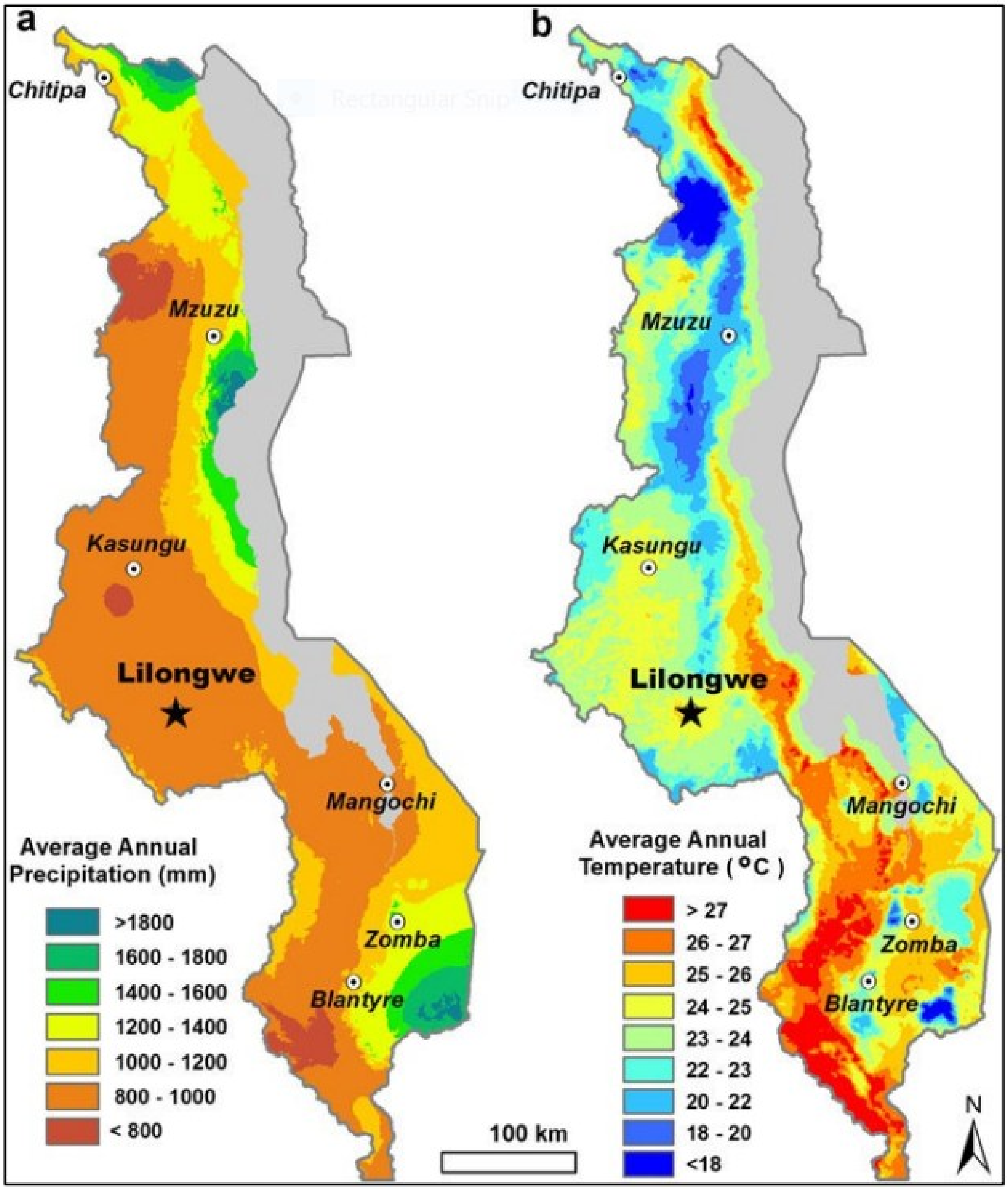


Figure 2: Distribution of annual rainfall and temperature (Source: GoM, 2023)

The rainfall regime is influenced by variations in altitude and proximity to Lake Malawi. Rainfall patterns display wide inter and intra seasonal variability.

Malawi is vulnerable to the vagaries of the El Nino and Southern Oscillation (ENSO) phenomena as well as the Indian Ocean Dipole (IOD). Studies about the ENSO warm phase episode done by Eastman *et al* (1996) for southern Africa showed the existence of two drought cells both of which affect Malawi, mainly the southern part of the country. The first drought cell shows a path originating from Namibia but covering Botswana, Zimbabwe, southern Zambia, northwest Mozambique and the southern part of Malawi, whereas the second drought cell has its center located near southern Mozambique and southern Zambia and appears to expand outwards. There are no signs at the moment to suggest that these drought cells will cease to wreak havoc in the country. Furthermore, it is envisaged that the intensity and frequency of these drought episodes will increase with climate change.

Physiographic Zones and Soils

Malawi is divided into four major physiographic zones, namely: the high land areas, plateau areas, rift valley escarpment and rift valley plains (Water Department/UNDP, 1986), Figure 3. The plateau areas occupy approximately 75% of the land surface and ranges in altitude from 750 - 1300 meters while the rift valley plains comprise the flat land along the shores of Lake Malawi, and ranges from 450 - 600 meters. The plateau areas are extensively peneplained gently undulating surfaces with broad valleys and large level areas on the interfluves. They are ancient erosion surfaces (the African Surface) of late Cretaceous to Miocene age, which slope away from the escarpment zones as a result of uplift along the Rift Valley System, but the drainage systems have kept pace with these earth movements and largely drain towards the rift valley (Water Department/UNDP, 1986). As a consequence, the valleys become more incised towards the escarpment. The plateau areas are drained largely by dambos, i.e., broad, grass-covered swampy valleys that are liable to flooding and commonly have no well-defined channels. The plateau areas are mostly covered by a thick mantle of saprolite derived by in-situ weathering of the underlying strata. The predominant soils covering the plateau and lakeshore areas are deep, calcimorphic alluvials and colluvials, with hydromorphic soil deposits found in isolated depressions (Figure 4). The Lower Shire Valley is a wide rift valley system at the extreme southern part of the country, lying at altitude 35 to 105 meters above sea level, and is chiefly covered by calcimorphic alluvials, with extensive areas dominated by hydromorphic soils and vertisols.

Vegetation

The wide variation in physiography, climate and edaphic factors has given rise to a large variety of vegetation types in Malawi (GoM, 2021), Figure 5. The following are the major biotic communities in Malawi:

1. Montane evergreen forest;
2. Montane grassland;
3. Semi-evergreen forest;
4. (a) Closed canopy woodland of wetter uplands (tall Brachystegia spp); (b) Open canopy woodland of plateaux (Brachystegia/Julbernadia/Isoberlinia);

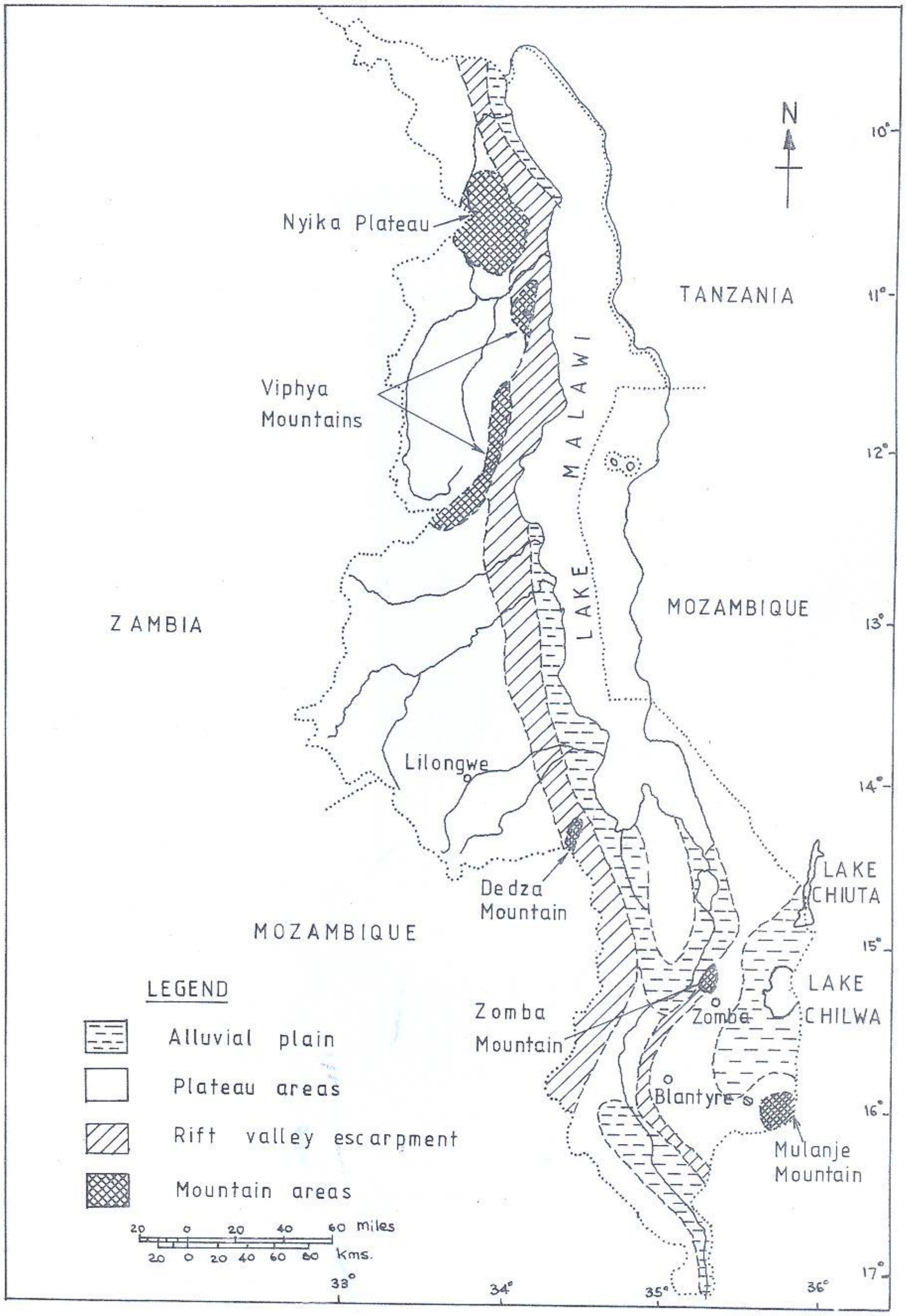


Figure 3: Physiographic Features (Source: Water Department/UNDP, 1986)

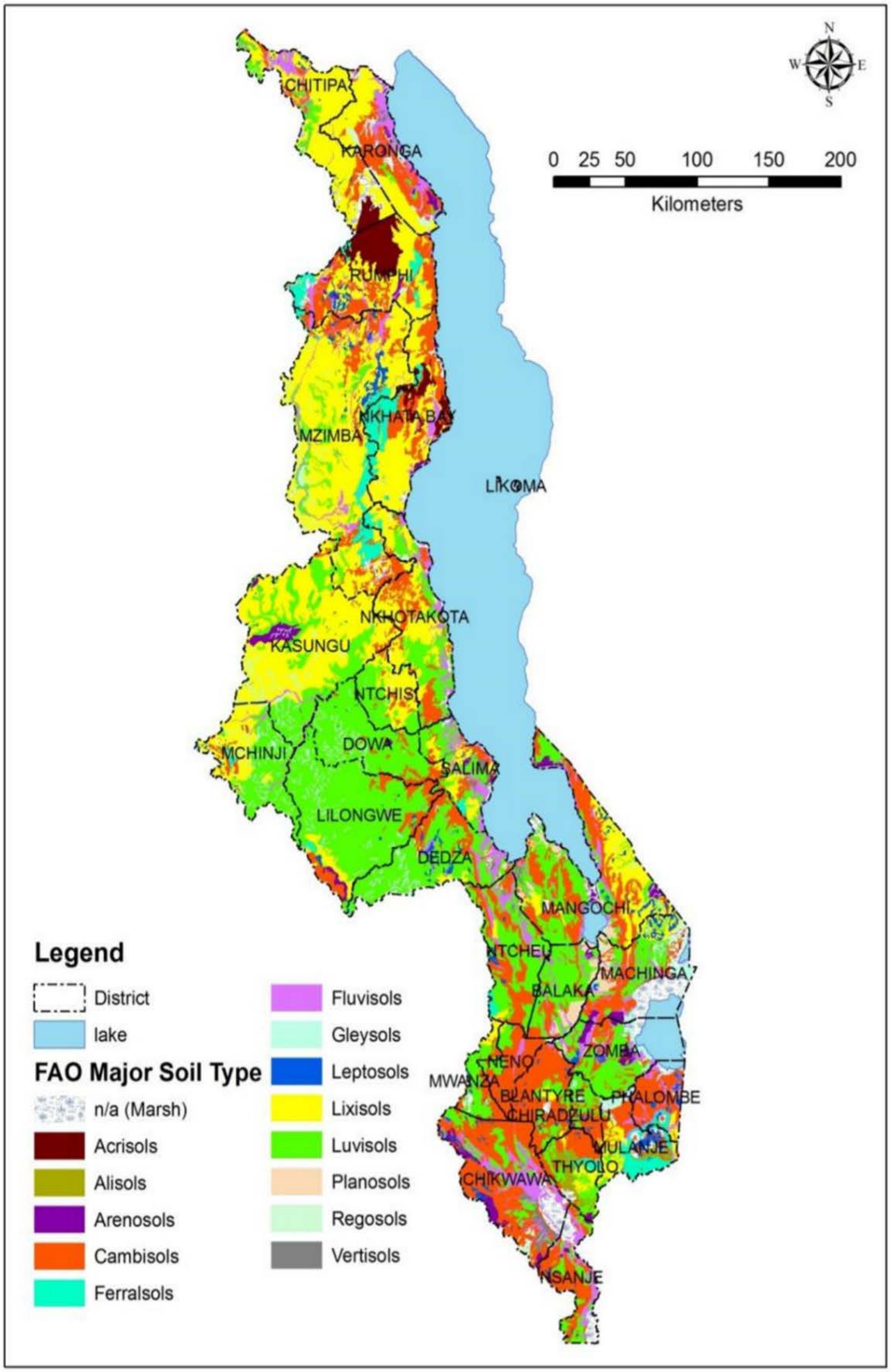


Figure 4: Soil Types (Source: GoM, 2021)

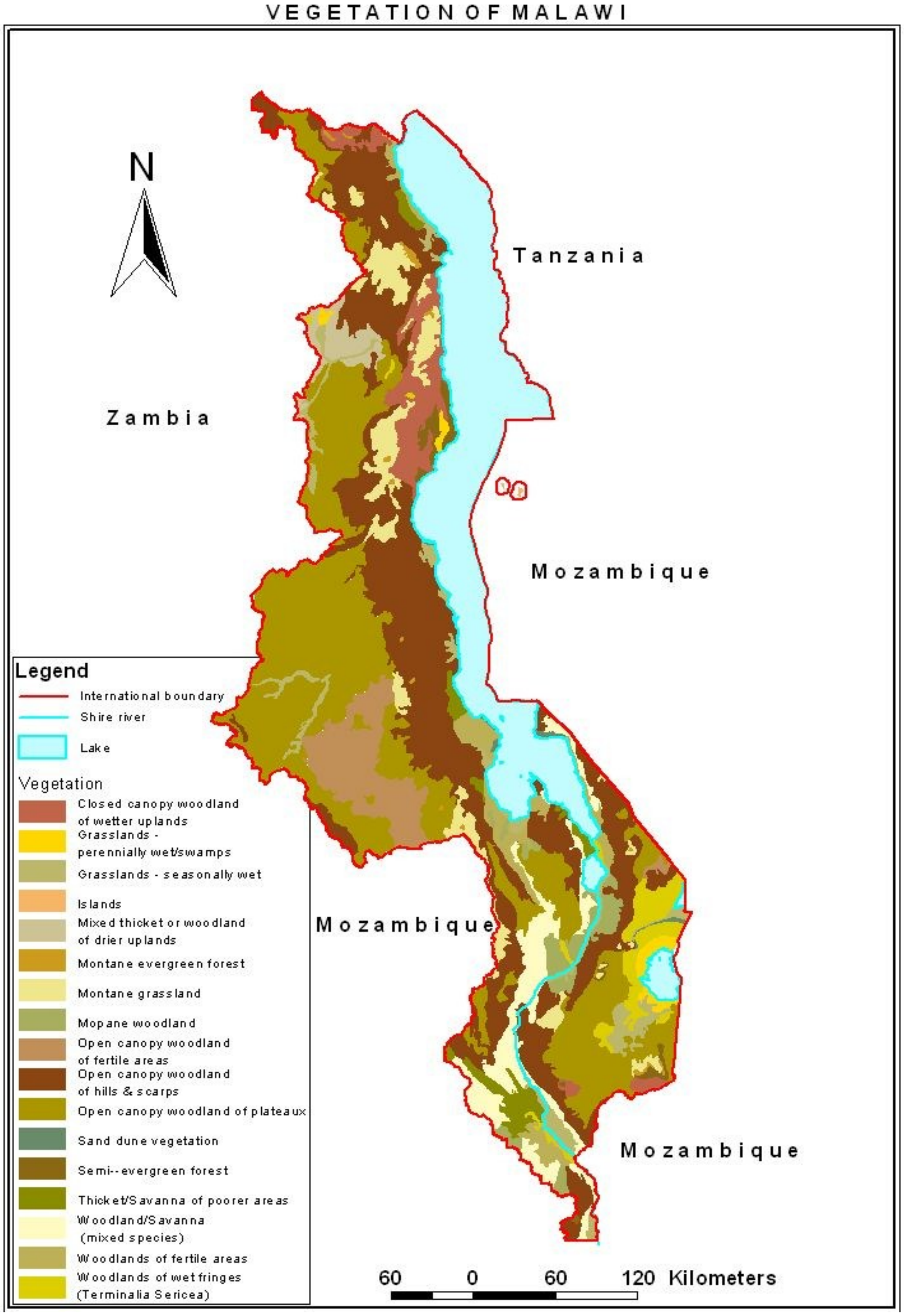


Figure 5: Vegetation (Source: GoM, 2021)

(c) Open canopy woodland of hills and scarps (Brachystegia spp); (d) Open canopy woodland fertile areas (Piliostigma/Acacia/Combretum); (e) Mixed thicket/woodland of drier upland;

5. (a) Mopane woodland; (b) Woodlands of fertile areas (Adansonia/Cordyla/Faldebia albida); (c) Thicket/savanna of poorer areas (Combretun/Acacia); (d) Woodland savanna of poorer areas (mixed species);
6. Sand dune vegetation;
7. (a) Grasslands (seasonally wet); (b) Grasslands (perennially wet/swamp);
8. (a) Lakes (fresh water); (b) Somewhat saline lakes (without outlet); and
9. Islands.

Economic and Sector Policies

Malawi is one of the least developed countries in the world. It largely depends on agriculture for its social and economic development. Agriculture production contributes over 90% of foreign exchange earnings. Maize is the main staple food, taking up nearly 80% of the cultivated land. The main export crops include tobacco, sugar, tea, coffee and cotton; followed by manufacturing and tourism. The performance of the tobacco sector is instrumental to short term growth as tobacco accounts for over 50% of the country's exports (EAD, 2008). However, the advent of the antismoking lobby by western countries, tobacco is now facing a serious crisis at the world market.

Being agro-based, Malawi's economy is largely vulnerable to weather related shocks and declining natural resource base. Efforts to diversify the agriculture sector and the economy to other productive sectors such as industry, mining, and tourism have not been effective enough because of infrastructural and economic challenges (Government of Malawi, 2021). Consequently, the share of the other sectors to GDP has increased marginally over the years, forcing the decline in the share of agriculture from 38 percent in 1994 to 28 percent in 2017.

According to the Malawi Labor Force Participation Survey of 2013, the country's employment rate stands at 79.6 percent. About 64.1 percent of employed persons are in the agriculture sector, but they face uncertain future as current institutions and governance arrangements are ill-equipped to deal with the increasing pressures arising from unsustainable environmental practices and climate change. Of the country's total labor force, 20.4 percent is unemployed. Unemployment is more common among females than males due, *inter alia*, to low levels of literacy, traditional beliefs and customs, and religious values. The youth of under 30 years of age constitute about 70 percent of the whole population, implying that the country needs to capitalize on the demographic dividend where the youth will help accelerate economic growth through increased productivity in the job market. This should be done through youth participation in decision making, employment creation and opening up opportunities for them to engage in businesses. If the window of opportunity is missed through failure to empower the youth, then the youth bulge will become a liability that would further undermine transition to sustainable development.

The development interventions being pursued by the Government of Malawi have not been able to reduce poverty significantly, such that 50.7 percent of the population still live under the poverty line (below $1 a day). Efforts to reduce poverty have not borne the desired result, with the poverty rate slightly declining from 52.4 percent in 2005 to 50.7 percent in 2015 while the incidence of ultra-poor increased from 22.4 percent to 25 percent over the same period. Income distribution has been worsening over the years. The Gini coefficient increased from 0.39 in 2005 to 0.45 in 2014 and remained around the same level in 2016. In terms of gender, female headed households (57.0 percent of the total households) are poorer than their male headed counterparts (43.0 percent) as of 2015. Several factors, including ineffectiveness of policy interventions, have led to low living standards of the people. This results from the fact that Malawi's economy in general and the majority of Malawian households in particular are vulnerable to social and economic shocks. In addition, the fact that 80 percent of the Malawian population relies on agriculture for their livelihoods, both for incomes and food provisions, it is a challenge when weather is not conducive for agriculture production.

Climate Change

A detailed treatise about potential impacts of climate change in the sectors of water, energy, and agriculture in Malawi and appropriate anticipatory adaptation strategies to counter the adverse impacts on mankind and the environment are provided in Malawi's Third National Communication of 2021 (GoM, 2021), a country report that was submitted to the Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) by the Government of Malawi. Suffice to say that projections of temperature and rainfall for the country were generated using statistically downscaled General Circulation Models (GCMs) following the procedure articulated in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), IPCC (2013). Figure 6 and Tables 1, 2 show the areal distribution of climatic zones and data on climate change scenarios for temperature and rainfall for Malawi. It is worth noting that AR5 is premised on two Representative Concentration Pathways (RCPs) of Greenhouse Gas (GHG) Emissions, namely: RCP 4.5 (Intermediate Emission), and RCP 8.5 (High Emission) as described by Moss *et al*. (2013). RCP 4.5 and 8.5 are respectively equivalent to story lines B1 and A1F1 in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007). RCP 8.5 or Scenario A1F1 is consistent with the following scenarios: (a) three times today's CO_2 emissions by 2100; (b) rapid increase in methane emissions; (c) increased use of croplands and grassland driven by an increase in population growth; (d) a world population of 12 billion by 2100; (e) lower rate of technology development; (f) heavy reliance on fossil fuels; (g) high energy intensity; and (h) no implementation of climate change policies. RCP 4.5, which is comparable to SRES B1 is consistent with the following scenarios: (a) lower energy intensity; strong reforestation programmes; (b) decreasing use of croplands and grasslands due to yield increases and dietary changes; (c) stringent climate policies; (d) stable methane emissions; and (e) CO_2 emissions increase only slightly before decline commences around the year 2040.

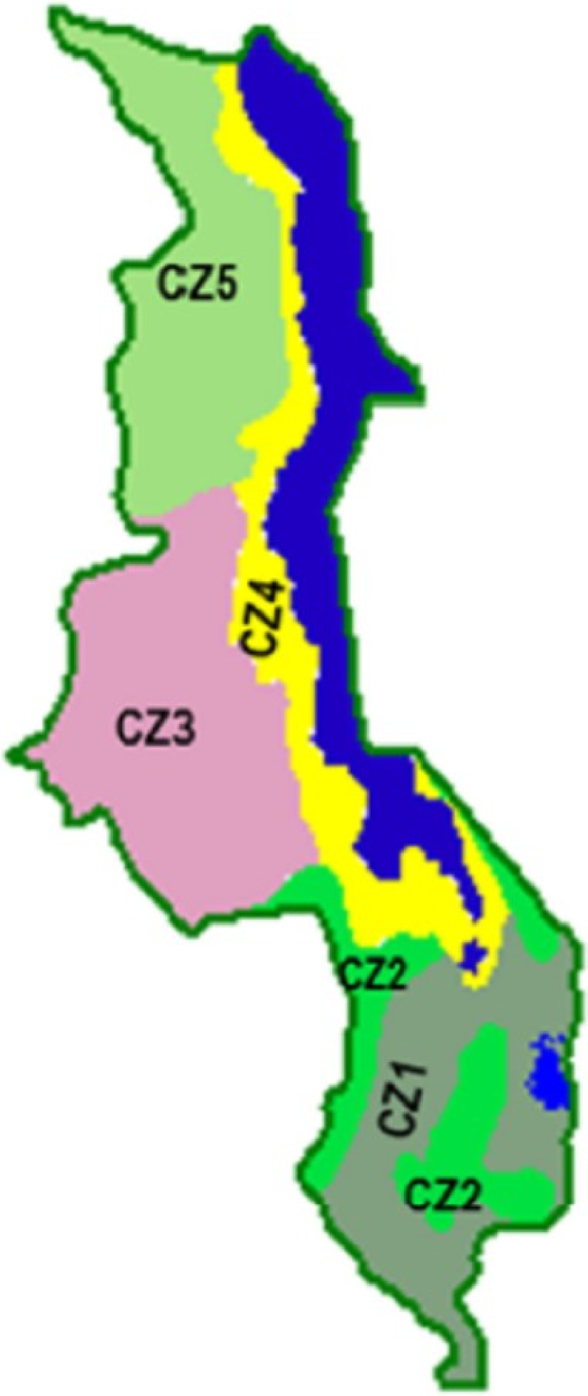


Figure 6: Climatic Zones based on Future Scenarios, i.e., CZ1 = Shire Valley; CZ2 = Shire Highlands; CZ3 = Central Areas; CZ4 = Lake Shore Areas; and CZ5 = Northern Areas

Table 1: Temperature Scenarios

Location	**Near Century Period: 2011-2040.**	**Mid Century Period: 2041-2070.**	**End Century Period: 2071-2100.**
Lower Shire Valley	0.03°C-0.04°C: temperature increase.	1.4°C-2.8°C: temperature increase.	2.5°C-4.2°C: temperature increase.
Shire Highlands	0.034°C: temperature increase (Jun-Dec).	1.0°C: temperature increase.	1.5°C-2.4°C: temperature increase.
Central Areas	0.7°C-0.9°C: temperature increase.	1.3°C: temperature increase.	temperature increase.
Lakeshore Areas	0.8°C-0.9°C: temperature increase.	1.5°C-2.0°C: temperature increase.	2.5°C-3.0°C: temperature increase.
Northern Areas	0.2C-0.9°C: temperature increase.	1.4°C-1.9°C: temperature increase.	1.7°C-2.3°C: temperature increase.

Table 2: Rainfall Scenarios

Location	**Near Century Period: 2011-2040.**	**Mid Century Period: 2041-2070.**	**End Century Period: 2071-2100.**
Lower Shire Valley	800 mm – 1000 mm: mean rainfall.	January rainfall to increase by 8% while summer will be drier by 3% to 5%.	Rainfall to decrease by about 15%.
Shire Highlands	1000 mm – 1200 mm: mean rainfall.	Winter rainfall to increase by 15% while summer rainfall will decrease by 10%	Summer rainfall to decrease by 25%.
Central Areas	800 mm -1100 mm: mean rainfall.	October to December rainfall to decrease by 10% to 22%.	October to December rainfall to decrease by 20% to 56%.
Lakeshore Areas	March to April rainfall will increase by 5% to 25%.	Winter rainfall will decrease by 65%.	There will be a general decrease in rainfall by 60%.
Northern Areas	Increase in rainfall by 3% to 8% during the period January to April.	October to December rainfall to decrease by 10% to 36%.	Rainfall to decrease by 56%.

A2 Storyline describes a very heterogeneous world, with self-reliance and preservation of local identities as the underlying theme. Fertility patterns across regions converge very slowly, which results in continuously increasing population growth. Economic development is primarily regionally oriented, with more fragmented and slower per capita economic growth and technological change than other storylines. Scenario A1B depicts a scenario with a balance across all sources, where balance is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies. The main finding from the comparison of SRES with scenarios described in the Fifth Assessment Report is that the uncertainties as represented by the ranges of main driving forces and emissions have not changed very much. The following conclusions may be drawn from climate change scenario analysis results presented in Tables 2 and 3 about future expected temperature and rainfall regimes in Malawi using the two RCPs: (a) there is a positive trend in temperature rise, i.e., there will be an increase in temperature in Malawi with climate change; (b) minimum temperatures exhibit a faster rise in temperature with climate change than maximum temperatures; (c) generally, there is an insignificant decrease in rainfall during the OND period, and an increase during JFM; (d) future temperatures will rise by 1.3 ^{o}C to 2.6 ^{o}C; and (e) El Nino conditions will likely increase climate extremes, resulting in the increased severity, or magnitude/intensity, and frequency of floods, droughts, and strong winds.

Studies done by McSweeney *et al*. (2008) show a temperature increase of 0.9 ^{o}C between 1960 and 2006 for Malawi, an average rate of 0.21^{o}C per decade. The increase in temperature has been most rapid in December-January-February (DJF) and slowest in September-October-November (SON). Daily temperature observations show an increase in the frequency of hot days and nights in all the seasons. The frequency of cold days and nights has significantly decreased in all the seasons, except in SON. Observed rainfall over Malawi does not show statistically significant trends. Also, there are no statistically significant trends in the extremes indices calculated using daily precipitation observations (McSweeney *et al*., 2008).

What is clear from the description of climate change scenarios for Malawi presented above is that floods, droughts and strong winds will continue to wreak havoc in the country. Thus, the country's vulnerability to the vagaries of severe floods, droughts, and strong winds should be taken as a serious cause for worry by the Government of Malawi and the citizenry, and hence the urgent need by the country to implement robust climate change adaptation strategies in order to avert impending disasters associated with these three hazards.

2.0 Importance of Nexus approach in Malawi

The potential that Malawi has in terms of water resources (both surface water and groundwater), energy resources (i.e., hydropower, solar and wind); and the availability of land resources (hectarage of irrigable land) are key in the country's poverty alleviation efforts.

Water Resources Potential

Malawi is generally rich in both surface and ground water resources. Surface water resources comprise a network of rivers (e.g., Shire, Ruo, Linthipe, Bua, Dwangwa, Rukuru, songwe, Ruhuhu, Kiwira, etc) and lakes (Lake Malawi, Lake Chilwa, Lake Chiuta), Figure 7. The country's drainage system has been divided into 17 Water Resources Areas (WRAs), two of which drain outside the Lake Malawi/Shire system, i.e., they drain into Lake Chilwa and Lake Chiuta. Water Resources Areas (WRA) are further subdivided into 78 Water Resources Units (WRUs), Figure 8 (Water Department/UNDP, 1986).

Lake Malawi, with a surface area of about 28760 km^2, has a great influence on the country's water balance. The mean annual rainfall over the lake is estimated to be 1549 mm. The total inflow into Lake Malawi is 927 m^3/s, out of which 400 m^3/s is from Malawi, 486 m^3/s from Tanzania and 41 m^3/s from Mozambique. The average outflow is 395 m^3/s. The mean lake level is 474.4 m. The only outlet of the lake is the Shire River (Chavula, 2008). The highest annual outflow of 825 m^3/s occurred during the 1979/1980 hydrological season, with the highest monthly outflow of 963 m^3/s taking place in May 1980. Runoff depths of each WRA are presented in Table 2. It is clear from Table 2 that runoff is generally high along the shore of Lake Malawi. This is also true of rivers that drain the Mulanje Massif.

The catchment area of Lake Chilwa is estimated to be 5000 km^2. Most of the rivers that drain their water into Lake Chilwa arise from the northern slopes of Zomba and Mulanje Massif. All the rivers are perennial in their upper reaches but they gradually lose their flow and recharge aquifer systems in the Chilwa-Phalombe plains due to the porous nature of the area (Kululanga and Chavula 1993).

The quantity of surface water resources, especially in rivers, is highly dependent on the availability of rainfall which sustains runoff. Surface water resources are more abundant during the rainy season than during the dry season. Incidents of floods are a common feature in the country, particulary in the Lower Shire Shire Valley (Chikwawa and Nsanje districts), and Salima and Karonga districts. For example, the severe flooding that took place in 2015affected 15 out 28 districts in Malawi, with severe loss of life and damage to property and crops.

Many river basins in the country are under severe pressures due to deforestation, unsustainable agriculture, settlements, mining, industry, commerce, tourism and climate change. These activities have influenced changes in water quality especially due to sediment loads, industrial wastes, chemicals from agricultural lands, and the proliferation of aquatic vegetation.

The quality of surface water resources is dictated by three major factors, namely: the chemical composition of the parent rocks at the base of the water body or traversed by the river, agricultural actives taking place in the catchment area, and effluent discharges (including disposal waste from residential areas and industrial sites).

The chemistry of the majority of surface water resources is characterised by alkaline earth (calcium and magnesium) dominance in the cation group, and by the carbonate system in the anion group. Most of the water can be classified as soft to moderately soft, with hardness less than 100 mg/L of $CaCO_3$. Values of Total Dissolved Solids (TDS) content are generally less than 100 mg/L. Known areas of hard water are confines to the following WRUs: 1C, 1E, 1R, 4E, 4F and part of 5D. The hardness of water in WRUs 1C, 1E, and 1R is attributable to locally occurring outcrops of limestones; whereas in 4E, 4F, and part of 5D the hardness is non-carbonate, but caused by evaporite deposits of gypsum prevalent in dambos.

Table 6: Catchment Runoff Values

Name of River Basin	Catchment Area (km^2)	Rainfall (mm)	Runoff (mm)	Runoff (m^3/s)	Runoff (%)
Shire	18945	902	137	82	15.2
Lake Chilwa	4981	1053	213	34	20.2
South West Lakeshore	4958	851	169	27	19.9
Linthipe	8641	964	151	41	15.7
Bua	10654	1032	103	35	10.0
Dwangwa	7768	902	109	27	12.1
South Rukuru	11993	873	115	44	13.2
North Rumphi	712	1530	674	15	44.1
North Rukuru	2091	970	252	17	26.0
Lufirya	1790	1391	244	114	17.5
Songwe	1890	1601	327	120	20.4
South East Lakeshore	1540	887	201	10	22.7
Lake Chiuta	2462	1135	247	19	21.8
Likoma Island	18.7	1121	280	-	-
Chizumulo Island	3.3	1121	280	-	-
Ruo	3494	1373	538	60	39.2
Nkhotakota Lakeshore	4949	1399	260	41	18.6
Nkhata Bay Lakeshore	5458	1438	461	80	32.1
Karonga Lakeshore	1928	1028	361	22	35.1

Since Malawi's economy is highly dependent on agriculture, vast expanses of land are being cleared every year for agriculture production. As the vegetation cover is removed, soils become vulnerable to erosion. This is manifested in the highly turbid waters observed in rivers and lakes during the rainy season. Soil erosion taking place in catchment areas that have been severely degraded and deforested is evident throughout the country. Tonnes of soil loads carried by rivers and streams change the configuration of river channels. As a result, these rivers and streams are unable to effectively convey surface runoff due to drastic reductions in the cross-sectional area of flow, increasing the risk of flooding. The large deposits of sediments in river beds reveals the gravity of the problem of soil erosion and sedimentation in river channels in Malawi.

While agrochemicals such as inorganic fertilisers, herbicides and pesticides are essential for increasing agricultural productivity and preventing postharvest crop losses, they play a major role in promoting eutrophication in water bodies. Fertilisers are also the reason for the growth of other riverine vegetation that inhibit the smooth flow of water in the river channels by increasing the Manning's roughness. Mwendera (1993) confirmed that runoff from estates contained agrochemicals that polluted water in rivers and reservoirs. High TDS values observed during the rainy season are a direct result of soil erosion caused by highly degraded catchments in the country.

The biological quality of rivers, especially those flowing through the cities of Blantyre (e.g., Mudi, Chitawira, and Naperi), Zomba (Likangala), Lilongwe (e.g., Lilongwe, Lingadzi), and Mzuzu (e.g., Lunyangwa) is generally poor because of effluent discharges and poor siting of pit latrines. Values as high

as 20,000 faecal coliforms per 100 ml have been observed in Lilongwe and Likangala Rivers downstream of the sewage plants during periods when the treatment plants have broken down.
Malawi has three major aquifer systems, namely: the extensive but low yielding weathered Precambrian Basement Complex aquifer of the plateau area (1-2 L/s), the high yielding alluvial aquifer of the lake shore plains and the Lower Shire Valley and the Lake Chilwa - Mphalombe Plain (>15 L/s), and the medium yielding aquifer of the fracture zone in the rift valley escarpment (5-7 L/s), Figures 3 and 8. The prolonged in situ weathering of the crystalline basement rocks has produced a layer of unconsolidated saprolite material (Figure 9) that forms an important source of water supply for domestic requirements. The weathered zone is best developed over plateau areas where it is commonly 15-30 m thick and locally even thicker (Water Department/UNDP, 1986). Towards the crest of the escarpment, the uplift associated with the development of the rift valley has resulted in the rejuvenation of rivers and increased erosion, and thus the thickness of the aquifer tends to be reduced in these areas. It also thins towards bedrock outcrops. The saprolite thickness tends to be greatest along fracture zones.

Alluvial aquifers are fluvial and lacustrine sediments that are highly variable in character in both vertical sequence and lateral extent. They occur in several basins which, apart from Lake Chilwa, are all located along the rift valley floor:

1. Karonga Lakeshore,
2. Salima-Nkhotakota Lakeshore,
3. Upper Shire Valley, and
4. Lower Shire Valley.

Most lithological records from boreholes give very little information about the successions. The overall impression is that clays usually dominate the sequence although in many localities there are significant thicknesses of poorly sorted sands. The sedimentary environment likely to produce the highest groundwater yields are buried river channels and littoral (beach and dune) zones of the lakeshore where deposits are usually coarse grained and well sorted. The Lake Chilwa Basin is different from the other alluvial areas in that it is not in the bottom of the rift valley floor but perched on the eastern side of it. The lithological logs suggest that much of the succession is clayey.

As stated in the preceding discussion, the average yield in the weathered zone of the basement complex lies in the range of 1-2 L/s. In alluvial areas, yields greater than 15 L/s are possible, whereas in the escarpment zone boreholes yields normally range from 5-7 L/s. Typical transmissivity values for alluvial aquifers lie in the range of 50-300 m^2/day whereas in the weathered basement complex aquifers values are much lower: 5-35 m^2/day. Hydraulic conductivity values for the weathered basement complex aquifer range from 0.5-1.5 metres per day whereas estimated values of permeability for alluvial aquifers are in the order of 1-10 metres per day. Storage coefficient values for aquifers normally lie in the range of $5*10^{-3}$ to $1*10^{-2}$ and $1*10^{-2}$ to $5*10^{-2}$ for the weathered aquifers and alluvial aquifers, respectively.

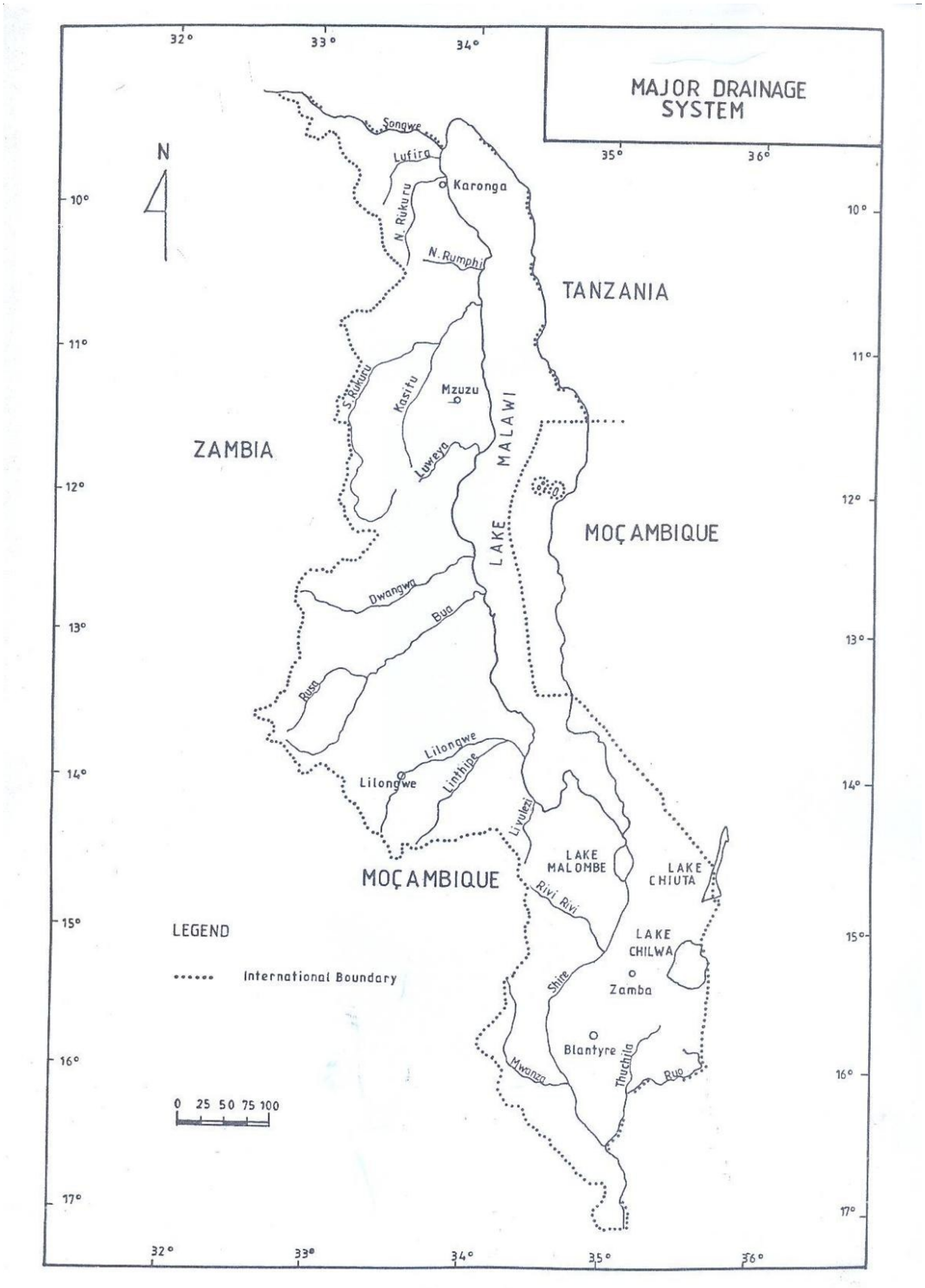


Figure 7: Drainage Basin (Source: Water Department/UNDP, 1986)

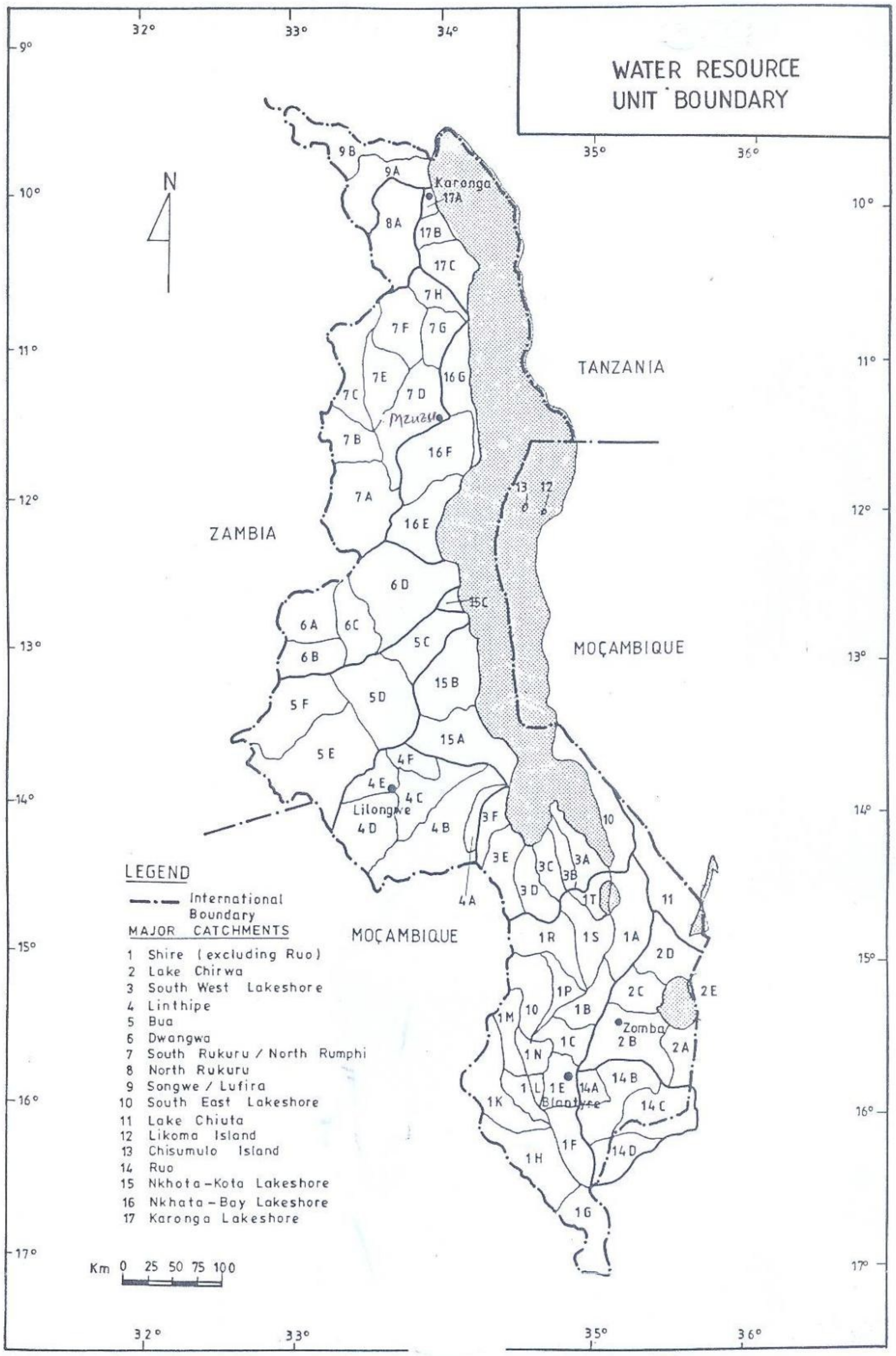


Figure 8: Water Resources Units (Source: Water Department/UNDP, 1986)

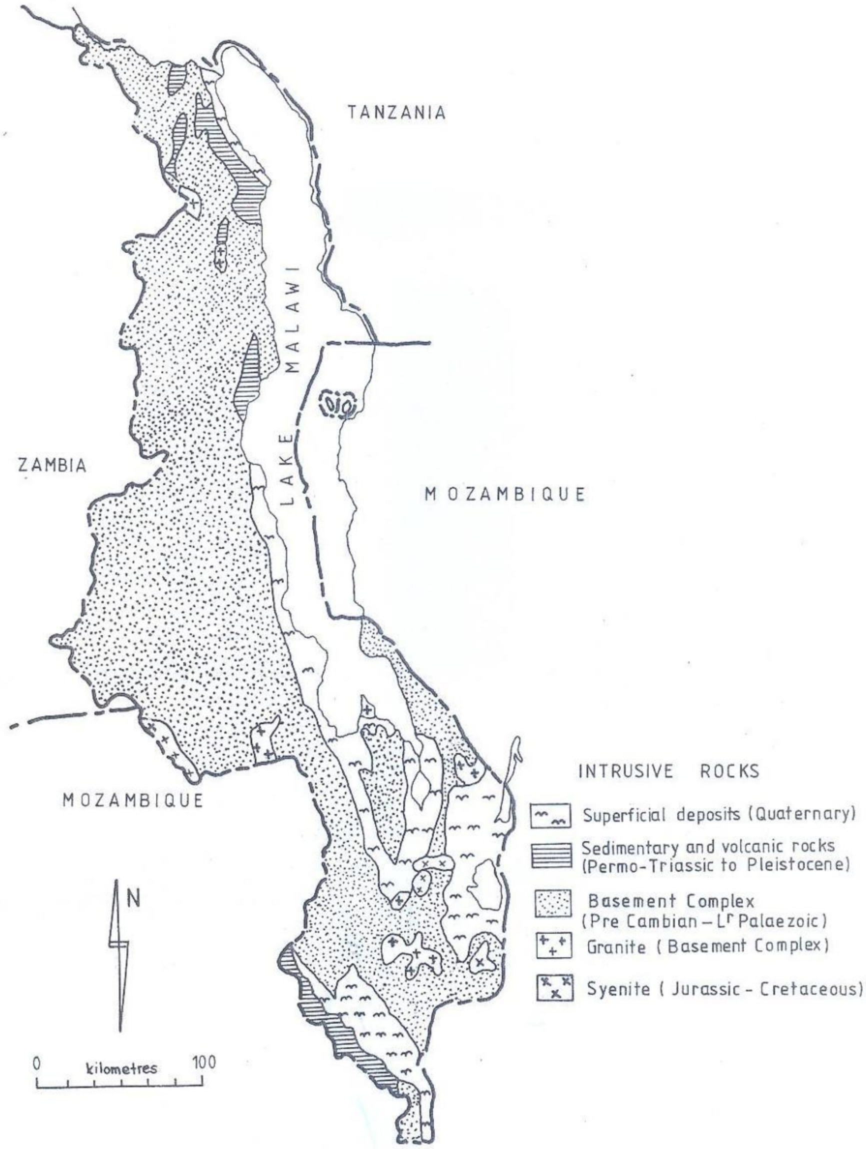


Figure 9: Geological Map (Source: Water Department/UNDP, 1986)

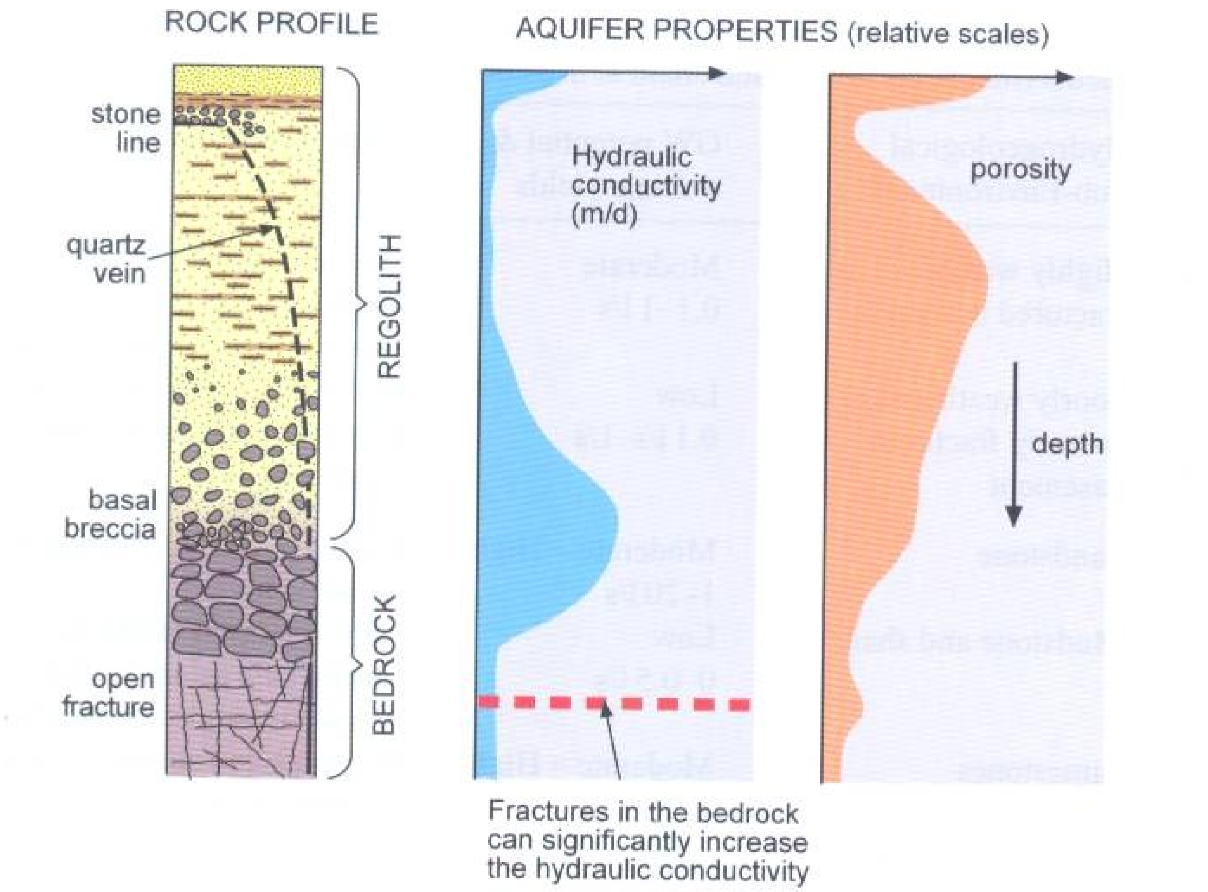


Figure 10: Profile of Precambrian Basement Complex Aquifer (Chilton and Foster, 1995)

Estimates of recharge have been made from the analysis of flow hydrographs, groundwater level fluctuations, flow nets and catchment balances. Although the results vary considerably, annual groundwater recharge ranges from 15-80 mm (Water Department/UNDP, 1986). However, studies done by Chavula (1989) established that the annual recharge for the eastern side of the Lower Shire Valley alluvial aquifer is greater than 200 mm/year. It is worth noting that the Malawi Government has not yet developed a hydrogeological map showing the distribution of groundwater recharge in the country. Suffice to say that areas with receive high rainfall exhibit high groundwater recharge and vice versa. But the rate of groundwater abstraction still remains very low and estimates put the figure at less than 1 mm per year (Water Department/UNDP, 1986; Chavula, 1989).

There are at present about 30,000 boreholes and 8,000 protected hand-dug wells in Malawi. The Ministry of Irrigation and Water Development is in the final stages of developing a map showing the distribution of boreholes in the country. GPS Units are used for collecting information on borehole location and the data are fed into a GIS software.

Current estimates indicate that groundwater constitutes only 3% of the overall national water use. Groundwater usage for irrigation potential is limited by the low yielding aquifers and is generally restricted to small gardens in many areas (Atkins, 2010). Notable among these is Ngolowindo Irrigation Scheme in Salima District that has a total land area of 17 ha. UNICEF (1995) estimated that 31% of the rural population was served by boreholes.

On a national scale, groundwater quality is generally acceptable for human consumption. Groundwater resources in the basement complex aquifer are characterized by the dominance of alkaline earths in the cation group, and by the carbonates in the anion group (Water Department/UNDP, 1986). Total dissolved solids content values are generally less than 1000 mg/L and typically around 350 mg/L. Groundwater in the alluvial aquifers is more mineralized than in the basement aquifers. A number of boreholes have been abandoned due to high salinities, notably in the Lower Shire Valley and the eastern part of Bwanje Valley. Chemical parameters which cause a lot of concern are fluoride, sulphate, iron, chloride and nitrate. Groundwaters with fluoride content in excess of 1.5 mg/L are common in the Salima/Nkhotakota and Karonga Lakeshore areas. In these areas, high fluoride content is associated with fault zones and hydrothermal activity in the rift valley. High sulphate groundwater is common in the western part of Dowa District. The high sulphate concentration is thought to be a direct result of progressive oxidation of sulphides rich parent material, probably pyrite and phyrrotite in veins producing sulphuric acid and the subsequent reaction with minerals containing magnesium and calcium.

Chloride rich groundwater resources are common in the Lower Shire Valley and are associated with the dissolution of evaporate minerals and chemical filtration as described by Bath (1980) and Chavula (1989). However, a detailed map showing the distribution of groundwater quality for the entire country has not yet been developed.

Generally, boreholes supply water of superior microbiological quality to other sources such as dug wells. The inferior quality of water drawn from hand-dug wells may be explained by the following reasons (Water Department/UNDP, 1986; Kululanga and Chavula, 1993):

a) Shallow groundwater tables (less than 2 metres depth) with seasonal fluctuations which bring them near to the ground surface where water can easily get polluted

b) Faecal contamination since dambos are extensively used for grazing and watering livestock all year round; and

c) Poor siting of water points since dug wells are sometimes sited very close to traditional water sources which are always open and invariably grossly polluted.

Energy Potential

The Malawi Biomass Energy Strategy (BEST) of 2009 states that the country's current total energy need is largely dependent on biomass which meets about 88.5% of the energy demand. The rest of the energy is supplied by other sources in the following proportions: hydrocarbon fuels 6.4%, electricity 2.8%, and coal 2.4%. This is a slight change from the situation in 2002 when biomass accounted for 93% of the country's aggregate energy demand, electricity 2.3%, petroleum products 3.5%, coal 1% and other renewable energy sources 0.2% (GoM, 2006). Other potential sources of energy include solar, wind and geothermal. Malawi receives about 21.1 MJ/m^2/day of solar energy and has wind speeds averaging 2 - 7 m/second which can be harnessed to produce electricity. Additionally, the country has hot springs for geothermal power, and uranium deposits for nuclear power generation (GoM, 2010). Petroleum products are exclusively imported.

For planning purposes, energy resources highlighted above are conveniently categorized into five sub-sectors, namely:

a) biomass (firewood, charcoal, crop and industrial residues);

b) electricity (hydro and thermal);

c) liquid fuel and gas (petrol, diesel, paraffin, ethanol, Gel-Fuel, avgas, JetA1, LPG);

d) coal and peat; and

e) other renewables (solar, wind, biogas, mini and micro-hydro).

Biomass: As stated in the preceding discussion, Malawi's energy balance is dominated by biomass. These sources account for 88.5% of energy production in the country. Fifty-nine percent of biomass energy is used in its primary form as firewood (52%) and residues (7%), the remaining 41% is converted into charcoal in traditional earth moulds, at estimated thermal efficiencies of between 12% - 14%. These efficiencies are much lower than those obtained from modern charcoal carbonization kilns (for example, Retorts, Bee-Hives, Mark V) whose efficiency is estimated at nearly 35% (GoM, 2011). About 67% of fuel wood is used in rural households for cooking and heating, 15% in urban households, 7% is used in tobacco and tea industries, and the remainder (11%) is used for other purposes, including small scale and urban industries. In a report released in 2010, the Millennium Challenge Corporation (MCC) suggested that 98% of rural households, 64% of urban households in Lilongwe and 42% in Blantyre and Mzuzu use fuel wood for cooking.

Use of biomass energy in Malawi has serious repercussion on deforestation in the country as many trees are felled down for charcoal production and firewood. The wanton cutting down of trees is exacerbated by the expansion of agriculture production as vast expanses of land are cleared every year for crop production. Statistics show that between 1991 and 2008, about 669,000 hectares of woodlands were converted to farmland (Gamula *et al.*, 2013). Malawi's biomass energy supply is covered under the National Forest Policy of 1997, the Forestry Act of 1997, and the Land Policy Act of 2002 while general issues of energy supply fall under the Energy Policy of 2003. While the energy policy envisages an ambitious transition from wood fuels to electricity, liquid fuels, coal and renewable energies, little is written concerning modernization, development or sustainability of the wood fuel sector (Gamula *et al.*, 2013). And in order to fill this gap, a Biomass Energy Strategy was formulated in 2009 as mentioned in the preceding discussion. The strategy provides approaches that the country should adopt in managing and developing the biomass energy sector in Malawi. The Forest Policy recognizes the importance of wood fuels for the sustenance of rural livelihoods and promotes sustainable wood fuel production.

In an attempt to minimize the use of biomass fuels and provide rural and urban communities with alternative source of energy, the Government of Malawi has undertaken a number of initiatives, including: the program for biomass energy conservation (ProBEC), which seeks to use more energy efficient technologies, e.g., improved stoves; introducing more efficient firewood management through drying and splitting wood among other methods; and promoting the use of Chitetezo Mbaula clay stove (Figure 15). Chitetezo Mbaula uses much less firewood than traditional stoves, and is easy and convenient to use, thereby helping households to take the first step away from open fires, which pollute the air both inside and outside the home. These stoves are affordable, locally made, and easily accessible to rural women who normally use wood for cooking on open fires.

Figure 11: Chitetezo Mbaula Clay Stove

The Government of Malawi is fully aware that the availability and quality of biomass for energy is declining because of the rising pressure on land and forest resources by agriculture, urbanization and energy needs of the urban poor. Symptoms of this problem are manifested in the increased distances and time taken by users to collect or buy firewood, the increased use of inferior materials (for example, leaves and agricultural residues) for cooking, the reduced number of hot meals taken in a day and the increased incidence of eating raw food, e.g., example, fruits and salads (GoM, 2010). This adversely affects people's nutritional status and imposes a high opportunity cost in time that could have been used to improve the economic status of the families by, for example, engaging in income generating activities (IGAs).

Electricity: Malawi's electricity is mainly derived from hydropower plants installed in the middle-reach of the Shire River, where 98% of the country's electricity is generated at the three stations, namely: Nkula, Tedzani and Kapichira hydropower plants. The remaining 2% (4.5 MW) is produced at Wowve HEP station in the Northern Region (GoM, 2010). Electricity Supply Corporation of Malawi (ESCOM) Limited is the only electrical power supplier in the country, and it is a publicly owned company which was established by an Act of Parliament in 1957, but was revised in 1963, and then in 1998. The country's current generation capacity stands at 351 MW against an estimated suppressed demand of 400 MW. Electricity is transmitted to the rest of the country through 132 kV network, with 66 kV being used in a few selected areas. The distribution network is at 33 kV, 11 kV and 400/230 V. Overall, the national grid is not very efficient, resulting in substantial transmission and distribution losses, estimated at 18% - 22% of the generated electrical energy. Access to electricity stands at 10%, one of the lowest in the SADC region and the world as a whole. Malawi's electricity generation deficit is not only a hindrance to new investments in manufacturing, industry, mining and tourism but also a deterrent to the advancement of the social and economic well-being of the citizenry. Thus, investments that would enhance the generation, transmission, distribution and utilization of electricity and other sources of energy are key to the development of the country.

Malawi has several potential sites for hydropower generation, including the following: Manolo, with a potential output of 60 to 130 MW; Henga Valley, with a potential output of 20 to 40 MW; Rumphi, with a potential capacity of 3 to 13 MW; Chizuma, with a potential capacity of 25 to 50 MW; Chasombo, with a potential capacity of 25 to 50 MW; Malenga, with a potential capacity of 30 to 60 MW; Mbongozi, with a potential capacity of 25 to 50 MW; Kholombizo, with a potential capacity of 140 to 280 MW; Mpatamanga, with a potential capacity of 135 to 300 MW; Low Fufu, with a potential capacity of 75 to 140 MW; Low Fufu and Tran, with a potential capacity of 90 to 180 MW; High Fufu, with a potential capacity of 90 to 175 MW; Chimgonda, with a potential capacity of 20 to 50 MW; and Zoa Falls, with a potential capacity of 20 to 45 MW (2010 b: Malawi Government, 2010 , "Malawi Electricity Investment Plan," Ministry of Natural Resources, Energy and Environment, Lilongwe, Malawi).

Overreliance on the Shire for the generation of electricity is risky because chances of outflow from Lake Malawi receding below the minimum elevation of 474 m above sea level, as was the case from 1915 to 1937 when there was no outflow from Lake Malawi into the Shire for 20 years, are very high. If the secession of flows from Lake Malawi into the Shire happens again, Malawi would fail to generate enough electricity for both industrial and domestic use. To manage this risk, electricity generation is being diversified beyond the Shire River through the development of several mini hydropower schemes (GoM, 2010). Malawi has also been exploring prospects of importing electricity from the SADC Power Pool, and from Cahora Bassa Dam in Mozambique.

Liquid Fuels and Gas: Malawi is a net importer of liquid and gaseous fuels. Supplies of these products are vulnerable to international oil prices, global events, and marketing arrangements. Liquid fuels and gas are also seriously affected by the value of the Malawi Kwacha against the US Dollar. The sensitivity of the economy to fuel imports is manifested in the huge proportion of transport costs incurred in the import bill which stands at 60% (Gamula et al., 2013). Since Malawi is a landlocked country, it relies on the cooperation of the neighboring countries for the continuous and unhindered availability of seaports and transit routes and handling facilities for its liquid fuels and gas. This renders fuel haulage into Malawi subject to high-level diplomacy, requiring inter-governmental goodwill.

Given the strategic importance of fuel to its economy, the Government of Malawi is undertaking measures to reduce the country's dependence on imports by supporting import substitution energy industries and by establishing institution al arrangements that provide an adequate balance between public and private participation in the supply of liquid fuels and gas in the country. Specifically, the Government of Malawi will:

a) Work with SADC and other international partners to promote oil and gas exploration;

b) Work with the private sector to encourage the expansion of fuel – ethanol production capacity to maintain a 20:80 petrol - ethanol blend, and support other fuel - ethanol applications, such as ethanol - diesel blends, gelfuel, etc;

c) Support Research and Development into new fuel ethanol applications and into other materials, to complement sugar by products, for its production;

d) Require oil supply companies to diversify fuel haulage routes and modes of transport through appropriate legislative instruments e.g. licensing arrangements;

e) Be actively involved in upstream activities through public investment in the National Oil Company of Malawi (NOCMA). NOCMA will be responsible for spearheading oil and gas exploration, and managing the country's strategic fuel reserve facility; and

f) Increase the country's storage capacity by acquiring, establishing and maintaining inland and coastal strategic fuel reserve facilities equivalent to 60 days consumption cover.

It is worth noting that sugar manufacturing companies at Illovo and Dwangwa are currently producing ethanol from molasses. Some of the molasses is sold to other companies to expand ethanol production and reduce overreliance on the national electricity grid for small industries.

Coal Supply: In Malawi, coal is used exclusively as an energy source for industrial production, mainly for tobacco processing, textile and sugar production, and beer brewing.

The estimated coal reserves in Malawi are between 80 million tons and 1 billion tons of which 20 million tons are proven reserves of bituminous type. Quality of the coal varies with energy values ranging from 17 to 29 MJ/kg. There are four coal fields in Malawi, three in the northern region and one in the southern region. Three are in Karonga and Rumphi districts while the fourth one is at Ngachira in Chikhwawa district in the Lower Shire Valley.

Coal mining in Malawi started in 1985 and currently two fields are being mined in Rumphi district. The coal produced from these sites is not adequate to meet the country's industrial needs; consequently, the balance is imported from Mozambique.

In order to address these bottlenecks, the DoE will work closely with the Mines Department and the Geological Surveys Department to expand privately invested coal - mining in the country and to break the trucking monopoly by rationalizing coal trucking to allow other players to participate.

Other Renewable Energy Sources: Malawi is endowed with a number of renewable energy resources, yet utilization of these resources is still in infancy stages. The energy sources include: solar, wind, and geothermal. There have been a number of initiatives in the renewable energy sources sector with the notable ones being the National Sustainable and Renewable Energy Program (NSREP, 1999), Barrier Removal to Renewable Energy in Malawi (BARREM, 1999), Program for Biomass Energy Conservation (ProBEC, 2002) and the Promotion of Alternative Energy Sources Project (PAESP).

Nuclear Supply: Malawi has about 63,000 tons of proven reserves of uranium at Kayerekera in Karonga District. Another deposit which is yet to be quantified is at Illomba in Chitipa district. Mining of uranium started in 2008 at Kayerekera, but the production was stopped when the price of uranium at the world market slumped. Electrical generators operating on diesel were used for electrical power supply to the mining site. There are plans by the government to build a nuclear power station in future.

Agriculture and Food Security

Malawi's economy remains agro-based, with agriculture accounting for more than 80 percent of export earnings, contributing 36 percent of gross domestic product (GDP), and providing livelihood for 85 percent of the population. Smallholder farmers contribute about three-quarters of agricultural production, with cropping systems dominated by maize. Therefore, it is obvious that good performance of the economy is directly linked to the performance of the agriculture sector. Over-dependence on rain fed agriculture has oftentimes led to low agricultural production and productivity due to weather shocks and natural disasters (erratic rains, dry spells, pest and diseases, droughts, floods, etc.). This has led to low socio-economic growth and development in the country.

Food security is commonly defined as "when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO 1996). Nutrition is, therefore, inherent in the definition; but, it is often a component that is minimized. Physical food availability at a national or community level is determined by food production, stock levels, and net trade. The FAO definition of food security entails producing enough food for the household and selling the surplus for income, whereas the USAID definition of food security entails having adequate income at household level for purchasing food.

Food utilization is commonly understood to mean energy and nutrient intake by individuals as a result of care and feeding practices, food preparation, diversity of the diet, and intra-household distribution of food. Food utilization can be considered the most explicitly nutrition-oriented aspect of food security. It is important to note that utilization of food is a biological process that is affected not only by food intake, but also by the presence of infection or disease, since a sick individual will absorb or utilize the nutrients in food less well than someone who is healthy.

Due to the experience in food insecurity both at national and household level, the Government of Malawi has put in place several sectoral and national policies and strategies to avert the food insecurity problem. In 2006 the Government, in conjunction with its development partners, developed the Malawi Growth and Development Strategy (MGDS) as a medium-term development strategy for achieving Malawi's long-term goals. MGDS aspires to attain the Malawi Vision 2020 formulated in the late 1990s and the Millennium Development Goals (MGDs) especially Goal Number One, of halving extreme poverty and hunger by 2015. Food security issues are currently being addressed by Goal Number Two of the Sustainable Development Goals (SDGs). The MGDS recognizes that 'the prospects for economic growth in the medium- term will continue to be driven by the agriculture sector. The main thrust of the MGDS is to create wealth through sustainable economic growth and infrastructure development as a means of achieving poverty reduction. The MGDS is expected to transform the country from being a predominantly importing and consuming economy to a predominantly producing and exporting economy. Sectors have thus aligned sectoral activities to the MGDS framework and have also adopted program-based Sector Wide Approaches (SWAps).

While hunger and undernutrition are still serious problems in Malawi, the country has made progress to reduce both. Nonetheless, Malawi has not attained stability in food security and nutrition for all citizens, resulting in high levels of hunger as well as undernutrition, which contributed to 23 percent of all child mortalities in Malawi between 2008 and 2012. Moreover, despite some advances in poverty reduction, economic growth has been inconsistent. However, Malawi has made improvements in some of the underlying determinants of undernutrition, including increasing calorie access and access to safe drinking water. Much more is needed to diversify agriculture and food systems to assure all food groups are available and accessible year-round.

Notwithstanding Malawi's progress in reducing its food deficit, shocks including the recent El Niño, combined with environmental degradation, exacerbate production challenges and contribute to food insecurity for many Malawians. During the period 2011–2013, the share of food expenditures in total expenditures for poor households in Malawi was 77 percent (FAO, 2016). In addition, research shows that households are allocating a larger share of their budgets to food than they did in the past, in spite of rising incomes. And while the country as a whole is consuming more of some nutrient-rich foods, only 15 percent of the children consume a minimum acceptable diet for quality with the required frequency. During shocks, nearly 60 percent of households consume a borderline diet. The high food share makes households vulnerable to price shocks; and price shocks for staple foods in Malawi exacerbate food insecurity, with particularly strong effects on poor net food buyers. In Malawi, 60 percent of households are net maize buyers.

In general, Malawian diets are heavily dominated by staple foods, maize first and foremost, but also rice and cassava in some areas. As such, food security in Malawi is often equated with maize production, or the ability of households to acquire enough calories from their chosen staple foods. What is missing by this measure is the importance of the quality, in addition to the quantity, of dietary intake. While maize and most other popular staple crops are high in carbohydrates, they are low in proteins, vitamins, and minerals. Because most Malawian meals rely heavily on these staples, other nutrient-rich foods, such as fruit, vegetables, fish, beans, and meat, are often consumed in small amounts or not at all. As a result, meals are often adequate in terms of total calories or quantity, but likely to be inadequate in terms of quality.

Land Resources (Irrigable Land Area)

Malawi has a total territorial area of approximately 11.8 million hectares, of which 20% is covered by water (GoM, 2002). Forests, wildlife reserves, settlements and infrastructure cover about 19% of the total area. The remaining 61% of land is used for different purposes depending on the topography, soils, agro-climate and other social and cultural factors. Protected areas cover 1.7 million hectares of land. This leaves 7.7 million hectares available for agriculture. However, not all land is suitable for agriculture, due to limitations such as poor soil quality and access. At present, Malawi's irrigation potential stands at 400,000 hectares (Figure 16), with water being the main limiting factor in most parts of the country.

Land is a key asset for Malawi's economic growth and development. The economy continues to rely heavily on agriculture and natural resources for a significant share of Gross Domestic Product (GDP), national food needs, employment, and export revenue. Agriculture, natural

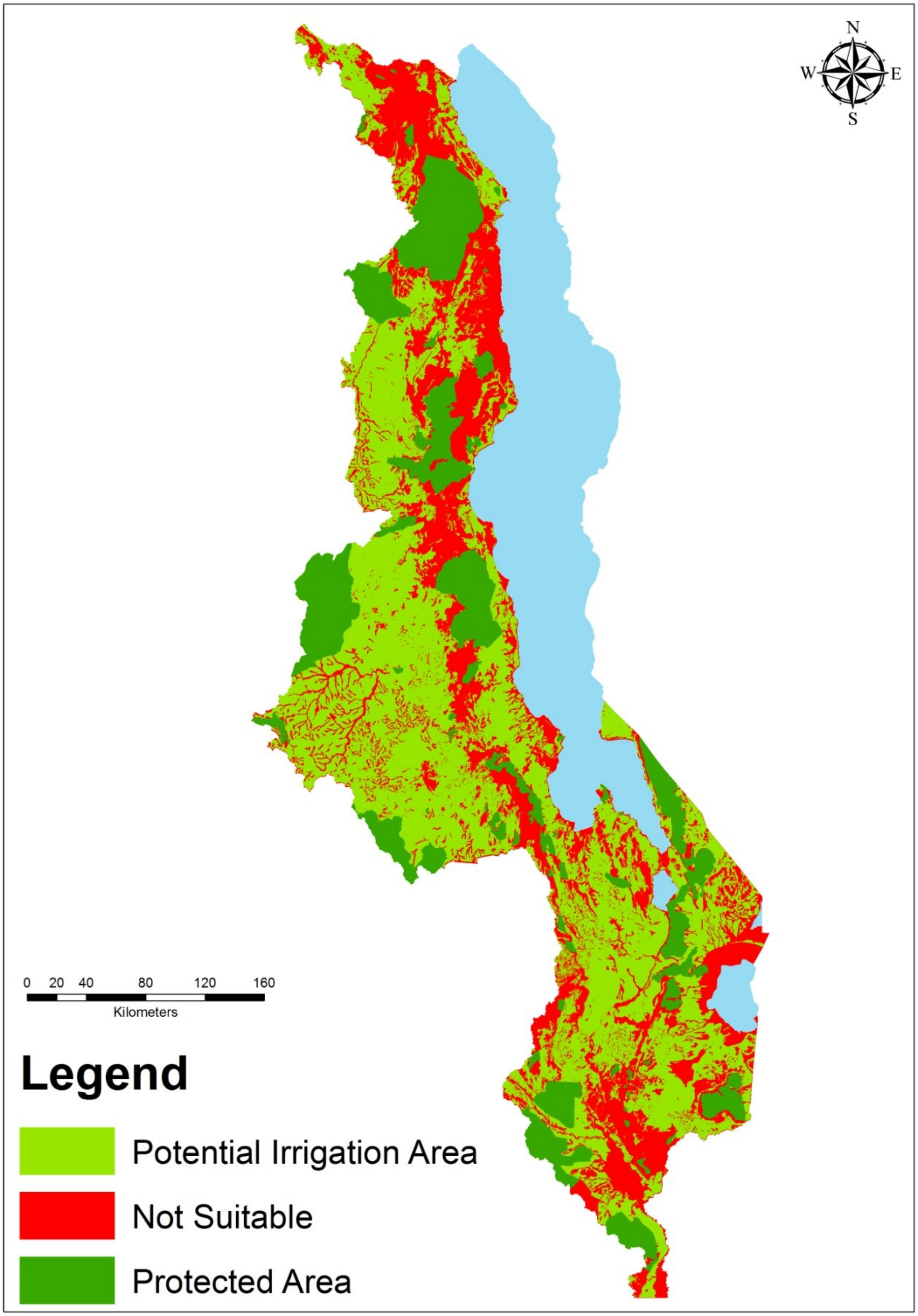


Figure 12: Map showing Malawi's Irrigation Potential (Source: GoM, 2014)

resource use and other land-based activities are also the primary sources of livelihoods for Malawians. The average land holding size per household is 1.2 hectares; and available land per capita is estimated at 0.33 hectares (GoM, 2010). Per capita land holdings have been declining from about 0.4 hectares in 1970 to about 0.2 hectares in 2007, partly due to a high population growth rate that has led to intergenerational fragmentation of land holdings. In addition, per capita land holdings are highly skewed, with the poor holding only 0.23 hectares per capita compared to the rich, who hold 0.42 hectares per capita. The pressure on land leads to degradation that affects all sectors of the economy, including mining, tourism, agriculture, irrigation, water, forestry and wildlife.

The Malawi Growth and Development Strategy (MGDS) recognizes the importance of both agriculture and land. Many of its targets are focused on developing this sector. For instance, the MGDS seeks to increase agricultural productivity, encourage agro-processing for export, maintain biodiversity in agriculture, and ensure tenurial security and equitable access to land. It is hoped that this will allow Malawi to attain broad based social and economic development that respects the ecological integrity of land and land-based resources.

The need to develop irrigated agriculture in Malawi is justified by a number of factors, namely: the country's vulnerability to droughts and dry spells, the need to make use of idle labor which is abundant during the dry season, and the need to produce pasture for livestock.

Most of the droughts that Malawi experiences are associated with the El Nino and the Southern Oscillation (ENSO) phenomena and the Indian Ocean Dipole (IOD). Notable drought episodes occurred in 1948/49 and 1991/92 seasons. Recent studies about the ENSO warm phase events in southern Africa indicate the existence of two drought cells, both of which affect Malawi, mainly the southern part of the country. The first drought cell shows a path originating from Namibia, but covering Botswana, Zimbabwe, southern Zambia, northwest Mozambique and the southern part of Malawi; whereas the second drought cell has its center located near southern Mozambique and southern Zambia and appears to expand outwards. There are no signs at the moment to suggest that these drought cells will cease to wreak havoc in the region. The prevailing situation will be exacerbated by climate change as evidenced by recent studies undertaken in Malawi which show increased intensity and frequency of droughts with climate change.

Long dry spells occasionally disrupt the rainfall season. Malawi experiences a unimodal rainfall season, which generally runs from November to March; and it is during this period that most of the crops are grown. However, protracted dry spells sometimes interrupt the rainy season, with serious repercussions on crop production. Even minor water deficits have had dramatic impacts on crop yields especially when these shortages take place during the flowering stage of the crop. A good example of such droughts occurred in 1949 when the whole country experienced a cessation of rainfall in the month of January, resulting in acute shortages of food. Under such circumstances supplementary irrigation is crucial for the sustenance of crop growth and maturity. The unimodal nature of rainfall pattern places limitations on varieties of crops that can be produced. Crops that require a lot of water during the dry season months can only be grown under irrigation systems.

The seasonality of crop production in Malawi forces farmers to stay idle during the dry season. This labor may be put to good use by employing it on irrigated farming, with consequent benefits such as income generation and creation of employment opportunities.

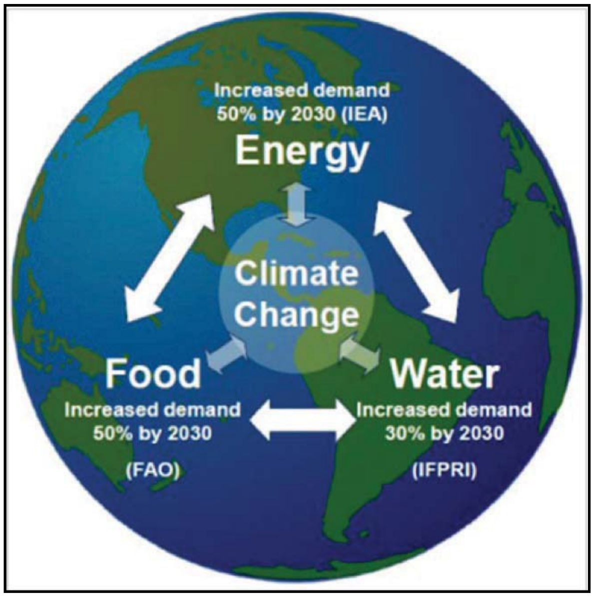
The increase in population growth calls for improved agricultural production to meet the increasing demand for food. Increased population growth has led to declining amount of available arable land countrywide such that one third of smallholders cultivate less than 0.5 ha. Under rainfed conditions, crop production on such small pieces of land is inadequate for the sustenance of food security. However, with the introduction of dry season farming through irrigation the productivity can be enhanced. Hence there is need for intensification of agriculture production through irrigation to keep pace with population growth.

Livestock productivity is highly constrained by lack of adequate feed and drinking water during the dry season. Where conditions of acute shortages of forage prevail, severe reductions in livestock numbers occur. Irrigated agriculture has potential to produce livestock feed and also provide drinking water for animals during the dry season.

3.0 A Case for the Adoption of the WEF Nexus in Malawi

The discourse on food, water, and energy security is driven by the growing pressure on natural resources (Rasul and Sharma, 2015). The demand for food, water, and energy is increasing steadily, but the resources required to generate them are limited, and in many cases dwindling. Furthermore, the situation is exacerbated by climate change. The interdependencies among water, energy, and food are numerous and multidimensional, and their relationship is often called the Water, Energy, and Food (WEF) nexus (Figure 6). Although the discourse on this nexus has been gaining currency, it is not yet clearly understood how the concept can be applied to ensure food, water, and energy security. Thus, understanding the different interfaces in the food, water, and energy nexus will be critical for taking action in achieving water, energy, and food security (Rasul and Sharma, 2015).

The interlinkage between the water, energy and food supply systems is a major consideration in the formulation of sustainable development strategies for countries. Rapid economic growth, expanding populations and increasing prosperity are driving up the demand for energy, water and food, especially in developing countries. By 2050, the demand for energy will nearly double globally, with water and food demand estimated to increase by over 50% (Rasul and Sharma, 2015). The ability of existing water, energy and food systems to meet this growing demand, meanwhile, is constrained by the competing needs for limited resources. As stated in the preceding



Source: Beddington, 2009

Figure 13: The Water-Energy-Food (WEF) Nexus (Source: Beddington, 2009)

discussion, the challenge of meeting growing demand is further compounded by climate change. The nexus is already posing a significant challenge for improving water, energy and food security, a concern for policymakers today.

The International Energy Agency defines energy security as: "the uninterrupted availability of energy sources at an affordable price" . While there is no single definition of the concept of energy security, it has evolved from a narrow link to the stable supply of oil products to integrate other energy sources, as well as the essential dimension of sustainability.

A working definition of water security by the United Nations is stated as: "the capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability".

The Food and Agriculture Organization of the United Nations defines food security as existing "when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life".

One of the important interfaces in this nexus is that of water with food and energy. Water plays a vital role in both food and energy production (e.g., generation of hydropower), and in sustaining ecosystems that support agriculture and other economic activities that are critical for achieving food security. A second important interface is that of energy with food and water. Energy is required for food production (e.g., irrigated agriculture, ploughing fields using tractors, etc.) and for water supply, including the abstraction, purification, and distribution of water through complex pipe networks. The third interface in the WEF nexus entails food production, a process that involves the "consumption" of land, energy, and water. Agriculture production, an activity responsible for growing food, is a major user of water (more than 70% of all water use globally) and energy (Rasul and Sharma, 2015). Agriculture and food production further affect the water sector through land degradation, changes in runoff, and disruption of groundwater recharge. Sustainable agricultural practices, such as those designed to prevent land degradation, save water and energy by increasing water storage in the soil and enhancing groundwater recharge, and by reducing the use of energy-intensive fertilizers.

The relationships among food, energy, and water are dynamic. Actions in one area usually have serious repercussions on other sectors, with profound economic, environmental, and social consequences. Thus, the security of one sector cannot be achieved without undermining another sector. The environmental footprints associated with increased water and energy use for food production impose external costs to water and ecosystems, thus threatening the sustainability and resilience of global water and food systems, and demonstrating the need for integrated solutions.

The nexus approach aims to systematize the interconnections and provide tools to assess the use of all resources. It is a system-wise approach that recognizes the inherent interdependencies of the food, water, and energy sectors for resource use, seeks to optimize trade-offs and synergies, and recognizes social and environmental consequences. Understanding the linkages within the food, energy, and water nexus can provide opportunities to increase resource use efficiency and enhance cooperation and policy coherence among the three sectors. The nexus perspective should help to promote interdisciplinary and mutually beneficial actions. It can contribute to meeting the future needs of the global population, particularly those who do not have access to safe drinking water and modern energy. From this perspective, the identification of crucial interactions, conflicting demands, and potential synergies in the water, energy, and food nexus can be a powerful entry point for achieving sustainable adaptation.

Rasul and Sharma (2015), summarized the nexus approach as follows:

a) Understand the interdependence of subsystems within a system across space and time and focus on system efficiency rather than the productivity of individual sectors to provide integrated solutions that contribute to water, energy, and food policy objectives;

b) Recognize the interdependence between water, energy, and food and promote economically rational decision making and efficient use of these resources in an environmentally responsible manner;

c) Identify integrated policy solutions to minimize trade-offs and maximize synergies across sectors, and encourage mutually beneficial responses that enhance the potential for cooperation between and among all sectors, and public–private partnership at multiple scales;

d) Ensure policy coherence and coordination across sectors and stakeholders to build synergies and generate co-benefits to produce more with less and contribute to long-term sustainability with limited environmental impact; and

e) Value the natural capital of land, water, energy, and ecosystems and encourage business to support the transition to sustainability.

The water, energy, and food nexus and climate change adaptation responses are interlinked in numerous ways. The main elements of the nexus and links with climate change adaptation are shown in Figure 7. It is critically important for policy makers to understand the linkages between the water, energy, and food nexus and climate change adaptation when devising sustainable adaptation strategies.

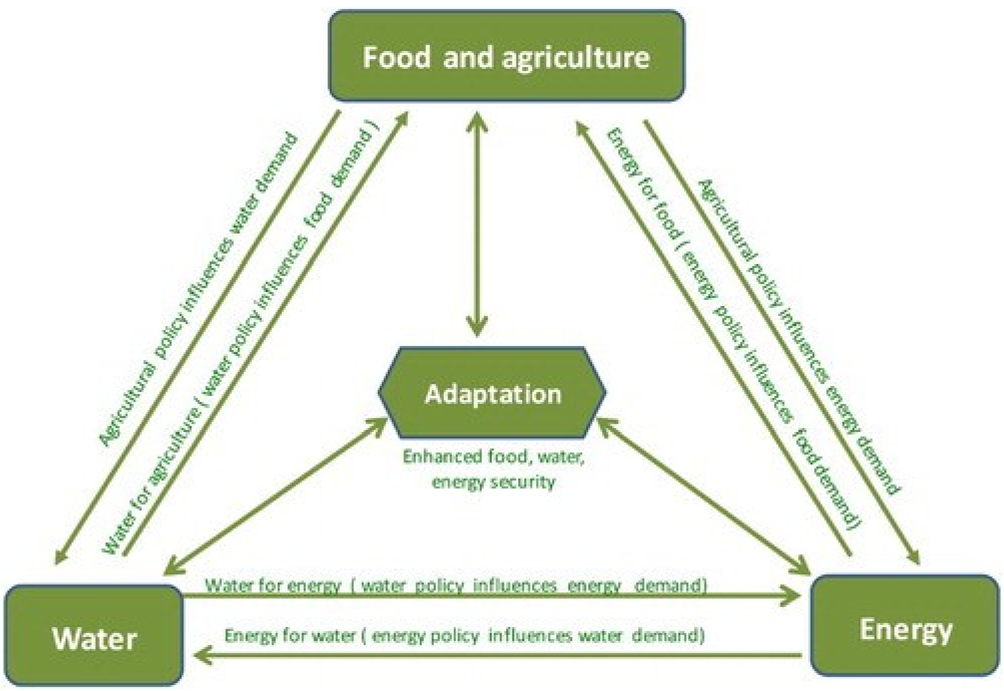


Figure 14: The interfaces among water, energy, food, and climate change adaptation (Source: Rasul and Sharma, 2015).

As water, energy, and food are vital resources for poverty and vulnerability reduction, understanding the linkages among them is critical for adaptation planning. Understanding trade-offs and synergies or complementarities in the water, energy, and food nexus can provide new insights for developing effective adaptation strategies. Given the complex interplay of water, energy, and food demand and supply, numerous challenges and opportunities exist to minimize trade-offs and promote synergies to formulate effective adaptation options. The nexus approach provides a framework for addressing competition for resources and enhancing resource use efficiency. The goals and principles of the nexus approach and of climate change adaptation are closely linked and interconnected, as are the focus and strategies. Effective adaptation and nexus approaches share many common features. Management of water, energy, and food security has an impact on adaptation, and the strategies and policies aimed at climate mitigation and adaptation have significant implications for nexus challenges.

Understanding the role of the water, energy, and food nexus in adaptation will be key to designing effective adaptation policies and strategies. The nexus outlook can also help to stimulate critical thinking on aligning the sustainable development goals (SDGs) with planetary boundaries in the post-2015 development agenda.

The complex interplay of food, energy, and water demand and supply requires a holistic approach and institutional mechanisms to coordinate the actions and strengthen complementarities and synergies among the three sectors of water, energy, and food. However, insufficient attention has been given to cross-sectoral issues, particularly the harmonization of sectoral goals and systemization of decision making, taking into account cross-sectoral dimensions. Moreover, ministries responsible for planning have little control over budgetary resource allocation. It is therefore critical to reinforce the nexus perspective at national planning level and strengthen the capacity for diagnosing interlinkages among sectors and bringing them into planning decisions. The nexus approach may help in the systemization of planning and decision making at the national level to support sustainable climate change adaptation by maximizing synergies and minimizing trade-offs in resource use and enhancing policy coherence across the three sectors.

To move from a sectoral approach to a holistic approach, an appropriate framework is required as indicated in Figure 8 (Rasul and Sharma, 2015). Area A in the Venn diagram represents the situation of an integrated nexus-based response strategy for sustainable adaptation to ensure the security of all three sectors. The central area represents the core principles of a nexus smart policy and the associated outcomes that underpin the three sustainability dimensions: economic (increasing resource efficiency), social (accelerating access for all), and environmental (investing to sustain ecosystem services). This means that we should devise a climate smart adaptation policy that not only improves the efficiency of resource use among the nexus sectors, but also takes a broader view of the impact of resource use on the overall environment and societal well-being. Finally, the third area stresses the need to target the vulnerability - poverty linkages (overlap between poverty eradication and vulnerability reduction) to reduce poverty and vulnerability concurrently, rather than treating them separately, in order to ensure that adaptation solutions are sustainable. All three areas must be underpinned by an enabling environment.

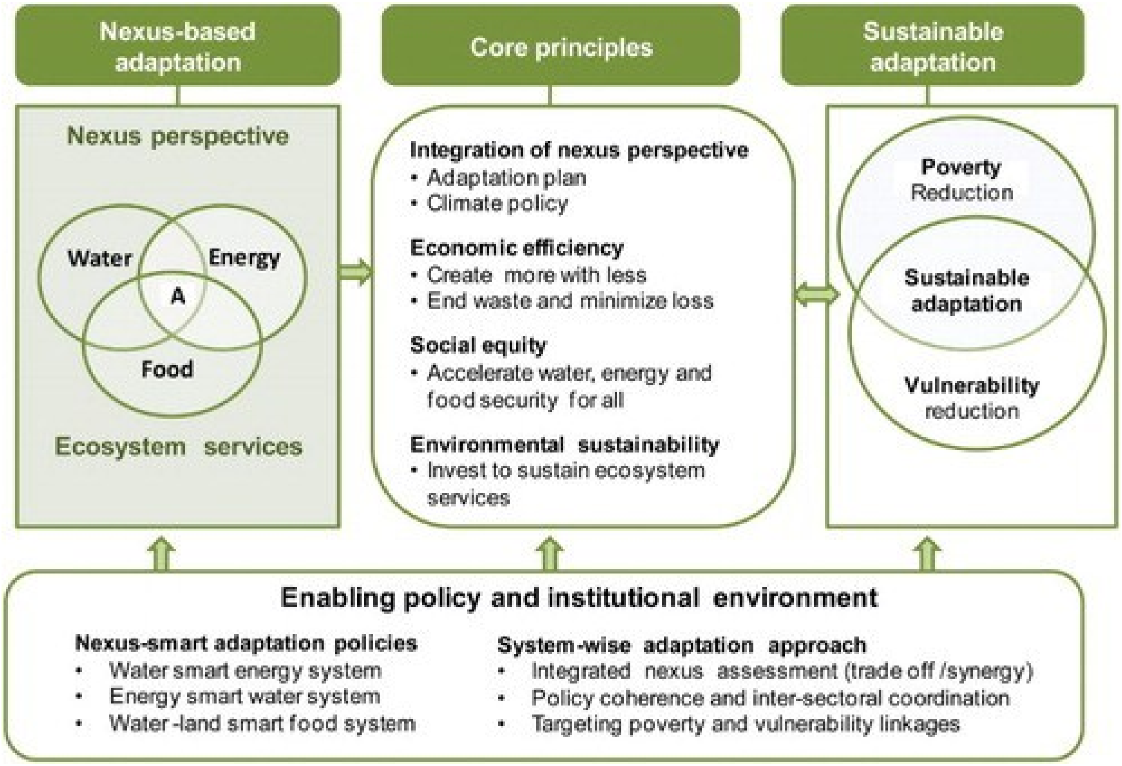


Figure 15: Outline for a nexus-based adaptation framework (Source: Rasul and Sharma, 2015)

Since the adaptive capacity of those affected by climate change ultimately depends on their access to poverty reducing opportunities, adaptation plans can only be effective if they are built into the wider development agenda. This is necessary to ensure that adaptation policies do not work counter to development efforts, so-called 'maladaptation'. The framework illustrates the need to understand how the context of vulnerability to both climate and non-climate change influences the development of poverty and how people adjust their adaptation strategies, before devising a nexus-based response strategy. It stresses the need to improve cross-sector and cross-border cooperation and coherence of efforts to properly tackle the nexus-based adaptation challenge. The following are some broad recommendations (Rasul and Sharma, 2015):

a) Integrate the nexus perspective into adaptation plans and the adaptation perspective into development plans for better policy integration. For effective integration, it is critical to recognize the importance of the nexus perspective and to integrate multiple policy objectives and increase stakeholder collaboration in sustainable adaptation and development planning and decision making;

b) Deepen the nexus knowledge base and internalize it into development and adaptation plans. Knowledge and understanding of the interlinkages between the nexus perspective and adaptation plans and responses are limited, so deepening the nexus knowledge base and developing mechanisms to strengthen institutions and internalize this knowledge in the planning process through nexus-based assessment and prioritization will be critical for effective adaptation;

c) Promote a system-wise adaptation approach. Move away from a sectoral to a trans-sectoral approach so that different adaptation responses and measures support each other, synergy is enhanced, and trade-offs are minimized;

d) Promote win–win options for nexus security and adaptation to climate change. Enhance the efficiency and productivity of resource use and increase multiple uses of resources through economic incentives, governance, institutional and policy coherence, and the promotion of public–private partnerships to increase the benefit from productive ecosystems;

e) Create and support an enabling environment. Strengthen policy integration between nexus and adaptation mechanisms across sectors at different scales and among the major actors (public - private - civil society partnerships) and strengthen institutional capacity for coordinating the water, energy, and food nexus and adaptation in a holistic way; and

f) Invest in nexus smart infrastructure, multifunctional ecosystems, and innovative technologies and institutions. Provide policy and institutional support for attracting investment in green infrastructure and design mechanisms to internalize externalities (environmental and social costs) into decision making by introducing appropriate incentives, regulations, and payments for ecosystem services.

Some of the key challenges for the WEF nexus are: increasing population and declining agricultural land; stagnating or declining food production; increasing water and energy intensive food production in the face of water and energy scarcity.

4.0 Establishing the context and case for supporting WEF nexus investments

The need to adopt the WEF nexus is influenced by the desire to address key problems that countries in the SADC region, including Malawi, are grappling with, namely: high population growth, urbanization, climate change, and resource degradation. Malawi's National Environmental Action Plan (NEAP) of 1994 identified nine environmental problems that beset the country, namely: soil erosion, deforestation, water resources degradation and depletion, threat to fish resources, threat to biodiversity, human habitat degradation, high population growth, air pollution, and climate change. The WEF nexus is therefore critical in addressing the nine environmental problems highlighted above, thereby enabling the Government of Malawi to achieve Sustainable Development Goals.

Malawi, like the rest of the countries in the SADC region, is experiencing high population growth, with serious repercussions on resource degradation, increased poverty levels, and generally declining standards of living. As mentioned above, the adoption of the WEF nexus has the potential to curb problems associated with population growth highlighted above.

With many people streaming from rural areas to cities to seek employment opportunities, provision of basic social services in cities and towns gets overwhelmed and overstretched by the increasing demand for health services, schools, housing, water supply, and many other social services. This results in a number of social problems, including increased crime rate, incidents of disease outbreaks (e.g., cholera and dysentery), and prostitution (resulting in the spread of HIV/AIDS). It is in light of the above that the

WEF nexus would be useful in guiding the Government of Malawi in coming up with robust policies to avert or curb problems highlighted above from manifesting themselves in urban areas.

Climate change is one of the most serious global concerns of our time and has already had observable impacts on the environment (Boko *et al*., 2007; IPCC, 2007). If not addressed now, this phenomenon will be a great impediment to sustainable development as it permeates all socio-economic sectors of our society. According to the 2010 United Nations Country Assessment Report for Malawi, climate change poses a serious threat to Malawi's development agenda such that in the short to medium term it will significantly affect the functioning of natural ecosystems, with major implications for several weather sensitive sectors, namely: agriculture, environment, forestry, water resources, energy and fisheries; and human systems, particularly human health and human settlements. In the long-term, climate change will undermine the attainment of Sustainable Development Goals and exacerbate poverty. It is therefore incumbent upon the Government of Malawi to put in place measures that will guarantee the country's resilience to the vagaries of climate change by, among other things, implementing anticipatory adaptive strategies. The WEF approach has been noted to be a valuable tool in the formulation and adoption of climate change adaptation measures.

Resource degradation is a common problem in the SADC region, manifested in deforestation, declining soil fertility fueled by soil erosion, siltation problems in water bodies (reservoirs, lakes, and rivers), water pollution, and infestation of invasive water weeds. Key underlining causes of resources degradation include high population growth, human settlements, agriculture production, climate change, poor management of land resources, and poverty. Unless these problems are addressed using the WEF nexus approach, the SADC region will continue to experience resource degradation and thus fail dismally to achieve Sustainable Development Goals.

In order to implement the WEF nexus, there is need for policy alignment and coherence among the three sectors, namely: water, energy, and food (agriculture). Also, there is need for improved institutional coordination of the three sectors; alignment of development strategies, targets, and programmes; and to manage/minimize tradeoffs and optimize synergies.

The close link between the WEF Nexus and Sustainable Development Goals (SDGs) makes it imperative for Malawi to embrace this concept as a key developmental tool. Highlighted below are some of the obvious linkages between WEF Nexus and the SDGs.

The World-Wide Fund (WWF) for Nature Report of 2017 titled: "***The food-energy-water nexus as a lens for delivering the UN's Sustainable Development Goals in southern Africa"*** presented a detailed account of the linkages between the elements of the WEF nexus (i.e., water, energy, and food) and Sustainable Development Goals.

Goal 2: Zero Hunger - Sub-Saharan Africa has close to half of the world's available uncultivated land, unused water resources and considerable potential for improved yields. This suggests the potential for self-sufficiency and a far bigger role for African agriculture in global food security in the future. However, climate change remains an unpredictable factor in future productivity.

Regional dialogue could help develop an expanded definition of food security or food self-sufficiency. A regional perspective on food as a resource would help to cope with issues of water management, food security and energy generation, and improve the prospects of achieving Goal 2.

Goal 6: Clean Water and Sanitation - Water is at the heart of meeting the SDGs since it underpins economic development and directly influences many other sectors. Therefore, it is difficult to address water without also addressing energy and food. With many shared rivers and river basins in the region, there are already a number of regional responses that can serve as good practice examples for other sectors.

Access to improved water sources and to sanitation facilities continues to be a challenge. With population growth and increasing urbanization, municipalities play an important role in achieving this SDG.

Goal 7: Affordable and Clean Energy - Unless urbanization is supported by increased access to affordable clean energy, urban energy poverty could increase dramatically, with households largely relying on unsafe, unhealthy forms of energy such as paraffin, coal and traditional biomass (wood, charcoal, waste and crop residue). These forms of energy not only pose a risk to human health but will also contribute to added deforestation in the region.

Insufficient and unreliable electricity infrastructure, the rising cost of electricity to pay for the addition of new energy capacity and the rehabilitation of energy infrastructure, and fluctuating petroleum fuel prices mean that charcoal may remain the fuel of choice even in many communities with access to electricity.

Connection of Goal 2 to Goal 6: massive volumes of water are needed for the irrigation of crops and processing; and agriculture has an impact on available water quantity and quality.

Connection of Goal 2 to Goal 7: agriculture is dependent on oil throughout the value chain; there could be a shift to production of fuel crops instead of food crops; and coal deposits often coincide with areas of high agricultural value.

Connection of Goal 6 to Goal 2: Agriculture needs water for irrigation and processing, resulting in reduced cases of hunger; whereas the mining of fossil fuels as well as agricultural production activities can cause water quality pollution.

Connection of Goal 6 to Goal 7: Different kinds of (thermal) power plants need water for cooling; hydropower plants rely on water availability for the generation of electricity; and a shortage of energy also affects delivery of water services, for example the energy required to operate pumps in water supply systems.

Connection of Goal 7 to Goal 2: Agriculture is dependent on oil throughout the value chain; there could be a shift to production of fuel crops instead of food crops; and food security cannot be achieved unless people can afford the fuel with which to cook the food

Connection of Goal 7 to Goal 6: Different kinds of (thermal) power plants need water for cooling; hydropower plants rely on water availability for the generation of electricity; and a shortage of energy affects the delivery of water services, for example the energy needs of pumps in water supply systems.

5.0 Conclusion

The potential that Malawi has in terms of the availability and good quality of water resources (both surface water and groundwater), energy resources (i.e., biomass, hydropower, solar and wind); and the availability of land resources (hectarage of irrigable land) for agriculture production offer the country a great opportunity to adopt the WEF Nexus, a critical approach for the sustainable management of natural resources in fostering poverty alleviation endeavors, particularly in light of climate change. The Shire and Songwe River Basins are typical examples in the country where the WEF Nexus could easily be employed and put to good use.

The need to adopt the WEF nexus is influenced by the desire to address key problems that countries in the SADC region, including Malawi, are grappling with, namely: high population growth, urbanization, climate change, and resource degradation. Malawi's National Environmental Action Plan (NEAP) of 1994 identified nine environmental problems that beset the country, namely: soil erosion, deforestation, water resources degradation and depletion, threat to fish resources, threat to biodiversity, human habitat degradation, high population growth, air pollution, and climate change. The WEF nexus is therefore critical in addressing the nine environmental problems highlighted above, thereby enabling the Government of Malawi to achieve Sustainable Development Goals.

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Paper 2: Evaluating the Feasible Wastewater Treatment Methodologies for Malawi – An Upgrade from the Conventional Waste Stabilisation Ponds (wsps) in Lilongwe City

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Keys: Membrane Bio Reactor, Conventional Activated Sludge, Sequential Batch Reactors, On-Site Sanitation (OSS),

ABSTRACT

The ongoing sanitation reform projects have so far concentrated on addressing some of the challenges in the sanitation infrastructure and network upgrades. Nevertheless, Lilongwe City remains reliant on On-Site Sanitation with only 5% connected to the sewer network. The paper aims at making an objective evaluation of alternative treatment systems in the industry to transition from the conventional Waste Stabilisation to more efficient systems with a focus on Activated Sludge based approaches such as the robust Sequential Batch Reactors (SBRs), Conventional Activated Sludge (CAS) and the Membrane Bio Reactors (MBRs). This is a bid to ensure the extended coverage of the sewer network to achieve the Malawi 2063 by adopting improved sanitation facilities as the current plant can only handle 6% (6,100m^3/day) of the ideal waterborne waste created and at maximum 8.7% (8,700 m^3/day) through a conceptualised installation of aerators. The appraisal shows WSP merits mainly on operation costs while demerits in other metrics such as foot print, effluent quality, aesthetics and Environment, and flexibility as far as urban wastewater treatment is concerned. The SBR and CAS are the feasible systems that can be adopted while the MBR is more suited for industrial WWTPs with less particulate in the influent that can cause frequent fouling. New patents in the SBR and AS technologies continue to evolve bringing more prospects in designing more user and climate-responsive systems.

1. Introduction

The Malawi Agenda 2063 identifies clean water, sanitation and hygiene as one of the key issues to be addressed in fostering Human Capital Development as an enabler in achieving a prosperous and self-reliant nation. Among others, the activities include the provision and promotion of the use of improved and accessible sanitation facilities in all public places as well as improving the management and disposal of liquid and solid waste (National Planning Commission, 2020). These initiatives are reflected in the ongoing major collaborative Water and Sanitation Projects such as the Lilongwe Water and Sanitation Project (LWSP) – Lilongwe City; Malawi Water and Sanitation Project – Blantyre (MWSP) and the Mzimba Water and Sanitation Project -Mzimba.

These major Projects on sanitation are addressing some of the key challenges the sector is facing including network extensions and enhancing existing treatment plant capacity of WSP. There is need to conceptualise and implement long term infrastructure solutions as far as waterborne waste is concerned. The paper hence evaluates some of the modern and eco-friendly alternatives to the current WSPs used in the country. The WSP treatment method is lacking with the rapid urbanisation, urban space constraints and the need for affordable and high-throughput sewage wastewater treatment systems

1.1. Background and Literature Review

In spite of the efforts by Malawi government and development partners, Malawi has a colossal gap in access to safely managed sanitation services and a continued challenge in supplying water to the ever-increasing urban population at a growth rate of around 4% per annum as well as 2.5-2.8% nationally (National Statistical Office, 2018).

The Malawi 2063 (2020) places baseline access to safely managed sanitation at 35.2% nationally and 65.5%, however, only 6% of the Nation Population has access to a sanitation facility based on International Standards (USAID, 2020) while on the same note, Lilongwe City has a connection rate to sewer services at just 5%. The 2024 Afro-barometer report on Water and Sanitation also identifies Malawi as the least development in the field of sanitation with 5% access to sewer services (Afrobarometer, 2024).

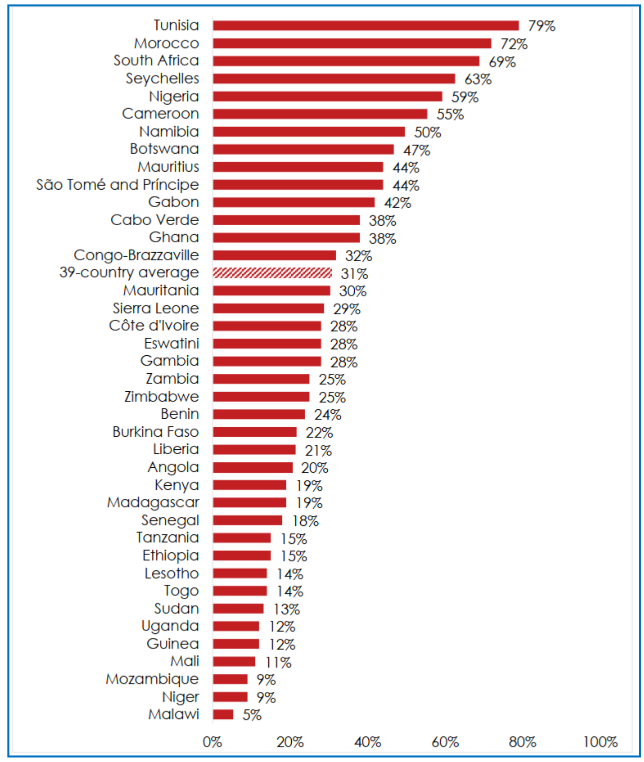


Figure 1-1. Access to Sanitation Infrastructure, Malawi at 5% ((Afrobarometer, 2024)

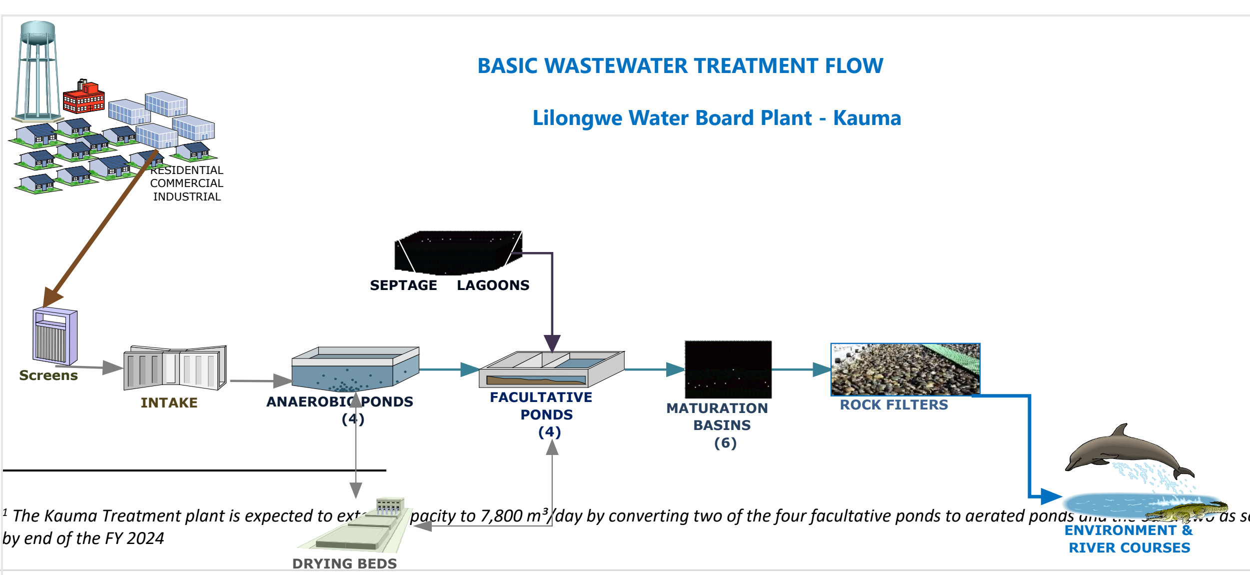
1.2. Lilongwe Wastewater Treatment Plants (WSPs)

Lilongwe City boasts of 3 WWTPs namely Lilongwe Wastewater Treatment Plant (Kauma), Kanengo Wastewater Treatment Plant and Lumbadzi Wastewater Treatment Plant (Lumbadzi).

The major treatment Plant in Kauma [1]has a design capacity of 6,100 m3/day and serves areas such as 1, 2, 3,4,6,11,12,13, 18,19,20, 32,34,37,40, 47,48 and 49 and also taking 80% of the sewer network.

The WSPs used in Malawi and Lilongwe follow through:

- Screening, anaerobic digestion, and the final stage Facultative process (restricted irrigation) and maturation Ponds for the unrestricted ((MoWDI, 2012) in treatment of influent



The effluent discharge parameters in Mala

[1] The Kauma Treatment plant is expected to ext… pacity to 7,800 m^3/day by converting two of the four facultative ponds to aerated ponds … as settling tanks by end of the FY 2024

Figure 1-2. Basic Wastewater Treatment Flow in Waste Stabilisation Ponds (WSPs) wi is guided by the Malawi Bureau of Standards (Malawi Bureau of Standards, 2013) (MS 539:2013), MS 619:2005, MS 691 and World Health Organisation (WHO) as follow:

Table 1-1. Discharge parameters for WSPs in Malawi

Discharge limits to the environment in accordance with the Malawi Standard; MS 539: 2013			
PH	6.5-9.0	TURB(NTU)	25≤
Temp(°C)	≤40	BOD(mg/l)	≤20
SS(mg/l)	≤30	COD (mg/l)	≤60
TURB(NTU)	≤25	DO (mg/l)	≥5

2. Objective

The paper aims at making an objective evaluation of alternative treatment systems in the industry to transition from the conventional WSPs to more efficient systems with a focus on MBRs and SBRs.

3. Methodology

The paper made cognizance of the literature for treatment systems in Developing nations. Furthermore, a case study has been selected for the Capital City Lilongwe with emphasis on Kauma Treatment Plant. The plant is the largest WSP in Malawi.

4. Comparative Analysis of Waste Stabilisation Ponds and Other Activated Sludge Processes - Findings

The treatment methods analysed are the activated sludge-based processes that have been adopted and in use across the world. The methods include the Sequential Batch Reactor, the Membrane Bio Reactor and the Conventional Activated Sludge.The comparatives include foot print, Effluent Quality Energy Consumption, Retention Time, Robustness, Effluent Reuse

Table 4-1. 4. Comparative Analysis of Waste Stabilisation Ponds and Activated Sludge Processes

Attribute	WSPs	SBR	MBR	Note
• **Foot print**	A range of 1 to 2 hec /10x10^3m3 [2]	A range of 0.2 to 0.5 hec /10x$10^3$$m^3$	Lowest Footprint of A range of 0.2 to 0.3 hec /10x$10^3$$m^3$	*Kauma WWTP is sited on a **19.4** hectares ground*
• **Effluent quality and reuse**	Adequate BOD removal upto 90% and TSS removal in the Range 60%-90% Normally for Agriculture	BOD removal upto 95% and TSS ~95% Water for industrial and potable use	TSS removal upto 100%. (<1 NTU) BOD removal efficiency to 99%. Water for industrial and potable use	*The Kauma Plant handle domestic, industrial and Faecal sludge, posing a challenge to maintain required effluent quality*
• **Energy Requirement**	N/A normally Natural Processes	~04kWh/ m3 of treated influent	~0.8 kWh/m3 of treated WW	*Kauma WWTP can require approx.*

[2] ***Error! Reference source not found.***

	(Mara, 2003)	Through Air blowers/ diffusers	Membrane Blowers and Pumps	*MK250k as SBR and around MK480k as MBR to treat 6,100m3*
• **Robustness/ Flexibility**	Limitation to change in influent characteristics especially industrial influent with dissolved nutrients. In terms of volume, have adequate FoS	The batch operation is robust to hance fluctuations in influent	Limited flexibility due to membranes that are susceptible to **Fouling** Require adequate pre-treatment (Halfor, 2020)	
• **Est Capital Costs**	\$200 to \$500 per cubic meter Typical No mechanical or electronics	\$1,000 to \$2,000 per cubic meter	\$1,500 to \$3,000 per cubic meter of treatment capacity	
• **Retention Time**	RT range from **20-60** days (Metcalf & Eddy, et *al.* 2013)	Typical **4 to 12** hours per Batch	**6-24 Hours** Loading Rates	*Kauma WWTP was designed with a retention time of 28-30 days*
• **O&M**	Monitoring and maintaining ecosystems	Routine Sludge Removal and Unit checks Require technical capacity building	Chemical Cleaning of Membranes Require technical capacity building Replacement of Membranes	
• **Aesthetics and Air Pollution**	Anaerobic Conditions produce methane gases which produce heavy odour. Advised distance 500m from plant	The batch cycles prevent ordour development by providing aerobic conditions Treatment Units can be covered,	Effective OM removal, can be covered	

5. OBSERVATIONS

- It is becoming less feasible to construct the WSPs in Lilongwe to serve the growing urbanisation of 4% due to the high foot print of WSPs which are currently solely dependent on terrain (gravity)
- The Retention Time for WSPs of ~30days possess an operational risk in case of any unforeseen occurrences and emergencies on the plant. An alternative is required for Business continuity
- As compared to Water Supply which is at ~90% coverage, more efficient activated Sludge systems are required

On average LWB produces = **125,000 m^3/day**

In Design ***-0.6-0.85*** *of Water Consumption is converted to Wastewater*

((MoWDI, 2012) *and* (Mara, 2003)*;*

Hence Vww = ~0.8 (Vwater)
= 100,000 m^3/day

Sewer System = 6,100 m3/day

OSS (On-Site Sanitation) ***= 93,900 m3/day***

NB: It would require 16 WSPs to achieve 0 OSS in Lilongwe City

- The rate at which groundwater sources are being polluted from the percentage of OSS is alarming
- The Sequential Batch Reactor Plant is flexible and economical for adoption as a variation to the conventional Activated Sludge Process.

6. CONCLUSION

- Sanitation is a basic need that has to be prioritised in the pursuit of the inclusively wealthy and self-reliant nation. At 5% connection to improved sanitation, Malawi remains the least developed in the area. It is imperative to adopt of eco-friendly, yet economic sanitation infrastructure that can sustain the fast-paced development in Lilongwe City.
- The assessments in this abstract form basis for further studies in selection and adoption of various treatment plant designs and recommends further appraisal in adoption of treatment technologies. There is however need for:
- Efficient and cost-effective systems such as SBR and CAS
    - For network expansion and accelerated connectivity to improve coverage in the city and achieve sanitation for all
    - For circular economy to recover and reuse effluent for industrial and agricultural purposes
- The MBR is susceptible to a number of factors including particulate load hence can be used in manufacturing industries for its efficiency in dissolved nutrients and pathogens and recovery percentage

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Paper 3: Vacuum Sewerage Systems as an Alternative to Conventional Gravity Sewer Systems: A cost benefit analysis in Central Malawi

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Abstract

In many developing countries there is a spur in the creation of new plots and these need to be connected to wastewater treatment plants as a component of area development. To introduce such infrastructure, problems emerge when conventional sewer systems (GSS) are not feasible. On the other hand, using on-site treatment methods like septic tanks is not environmentally friendly, so there is a need to seek alternatives. Vacuum Sewerage Systems (VSS) have emerged in recent years as an alternative to GSS. A cost-benefit analysis was conducted between the VSS and GSS to establish an alternative source of wastewater conveyance backed with technical and financial justifications. The two systems were designed for one common area in Lilongwe, Area 49 Old Gulliver. Costings for both systems were made based on design data and a cost-benefit analysis with a design life of 40 years was conducted. Results show that both systems are technically feasible. Both systems registered positive Net Present Value (VSS: USD 453,760, GSS: USD 263,939) and Profit Index (VSS: 1.34, GSS: 1.14) making the two systems financially viable. Although the VSS has higher operational and maintenance costs (VSS: USD 3,880,934.19, GSS: USD 2,069,395.04), overall, it is the most cost-effective system. The VSS is 26.4% more economical than the GSS in the investment stage, has a shorter payback period (VSS: 13.8, GSS: 13.9) and has a lower Equivalent Annual Cost (VSS: USD 227,074.65, GSS: USD 255,626.57) than the GSS. These results align with the findings of others on the cost comparison of the two systems. This calls for the government and other service providers to consider the VSS as an alternative.

Keywords: Gravity sewer system, vacuum sewer system, financial analysis.

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1. Introduction

In many developing countries there is a spur in the creation of new plots and these need to be connected to wastewater treatment plants as a component of area development. To introduce such infrastructure, problems emerge when conventional sewer systems, Gravity Sewer Systems (GSS) are not feasible. On the other hand, using on-site treatment methods like septic tanks is not environmentally friendly, so there is a need to seek alternatives. Vacuum Sewerage Systems (VSS) have emerged in recent years as an alternative to GSS. Wastewater conveyance is a big challenge in many developing countries and on a sad note, a lot of literature has mainly focused on the performance of the treatment plants other than the conveyance methods.

There are several alternative wastewater conveyance methods to the GSS like the pressure sewer systems, small diameter gravity sewer system and the hybrid sewer system. However, the VSS which falls under the pressure sewer system is fairly new in Africa and has only been tried in a few African countries like Botswana, South Africa and Namibia. So far, studies have been conducted by other authors like Islam (2016) on the cost comparison of the VSS and GSS. Another study by Makinen (2016), evaluated the performance of VSS in Ondangwa, Namibia. Much as the VSS has been tried in a few countries in Africa, there is still a lot more to learn in terms of the costs of the system as compared to the more familiar GSS. Flovac (2020) highlighted the benefits of the VSS against the GSS as a determining factor in its acceptance of the Kazungula Bridge Project in Botswana. However, apart from focusing on the environmental and public health benefits, a vivid approach to the cost benefit analysis of wastewater collection methods will go a long way in making better decisions on the choice of waste collection methods for new areas.

In this study, an area in Lilongwe (Area 49 Old Gulliver), Malawi, was selected as the study area. In terms of wastewater treatment, Lilongwe has the Kauma treatment plant as the major wastewater treatment facility. The Kauma Treatment Plant was designed to accommodate 6100 m^3/day of wastewater but so far, the maximum present volume of wastewater that is received at the plant is 4786 m^3/day which entails that the treatment plant can handle additional volumes of wastewater. Considering that the treatment plant is not fully utilized, the main problem in terms of wastewater management is the conveyance methods. The only present wastewater conveyance method is the GSS which now poses a big challenge to new areas that are being created especially those that are at a lower altitude than the treatment plant. The main objective of the study was to conduct a cost-benefit analysis between the VSS and GSS. In order to achieve the main objective, the specific objectives focused on the design of both systems, determination of investment, operation and maintenance costs and also on the financial analysis of both systems in order to ascertain the financial viability.

2. Methodology

The choice for the study area hinged on the basis that there was already a gravitational sewer-line project, funded by the World Bank, which was underway. The project presented the following two advantages:

- The GSS was already feasible and as such it allowed an alternative system to be designed and compared with the existing system.
- The construction costs and any site conditions formed a good basis for comparison with the alternative design.

The main areas of the research were the design of the two separate wastewater systems, GSS and VSS, and the financial appraisal to enable the researcher to conduct a cost-benefit analysis. Figure 1 shows the whole research methodology approach.

2.1 Population projection and sewage yield

The population of an area and its water consumption indicate the amount of wastewater that is generated. The population for the area was determined by conducting a physical count of the houses in the residential area. The study area was composed of medium income families and as such a family size of 5 people was adopted for the study. The sewage yield was classified into three, initial sewage yield, medium sewage yield and ultimate sewage yield. The initial sewage yield was determined to ensure that self-

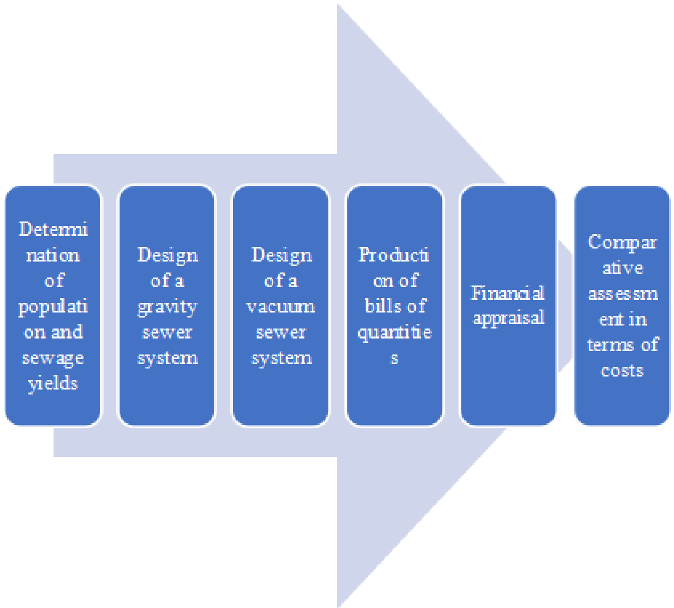


Figure 1: Research methodology process

cleansing velocities in the first years of operation were achieved. The medium and long-term sewage yields are determined to estimate pipe sizes and the likely volumes of sewage generated for treatment planning purposes (AFRICON Botswana, 2006). The ultimate sewage yield is the maximum yield when all areas scheduled for development in the catchment area have been developed and considering that Area 49 Gulliver is fully developed, only the ultimate sewage yield was considered.

During design, a sewerline pipe network was established and pipeline routes were established. The calculation for the sewage yield for a particular route was done using Equation 1.

$$Sewage\ yield = Total\ water\ usage\ \times Discahrge\ factor \ldots\ldots\ldots\ldots\ldots Equation\ 1$$

2.2 Design of gravity sewer system

The entire design process of the GSS is shown by Figure 2.

2.2.1 GSS routes

The routes for the sewer lines followed the existing road network. The choice of the routes depends on several factors; availability of space, the topography of the area, infrastructure development for the area, future flows from the catchment, suitability of receiving water bodies or receiving treatment plant and the adequacy of any existing system to accept the design flow (BSI, 2018).

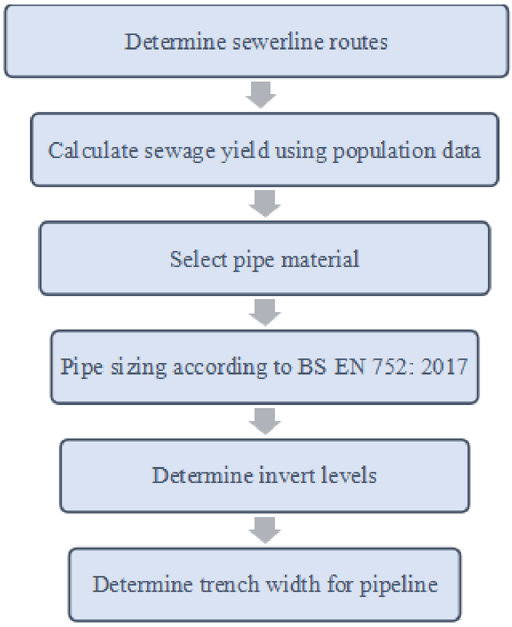


Figure 2: GSS design flow diagram

The road network for the area was sufficient to accommodate a sewer mainline and manholes. The positioning of the mainline was decided to be on the centre of the access roads taking into consideration that it is an already developed area and the project would have to cause minimum impact on the structures of the residents.

2.2.2 GSS sewage yield

The determined sewage yield values were considered for the design of the two systems. However, an infiltration rate of 10% of flow was assumed in all pipe sizing calculations for the GSS design. The infiltration flow is pernicious since the extra volume of water goes through the sewers and compromises the pipe and treatment capacity of sewer systems (Weiner & Mathews, 2003).

2.2.3 Pipe material selection

In sewerline construction, the selection of appropriate materials is crucial as the durability of materials used can be affected by the chemical action of groundwater and wastewater (BSI, 2018). There are different types of pipes in the Malawi market ranging from PVC pipes to Galvanized pipes. However, for the purposes of the study, PVC pipes were selected over the other pipes mainly due to the availability of the pipes on the market, easiness of usage and also costs

2.2.4 Pipe sizing

According to BS EN 752:2017, the minimum pipe size diameter for the main line is 150mm. The selection of pipe diameter is very crucial in sewer-line design to allow for the collection of all sewage and wastewater when other institutions wish to join the line. Pipe systems for surface water drainage and sewerage are normally designed to flow full, but not under pressure. Even though during design the main consideration is of full flow, an estimate of the discharge and velocity for the partially full condition is required as it enables the engineer to check if self-cleansing velocities are maintained at the minimum discharge. All calculations of flows and velocities within the sewerage system were based on the Manning's equation which has been shown as Equation 2. The Manning's equation was preferred due to its easiness in usage and also that it is the preferred equation by many designers in sewer system design. The Manning's equation is preferred over the Colebrook-White equation as the latter is generally not suitable for pipes or channels containing significant deposits of sediment.

$$V = \frac{1}{n} \times R^{\frac{2}{3}} \times S_o^{\frac{1}{2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation } 2$$

Where V: Velocity

R: Hydraulic Mean Radius

S_o: Slope

A hydraulic Elements Chart (HEC) depicted as Figure 3, was used to assist in the determination of the pipe size.

The procedure for the usage of the HEC was as follows;

1. Obtained the value of Q (ultimate sewage yield capacity) through calculations.
2. Calculated full velocity to check if it did not exceed the maximum velocity of 2.5m/s
3. Calculated Q (flow at full):

$$Q\ (flow\ at\ full) = VA \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation } 3$$

Where;

V= Velocity

A=Area

4. Calculated; $\frac{Q}{Q_{full}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation } 4$
5. Obtained V/V_{full} through the HEC; Entered on the figure on the abscissa at Q / Q full and drew a vertical line to the discharge curve labelled "n variable with depth." From the intersection point, a horizontal line was drawn to the velocity curve labelled "n variable with depth." From that intersection point, a vertical line was drawn down to the abscissa and read V / V_{full}.
6. The obtained value of V / V_{full} was used to calculate Partial full velocity as follows;

$$Partial\ full\ velocity = Full\ velocity\ \times \frac{V}{V_{full}} \ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation } 5$$

The partial full velocity is always required to surpass the minimum velocity of 0.6 m/s.

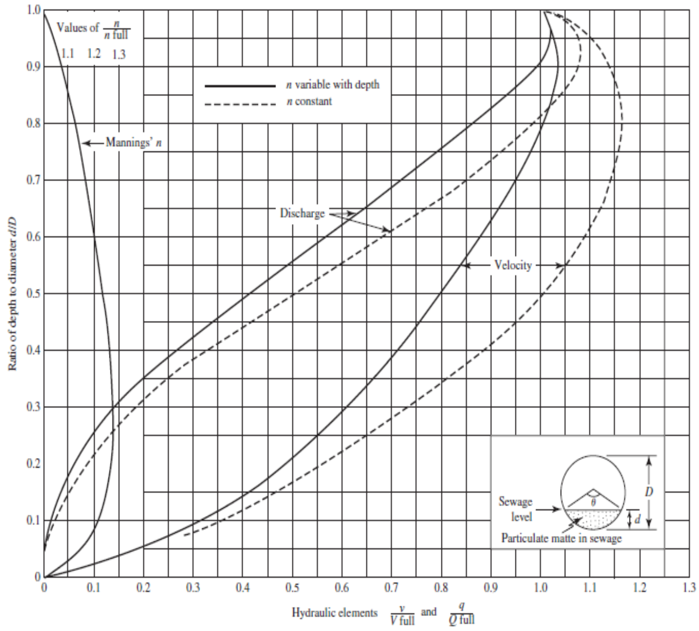


Figure 3: Hydraulic Elements Chart

2.2.5. Invert levels

The invert levels for the manholes were obtained using Equation 7.

$Invert\ level = |(a) - (b \times c\%)|$........ *Equation 6*

Where:

a = Existing Natural ground or previous manhole invert level

b = distance between points

c = proposed slope

2.2.6 Trench width

According to BS EN 752:2017, the trench width was determined using Equation 8.

For trench width of less than 2m width:

$W = \ Pipe\ diameter\ + 600mm$.......... Equation 7

2.2.7 Manholes

There were two types of manholes considered for the design phase; one serving the Mainline and the other type serving the Secondary lines. According to SANS 2001-DP4:2010, the maximum manhole spacing is 60m for 150mm diameter pipes and 75m for pipes of 200mm diameter and above. For the research, the manholes for the mainline were spaced 30m on average.

The positioning of manholes at various points was influenced with every change in direction, change in slope, pipe junctions and the presence of various obstacles on the route (Choi, 2003).

Depending on the invert levels, the manholes were classified as normal and drop-manholes. The drop manholes required fittings like bends and Tee's. Apart from the fittings, the drop manholes need step-irons to enable accessibility into the manholes. The specification of the arrangement of the fittings and step-irons was according to SANS 2001-CC1.

2.3 Design of vacuum sewer system

The design procedure for the design of the VSS was based on EN-1091 1996, Airvac 2018 Municipal Design Manual and ROEVAC 2000.

2.3.1 VSS route

The selection of the route for the VSS considered the same factors as for the selection of the GSS route. The main factors are availability of space, infrastructure development for the area and future flows from the catchment. Unlike the GSS which mainly takes into account the topography of the area for the system to work, it is a different case with the VSS in such a way that it can be used even in hilly areas.

2.3.2 Design flows

The sewage yield for the area was already determined Equation 1, however, for VSS, peak flows were determined by applying a peaking factor to the average daily flow (ADF) rate (Airvac, 2018). The ADF was determined as the first step to obtaining the peak flow. The ADF was calculated using Equation 1 which is the sewage yield.

$$ADF = Sewage\ yield \ldots\ldots\ldots\ldots\ldots\ldots Equation\ 1$$

The minimum and standard values of the peaking factor are 2.5 and 3.5 respectively (Airvac, 2018). However, in order to determine the peak factor values, Equation 8 was used as a standard equation for both Airvac and Roevac design standards.

$$Peak\ factor = \frac{18 + \sqrt{Population/1000}}{4 + \sqrt{Population/1000}} \ldots\ldots\ldots\ldots Equation\ 8$$

The values for the peak flows were determined by applying the peak factor to the ADF and such values were used as a basis for design (Airvac, 2018). Equation 9 as used in the Airvac Design Manual 2018, was used to obtain the peak flow values.

$$Q_a/1440\ min/day \times PF = Q_{max} \ldots\ldots\ Equation\ 9$$

Where: Q_a = ADF

PF = Peak factor

Q_{max} = Peak flow

The peak factor values in relation to the population were not supposed to exceed stated limits as presented in the Airvac Design Manual. Table 1 shows the peak factor limits in relation to the population figures.

Table 1: Standard Peak factor values in relation to the population

Population	Peak factor
100	4.25
500	4.00
1,200	3.75
2,500	3.50
5,000	3.25
9,000	3.00

2.3.3 Service and valve chamber

The connectivity of the houses to the chambers is very crucial and according to Airvac, the recommended maximum combined peak flow is 11.356l/m. For the purposes of the study, equations 8 and 9 were used to determine the peak flows for house connectivity. In the design process, the goal was to make sure that the peak flow emanating from the house connectivity could not exceed the recommended combined peak flow. In situations where such values were exceeded, a buffer tank was considered (Islam, 2016). The introduction of buffer tanks is of great importance as they can control up to 25% of the average daily flow (Fraunhofer, 2016).

2.3.4 Vacuum mains

The design of the pipelines take into consideration that the pipes can withstand subjected forces like construction forces, negative internal pressure and temperature (AFRICON Botswana, 2006). Pipe sizes were obtained from Table 2 (Fraunhofer, 2016). In terms of pressure rating, the minimum pressure rating adopted was 90kpa (AFRICON Botswana, 2006). Just as for pipes of the GSS, minimum cover to the vacuum pipelines is very important, especially in road reserves and open spaces. For the road reserves and public open spaces, the minimum cover adopted was 1m and under the roads, it was 1.2m. The minimum gradient adopted for the vacuum sewers was 0.2%. The minimum horizontal distance between lifts was 1.5m for service connections and 6m for vacuum sewers and the maximum adopted was 1.5m (AFRICON Botswana, 2006). The saw-tooth profile was selected as this is the most common profile used in VSS and also that it enables it to overcome heights up to 6m in flat terrains but at the same time providing sufficient slope (Fraunhofer, 2016).

Table 2: Pipe diameters and the relationship to maximum flow per minute and number of households

Pipe diameter		Max flow		Max number of houses served
Inch	mm	GPM	L/min	No.
4	100	55	208	70
6	150	150	577	260
8	200	305	1,155	570
10	250	545	2,063	1050

Source: (Fraunhofer, 2016)

2.3.4.1 Pipeline profiles

There are three pipeline profiles; Figure 4 (a), (b) and (c) depict the wave profile, saw tooth profile and reformer pocket profile respectively.

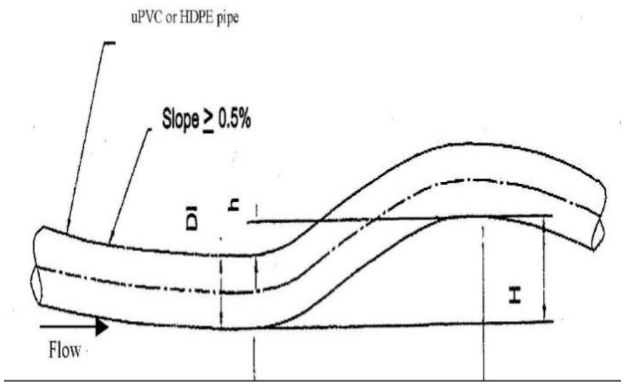


Figure 4 (a): Wave profile

Source: (Botswana Government, 2003)

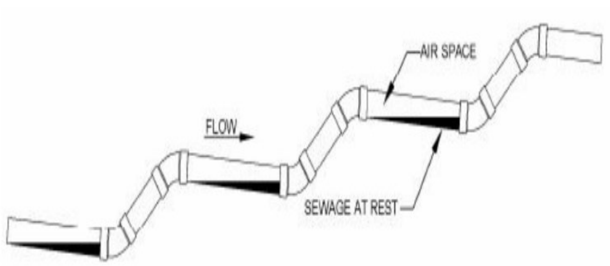


Figure 4 (b): Saw-tooth profile

Source: Fraunhofer (2016)

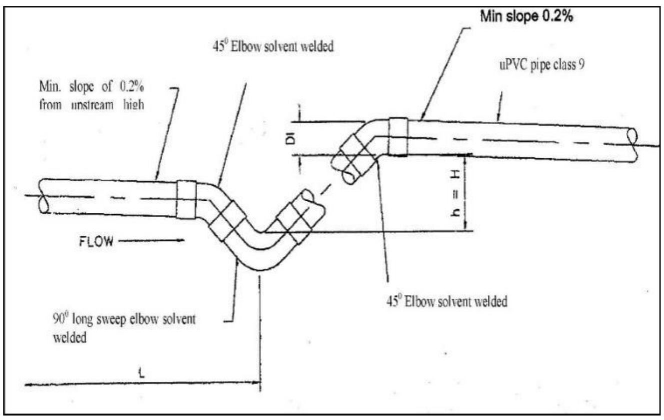


Figure 4 (c): Reformer pocket profile

Source: (Flovac, 2020)

2.3.5 Design of connections

All connections were designed to conform to the service and branch connections as stipulated in EN-1091 1996. It is stipulated that sewer connections into the vacuum main should be at an angle of at least 60^0 about the vertical axis.

2.3.6 Vacuum station

The vacuum station depending on the magnitude of the project, comprises a building that houses a collection tank, sewage and vacuum pumps (Fraunhofer, 2016). The vacuum station has vacuum and wastewater pumps to suck effluent from the valve chambers through the mains and to pump the effluent to the treatment plant respectively. For this research, the vacuum station was positioned at a place where the effluent could flow by gravity to the existing GSS line. In addition to the pumps, the station is also comprised of electronic components for monitoring, data logging and communication (Fraunhofer, 2016).

2.3.6.1 Collection tank

Vacuum collection tanks can be made from different materials like fiberglass, carbon steel or stainless steel (Fraunhofer, 2016). Depending on the availability of materials and expertise in the fabrication of tanks in Malawi, the stainless-steel tank was selected for the project. Equations 10 and 11 (modified from Airvac's design manual) were employed and have been presented as follows:

$$V_o = 15Q_{min}(Q_{dp} - Q_{min}) \div Q_{dp} \ldots\ldots Equation\ 10$$

$$V_{ct} = 3V_o + 1514 \ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 11$$

Where: V_o = Operating volume (l)

Q_{min} = Minimum flow (l/s) = $Q_a/2$

Q_{dp} = Discharge pump capacity (l/s)

Q_a = Station average flow (l/s)

V_{ct} = Collection tank size (l)

2.3.6.2 Sewage pumps

The sewage pumps play a crucial part in the vacuum system as they pump the effluent from the collection tank to either the treatment plant or to an already existing gravity sewerline. Airvac recommends that duplicate pumps that meet the design capacity at the specified Total Dynamic Head (TDH) should be used (Airvac, 2018). The pump capacity was determined using Equation 12 and other considerations like TDH and NPSH were determined using Equation 13 and 14 respectively.

$$Q_{dp} = Q_{max} = Q_a \times Peak\ Factor \ldots\ldots Equation\ 12$$

Where Q_{max}= Station peak flow (l/s)

Equations 13 and 14 are presented as follows:

$$TDH = H_s + H_f + H_v \ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 13$$

$$NPSH_a = h_{avt} + h_s - h_{vpa} \ldots\ldots\ldots\ldots\ldots Equation\ 14$$

Where H_s= Static head (m)

H_f= Friction head (m)

H_v= Vacuum head (m)

$NPSH_a$= Net positive suction head available (m)

h_a = Head available due to atmospheric pressure (m)

h_{avt} = Head available due to atmospheric pressure at liquid level less vacuum in collection tank (m)

h_s = Depth of wastewater above pump centerline (m)

h_{vpa} = Absolute vapour pressure of wastewater at its pumping temperature (m)

The number of sewage pumps was determined using Equation 15 and Airvac recommends that the minimum number of pumps should be two in case the other one develops a fault or is being serviced.

$$Q_{dp} \geq \frac{Q_s}{N_s - 1} \text{..............................} Equation\ 15$$

Where Q_s= Wasterwater discharge

N_s= Number of sewage pumps

2.3.6.3 Vacuum pumps

The vacuum pumps were designed based on the procedure presented in Airvac Design Manual. The procedure involves carrying out two separate calculations, vacuum pump sizing based on flow and line length and vacuum pump sizing based on pipe volume (Airvac, 2018). Based on the values obtained from such calculations, the larger value is used to select the vacuum pumps. Equations 16 and 17 are for the calculation of the vacuum pump size based on flow and line length and vacuum pump size based on pipe volume respectively.

$$Q_{vp} = A \times Q_{max}/7.5\, gal/ft^3 \text{...........} Equation\ 16$$

Where $Q_{vp} = Vacuum\ pump\ capacity\ required$

$Q_{max} = Expected\ peak\ flow$

$A = Factor\ for\ use\ in\ vacuum\ pump\ sizing\ obtained$

$from\ Table\ 4 - \quad 6\ in\ Airvac\ design\ manual$

$$Q_{vp} = \frac{(P_f)\ cfm - min}{gal} \times \frac{(2/3\, V_p + (V_{ct} - V_o))gal}{3\ min} \text{...} Equation\ 17$$

Where $P_f = Pressure\ factor$

$$V_p = Volume\ of\ collection\ system\ piping$$

The units for equations 16 and 17 are in Imperial System but the final value of the vacuum pump capacity was converted to the Metric System. The original formulas were not modified as they contain constants and as such the researcher avoided modifications to the formula.

2.3.6.4 Power consumption

The power consumption per vacuum pump (KW) was calculated using Equation 18 (Islam, 2016):

$$P_{L.P} = \left\{\frac{K}{K-1}\right\} \times Q_{vp} \times 1/2(P_{max} + P_{min}) \times \left[1 - \left(\frac{1}{2}\right)\left(\frac{(P_{max} + P_{min})}{P_u}\right)^{\left(\frac{K}{K-1}\right)}\right] \Big/ n_L \text{ .... } Equation\ 18$$

Where $n_L = Vacuum\ pump\ effciency$

$$K = 1.4 \text{ (air adiabatic coefficient)}$$

$$n_L = Vacuum\ pump\ effciency$$

$$P_{max} = Switch\ off\ pressure\ (45kPa)$$

$$P_{min} = Switch\ on\ pressure\ (35kPa)$$

$$P_u = Atmospheric\ pressure\ (100kPa)$$

The power consumption in KW for the sewage pump was calculated using Equation 19 as presented by Islam (2016).

$$P_{S.P} = {Q_{S.P} \times \rho \times g \times h_{man}}/{n_w} \text{ ....} Equation\ 19$$

The minimum daily running times for both vacuum ($T_L(d)$) and sewage ($T_S(d)$) pumps were calculated using Equations 20 and 21 respectively.

$$T_L(d) = \frac{Q_{s,d}}{Q_{L,p}} \text{..................................} Equation\ 20$$

$$T_s(d) = \frac{Q_{s,d}}{Q_{s,p}} \text{............................} Equation\ 21$$

In order to find the daily electrical consumption, Equation 22 was used and the units were kWh/d.

$$Q(d) = P_{S.P} \times T_s(d) + P_{L.P} \times T_L(d) \text{...} Equation\ 22$$

Depending on the electrical consumption required for a particular duration, the total numbers of days was multiplied to Equation 22. In addition to the power consumption of the pumps, it was assumed that the vacuum station would use 15 KWh per day for other uses like lighting and usage of station monitoring devices.

2.4 Bills of quantities

Bills of quantities were prepared for the two designed systems and the items covered were as follows:

- Site clearance
- Excavation
- Pipe bedding
- Pipe material and pipe laying
- Backfilling
- Construction of manholes/ valve chambers
- Construction of vacuum station

2.5 Financial analysis

Financial analysis is the process of evaluating businesses, projects, budgets and other finance-related transactions to determine their performance and suitability (Tuovila, 2022). Sanitation infrastructure is largely financed by governments and in most cases, the main focus is not profit-making but rather the provision of a basic need. However, since most of these projects are financed through aid or grants and at times loans, there is a need to conduct a financial appraisal to ascertain the viability of such projects. The adopted currency for all the costs in this study was the United States Dollars (USD) as it is used globally and as such provided a good base for comparison. As of 1st January 2024, the Malawi Kwacha (MWK) was trading at MWK 1,700/USD 1.

In order to conduct a financial appraisal, various costs were considered and these were the investment costs, operation and maintenance costs and revenue generated from the use of the sewer systems. The selected financial appraisal methods were the NPV and EAC. The Lilongwe Water and Sanitation Project assumed a discount rate of 12% with a consideration that LWB is meant to operate as a commercial enterprise and also because the Ministry of Finance indicated that 12% is the return that LWB should be able to generate within a 20 year period (World Bank, 2017). For this research, a discount rate of 12% was assumed to be in line with World Bank recommendations. The project design life is 40 years and as such the appraisal adopted a 40-year return period. Equations 23 and 24 were used to obtain the NPV and EAC respectively.

The NPV was calculated using Equation 23:

$$NPV = \frac{R_t}{(1+i)^t} \text{............................} Equation\ 23$$

Where

$$NPV = Net\ Present\ Value$$

$$R_t = net\ cash\ flow\ at\ time\ t$$

$$i = discount\ rate$$

$$t = time\ of\ the\ cash\ flow$$

The EAC was calculated using Equation 24:

$$EAC = \frac{Asset\ Price\ \times Discount\ Rate}{1-(1+Discount\ Rate)^{-n}} \text{......} Equation\ 24$$

Where n =number of periods.

As outlined by Cui et al. (2022), the calculation process followed the following steps;

Step 1: The calculation of the NPV of the cost of each potential replacement period.

Step 2: Calculating the EAC for each potential replacement cycle in this case 40 years.

Step 3: Selection of the lowest EAC.

The costs from the bills of quantities and the financial appraisal formed a basis for comparison in terms of costs. Each item as presented by the bills of quantities was compared for the separate systems. A summation of costs in addition to the financial appraisal for each system was used to compare the systems in terms of costs.

3. Results and Discussion

3.1 Gravity sewer systems

3.1.1 Sewer line routes

Figure 5 shows the mainline sewer routes that were identified for the GSS.

Figure 5: GSS Mainline Sewer Routes

According to the design, the area will be served by a total pipeline sewer network of 26.76km. Out of the total pipeline network, the secondary lines constitute a large percentage of 69% followed by the main lines at 29% and then the collection lines at 5%. Figure 6 shows the total pipe distance for each pipe category. The total distance of the main lines is 7.73km and the distance is almost the same as the road network as they follow the central position of the road network. Haile (2009), discussed the central positioning of the sewerlines as being ideal, especially in already developed areas. The total pipe length of the secondary lines which run parallel to the road network on either side of the road is 17.73km and their main function is to collect sewage, through the manholes, and later discharge the sewage into the main lines.

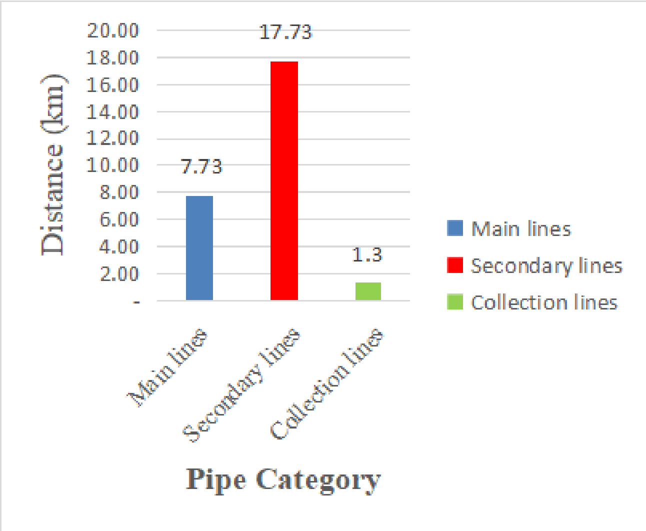


Figure 6: GSS pipeline categories and distances

The last category of the lines is the collection line and its total pipe length is 1.3km. The main function of these lines is to receive the wastewater for the area and discharge it into a manhole that connects to the existing Lilongwe City Council (LCC) line.

3.1.2 Population projection and sewage yield

Table 3 shows the projected population and sewage yield for each route.

Table 3: Population, water usage values and sewage yield values

Route	Population	Water usage (l/day)	Total Sewage yield (m3/day)
Route 1	610	106,750	93.94
Route 2	325	56,875	50.05
Route 3	265	46,375	40.81
Route 4	50	8,750	7.70
Route 5	35	6,125	5.39
Route 6	115	20,125	17.71
Route 7	705	123,375	108.57
Route 8	500	87,500	77.00
Route 9	390	68,250	60.06
Route 10	430	75,250	66.22
Route 11	110	19,250	16.94
Route 12	140	24,500	21.56
Route 13	105	18,375	16.17
Route 14	120	21,000	18.48
Route 15	100	17,500	15.40
Route 16	625	109,375	96.25
Route 17	15	2,625	2.31
Route 18	190	33,250	29.26
Route 19	95	16,625	14.63
Route 20	155	27,125	23.87
Total	**5080**	**889,000**	**782.32**

The total population for the area is 5,080 and the total sewage yield generated per day is 782.32 m^3. Route 7 has the most sewage yield (108.57 m^3/day) followed by Route 16 with a yield of 96.25 m^3/day. The route with the lowest yield is Route 17 with a yield of 2.31 m^3/day and a population of 15 people. Unlike in the other studies, Islam (2016) and AFRICON (2006), where initial sewage yields were considered to determine the self-cleansing velocities in the early years of operation and the medium- or long-term yields halfway through the design life of the system to cater for population growth, only the ultimate yields were considered in this study due to the fact that no further population growth is expected for the area.

3.1.2 Pipe type and sizes

PVC pipes were used and their preference over other pipes is mainly due to their availability on the Malawi market and also the easiness in installation. The PVC offer other advantages like: resistance to corrosion, easiness of transportation due to their lightweight and the economical aspect of laying as stated by JICA (2012). Islam (2016) also used PVC pipes for his study on comparative evaluation of the vacuum sewer and gravity sewer system.

Table 4: Achieved minimum and maximum velocities and adopted pipe sizes

Route	Expected minimum velocities (≥) (m/s)	Expected Maximum velocity (≤) (m/s)	Achieved Partial full velocity (m/s)	Achieved full velocity (m/s)	Adopted pipe size diameter (mm)
Route 1	0.6	2.5	0.8	1.6	150
Route 2	0.6	2.5	0.5	1.6	150
Route 3	0.6	2.5	0.4	1.6	150
Route 4	0.6	2.5	0.4	1.4	150
Route 5	0.6	2.5	0.4	1.3	150
Route 6	0.6	2.5	0.4	1.4	150
Route 7	0.6	2.5	0.7	1.6	150
Route 8	0.6	2.5	0.6	1.6	150
Route 9	0.6	2.5	0.6	1.6	150
Route 10	0.6	2.5	0.6	1.6	150
Route 11	0.6	2.5	0.4	1.6	150
Route 12	0.6	2.5	0.3	1.1	150
Route 13	0.6	2.5	0.4	1.3	150
Route 14	0.6	2.5	0.4	0.9	150
Route 15	0.6	2.5	0.4	1.6	150
Route 16	0.6	2.5	0.7	1.6	150
Route 17	0.6	2.5	0.4	1.5	150
Route 18	0.6	2.5	0.4	1.6	150
Route 19	0.6	2.5	0.4	1.3	150
Route 20	0.6	2.5	0.4	0.9	150
Collection line	0.6	2.5	1.2	2.5	315

According to the design results presented in Table 4.2, Routes 1, 7, 8, 9, 10, 16 and the collection line were equal to or surpassed the expected minimum velocity (0.6m/s). However, the maximum velocity (2.5m/s) was not exceeded. The low velocity values achieved for most of the routes is due to the low sewage yields achieved as the population using the route is too small. In most design manuals, there is heavy emphasis on achieving the minimum self-cleansing velocity as failure to adhere to that leads to the deposition of solids in the system (BSI, 2018; Groenkloof, 2010; JICA, 2012). In scenarios where the minimum self-cleansing velocity was not achieved (Routes 2,3,4,5,6,11,12,13,14,15,17,18,19 and 20) a minimum pipe diameter of 150mm for the mainlines was selected as per the BS EN 752: 2017 specification. The selection of the 150mm diameter pipe as a minimum even in situations that minimum self-cleansing velocities are not achieved was also employed by Choi (2003).

The accumulation of sludge in the sewer pipelines has both operational and financial effects. Consistent blockages of the line fall under the operational effects and the resulting remedies like flushing of the line have cost implications (Sperac et al., 2023). In this study, the design of the system adhered to the BS EN 752: 2017 specification to avoid the challenges that may come about due to failure of achieving the minimum velocity flow. In a study by Choi (2003) in which she designed a wastewater collection system for the historical center of Paraty in Brazil, it was observed that a lot of routes did not achieve the minimum velocity of 0.6 m/s and as such it was feared that deposition of sediment would occur. On the contrary, it was discovered after some studies that the sediment levels were not as feared. Just like the study area, the project under the World Bank Project implemented by LWB has so far not registered any problems, after commissioning, of solid deposition even in the routes that have low sewage yields. Considering that the minimum velocities for the study done by Choi ranged from 0.2 m/s to 0.8 m/s and that the values of this study range from 0.3 m/s to 1.2 m/s, the GSS under this study would perform without solid deposition challenges.

In terms of adhering to the maximum velocity flow (2.5m/s), the study design results presented in Table 4.2 indicate that all achieved values for all the routes are within range. In the study done by Islam (2016), the maximum velocities ranged between 2.5 m/s and 3 m/s. The main focus of Islam was to achieve the minimum self-cleansing velocity even if a maximum velocity of 2.5 m/s was exceeded. The effects of exceeding the maximum velocity include pipe abrasion and at times the deposition of solids as they are left behind due to the high velocity of the wastewater. In this study, all maximum velocity values achieved in all the routes did not the exceed the maximum velocity.

3.1.3 Earthwork volumes

Table 5 summarizes the pipeline length and the earthwork quantities for the mainline.

Table 5: Mainline pipeline lengths and earthwork quantities

Route	Pipeline length (m)	Excavation volume (m3)	Backfilling volume (m3)	Surplus excavated volume (m3)
Route 1	1,060.58	1,350.38	1,329.06	21.32
Route 2	347.96	377.34	370.34	7.00
Route 3	510.02	763.43	753.18	10.25
Route 4	123.57	127.06	124.58	2.48
Route 5	79.50	124.14	122.54	1.60
Route 6	120.35	188.03	185.61	2.42
Route 7	1,245	2,939.37	2,914.34	25.03
Route 8	634.68	1,442.74	1,429.98	12.76
Route 9	436.15	1,248.53	1,239.76	8.77
Route 10	801	1,441.55	1,425.45	16.11
Route 11	120	219.68	217.27	2.41
Route 12	150	322.20	319.18	3.02
Route 13	110	153.05	150.84	2.21
Route 14	150	330.24	327.23	3.02
Route 15	175	381.57	378.05	3.52
Route 16	942	1,561.74	1,542.80	18.94
Route 17	30	79.89	79.29	0.60
Route 18	383	970.96	963.26	7.70
Route 19	115	196.17	193.86	2.31
Route 20	192	432.41	428.55	3.86
Collection line	1,300	3,949.78	3,847.83	101.95
Total	**9,025.80**	**18,600.28**	**18,342.99**	**257.29**

Based on the results presented in Table 4.3, the line with the most excavated volume is the collection line (3,949.78 m^3) followed by Route 7 (2,939.37 m^3), Route 16 (1,561.74 m^3) and Route 8 (1,442.74 m^3) respectively. In terms of the volumes, there are other routes like Route 8 which have shorter pipe lengths (634.68 m) than for example Route 10 (801 m) and yet have larger volumes, this is due to the design slopes that are used which in turn affect earthworks volumes. For example, the minimum design slope for Route 8 is 1% whilst for Route 10 it is 0.5%. The design slope determines the excavation depths.

The pipe line length and earthwork volumes for the secondary lines are shown in Table 6. The total calculated excavation volume for the secondary lines is 11,349.13 m^3. Unlike for the main and collection where lines design slopes were employed in the design which later determined the excavation depths, an average depth of 1m was assumed for all the secondary lines. The assumption came about since accessibility to the septic tank receiving manholes was a challenge and as such the invert levels were not picked hence assuming a depth of 1m for the secondary lines.

Table 6: Secondary line pipeline lengths and earthwork volumes

Pipe size (mm)	Pipeline length (m)	Excavation volume (m^3)	Backfilling volume (m^3)	Surplus excavated volume (m^3)
110	17,733.02	11,349.13	11,180.61	168.52
Total	**17,733.02**	**11,349.13**	**11,180.61**	**168.52**

3.2 Vacuum sewer systems

3.2.1 Sewer line routes

Figure 6 shows the VSS routes and the proposed vacuum station position.

Figure 6: VSS routes and proposed vacuum station

The total pipe network for the whole study area covers a distance of 18.99 km. Figure 7 shows the pipe distances covered by different pipe categories.

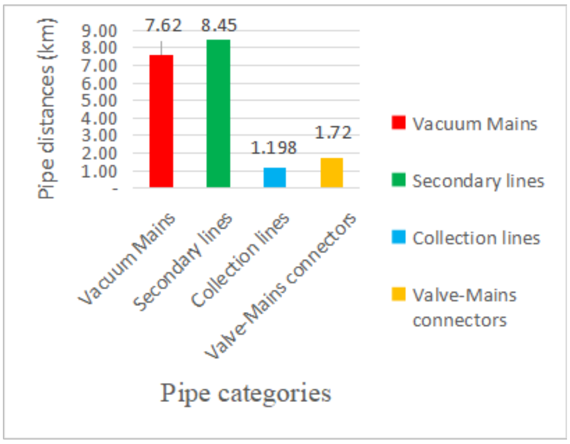
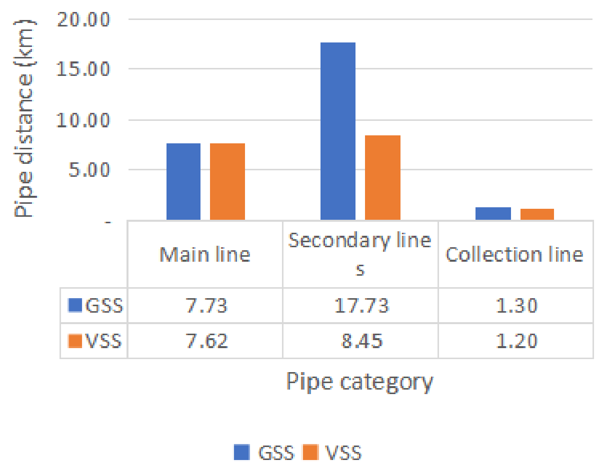


Figure 7: VSS pipeline and distances

The total pipe distances covered are 7.62 km, 8.45 km, 1.198 km and 1.72 km for the vacuum mains, secondary lines, collection lines and valve-mains connectors respectively. The distance covered by the vacuum mains constitutes 40.1% of the total pipe network whilst the Secondary lines cover 44.5%, the Collection line covers 6.3% and the valve-mains connectors cover 9.1%. In a study done by Islam (2016), the total pipe length of the VSS up to the vacuum station for one area (area X) was 12.635 Km and for another area (area Y) was 12.75 Km. In another study done in Ondangwa, Namibia, the total vacuum sewer network was 4.5 Km (Makinen, 2016). In this study, the total vacuum sewer network (less than the collection line) is 17.792 km which is greater than the vacuum sewer networks studied by both Islam and Makinen which entails that the studied area is bigger and in turn provides a bigger study area for the VSS.

Figure 8 shows the comparison in pipe length between the VSS and GSS. In terms of the mainline/vacuum mains, the GSS pipe network is 110m more than the VSS pipe network. The difference is not much since the main lines were all positioned in the centre of the road network and as such the pipe distances almost correlate with the total road length. The GSS pipe distance is more due to the excavation depths as in most cases the depth was averaging 1.2m against 1m for the VSS. That is the case as the pipes are laid due to the design slopes which range from 0.5% -3%, to enable the wastewater to flow due to gravity unlike the VSS pipes that can have a slope as small as 0.02% as stated in the Airvac Design Manual (2018).



	Main line	Secondary lines	Collection line
GSS	7.73	17.73	1.30
VSS	7.62	8.45	1.20

Figure 8: Pipeline distances between VSS and GSS

The main difference in pipe length is on the secondary lines. The GSS secondary lines cover a total distance of 17.73 km whilst the VSS secondary lines cover a total distance of 8.45 km. The GSS secondary lines run paralle to the mainline on both sides of the road reserve. They connect to the manholes that receive wastewater from the houses. Since they connect to the mainline through manhole on the mainline, they can cover a longer distance unlike the VSS lines that join to the vacuum mains through pipe connections. In total, the total pipe network for the GSS (26.76 km) is 8.968 km more than the VSS pipe network (17.792 km). In a study done by Islam (2016), he established that the GSS pipe network was 7.2 km more than the VSS pipe network. In terms of percentages, this study found that the VSS pipe network is 66% less than the GSS pipe network whilst Islam found that the VSS was 83% less than the GSS pipe network. The difference in percentages can be attributed to site conditions as the Islam (2016) study area was relatively flat which in turn results in deeper excavations as compared to the area of focus in this study.

3.2.2 Valve chamber

Table 7 shows the peak flow values achieved for different arrangements of the house-to-chamber connectivity. Based on the results presented in Table 7, the designed system allows a maximum number of three houses to be connected to one valve chamber as the peak flow value (6.41 l/m) achieved does not exceed the recommended maximum peak flow value of 11.36 l/m. However, the valve pit has a fourth opening but this is reserved for an air terminal connection (Airvac, 2018).

Table 7: Peak flow values for valve-house connections

No of houses	Recommended maximum peak flow (l/m)	Peak factor	Peak flow (l/m)
2	11.36	4.41	4.28
3	11.36	4.4	6.41

In the study of the Ondangwa VSS, Makinen (2016) estimated due to the lack of as-built drawings that there were 69 valve chambers and that each chamber could be connected to 4-6 houses. However, he observed that in most cases the chambers were flooding which can be attributed to the chambers being overloaded among other problems. In another study done on the Kosovo vacuum system, persistent blockages of the valve pits were mentioned and this highlights the importance of conducting a thorough analysis of the peak flow values (WIN-SA, 2013). In this study, the total number of valve chambers is 365 and the numbers for each route have been presented in Table 8. With the position of the valves, the distances of the pipes connecting from the houses (110mm PVC pipes) to the valves and those connecting from the valves to the mains (75mm PVC pipes) were determined. Table 8 summarizes the valve, pipe details and earthwork quantities for the valve chambers.

Table 8: Quantity, pipe and earthworks details for valve chamber sites

Route	No. of Valve Chambers	110mm PVC pipe distance (m)	75mm PVC pipe distance (m)	Excavation volume (m3)	Backfilling volume (m3)
Route 1	48	1266	222.00	1,569.43	1,506.31
Route 2	22	875.0	112.00	1,024.32	994.04
Route 3	25	110.5	33.00	185.91	155.83
Route 4	5	123	31.00	162.48	155.91
Route 5	25	110.5	33.00	185.91	155.83
Route 6	10	304.9	33.00	354.86	341.59
Route 7	39	304.9	212.90	583.96	535.73
Route 8	29	1132.0	156.00	1,337.20	1,297.34
Route 9	28	1065.0	172.00	1,284.50	1,246.05
Route 10	29	328.0	152.00	529.20	492.91
Route 11	9	192.0	43.00	250.27	238.63
Route 12	10	412	58.00	529.20	473.11
Route 13	10	212	46.00	274.96	262.04
Route 14	9	340	48.00	403.27	390.95
Route 15	10	289	40.00	345.96	332.73
Route 16	21	573	106.00	714.63	686.89
Route 17	7	209.5	31.00	252.38	243.07
Route 18	13	316	98.00	436.05	418.91
Route 19	8	108.0	48.00	169.57	159.46
Route 20	8	175.0	49.00	237.57	227.16
Total	**365**	**8446.3**	**1,723.90**	**10,831.64**	**10,314.47**

The total excavation volume is 10,831.64 m^3 and this encompasses the excavation works for the valve chambers, trenches for the 110mm PVC pipes and 75 mm PVC pipes. The excavation depth for all the trenches was estimated at a maximum depth of 1m.

3.2.3 Vacuum mains

The study preferred the use of PVC pipes as the vacuum mains. The choice for the PVC pipes was mainly due to their lightweight, ease of installation but also availability on the Malawi market as earlier stated. Islam (2016) preferred the PVC pipes over the HDPE pipes due to cost issues as the cost of the HDPE pipes was higher than the cost of the PVC pipes for the same area. In Botswana, AFRICON Botswana (2006) proposed the use of PVC pipes as vacuum mains for the Kanye Village Sanitation Scheme. The PVC pipes were also used as vacuum mains for the Ondangwa vacuum system (Makinen, 2016). Table 4.9 presents the vacuum mains details and the associated earthwork quantities.

Table 9: Vacuum mains details and associated earthworks quantities

Route	Pipe size (mm)	Pipe length (m)	Excavation volume (m3)	Backfilling volume (m3)	Surplus volume (m3)
Route 1	200	1,360.6	1,584.37	1,541.63	42.74
Route 2	110	348.0	356.02	352.72	3.31
Route 3	110	510.0	559.30	554.45	4.85
Route 4	110	79.5	123.83	123.07	0.76
Route 5	110	79.5	141.05	140.29	0.76
Route 6	110	120.3	124.13	122.98	1.14
Route 7	160	964.9	1,075.51	1,056.11	19.40
Route 8	160	634.7	687.55	674.79	12.76
Route 9	160	436.2	542.96	534.19	8.77
Route 10	160	801	837.82	821.72	16.11
Route 11	110	120	137.42	136.28	1.14
Route 12	110	150	180.90	179.47	1.43
Route 13	110	110	116.27	115.22	1.05
Route 14	110	150	207.84	206.42	1.43
Route 15	110	175	175.18	173.52	1.66
Route 16	110	345	394.76	391.49	3.28
Route 17	110	550	276.13	270.90	5.23
Route 18	110	383	468.05	464.41	3.64
Route 19	110	115	136.04	134.95	1.09
Route 20	110	192	233.24	231.42	1.82
Total		**7,624.6**	**8,358.38**	**8,226.03**	**132.35**

The vacuum mains for each route have different pipe diameters with the largest diameter being 200 mm for Route 1 then followed by the 160 mm diameter for Routes 7,8,9 and 10 and 110mm diameter for the other routes. The determination of the pipe sizes for each route was based on Table 3.5 which presented a relationship between pipe size, maximum flows and the maximum number of houses served by the line. Apart from the relationship between pipe size and maximum flow, the minimum slope design (0.2%), friction and static losses were also considered to come up with the vacuum mains. In terms of vacuum mains diameter sizes, different projects vary on the sizes as it is dependent on the discharge volumes for particular routes. In the study that Islam (2016) did, the pipe sizes were: 75 mm, 90 mm.110 mm, 125 mm, 160 mm, 200 mm and 250 mm. For the Ondangwa project studied by Makinen (2016), the pipe sizes were 75 mm, 90 mm, 110 mm and 160 mm. In another project, Palm Jumeirah in Dubai, the pipe sizes ranged from 90 mm to 250 mm (Corodex Electromechanic, 2002).

3.2.4 Vacuum station

3.2.4.1 Vacuum station building

The vacuum station building was designed to accommodate all the pumps and tank on the ground floor and an office and monitoring space on the top floor. The building was designed with a structural concrete frame with concrete columns, beams and concrete deck being the main structural elements. The inclusion of the vacuum station building in this study is vital as it has significant cost implications for the overall project cost. The total cost (USD 34,805.93) for the vacuum station building represents 2.59% of the total project cost (USD 1,342,275.44) for the entire VSS. In studies done by Islam

(2016), Makinen (2016) and Gikas et al (2017), the focus on the vacuum station was mainly only the pumps, tanks and other electro-mechanical equipment.

3.2.4.2 Collection tank

A stainless-steel tank was selected for the project and the tank sizing was based on a procedure and calculations as presented in the Airvac's Design Manual (2018). Table 10 summarizes the tank details and the design parameters. The station's peak flow was calculated as 26 l/s and the determination of such a flow is very important in tank sizing as it allows the designer to work on the tank sizing whilst considering worst-case scenario flows.

Table 10: Collection Tank Details

Station Peak Flow (l/s)	Station Average Flow (l/s)	Station Minimum Flow (l/s)	Recommended Minimum Tank Size (l)	Designed Tank Size (l)
26	8	4	3,785	11,000

The designed collection tank capacity is 11,000 liters surpassing the minimum recommended tank size of 3,785 liters. The final decision on the tank capacity was made after several calculations and ensured that the calculated volume was adequate for operational purposes and also that the volume is enough to prevent sewage pump short cycles (Airvac, 2018). According to Airvac's design manual, it is imperative to consider any future growth during tank sizing and as such this was considered during the calculations. Even though a consideration of future growth was considered, the study area is already developed and it is highly unlikely that there will be significant changes to the population of the area. However, the consideration was made to avoid altering the tank sizing formula as stated by Airvac.

3.2.4.3 Sewage and Vacuum Pumps

Table 11 and 12 indicate the sewage and vacuum pump details.

Table 11: Sewage Pump Details

Discharge Pump Capacity (l/s)	Maximum Head (m)	Liquid Temperature (°C)	Type of Pump	No. of Pumps
26	13	0-40	Dry-pit Submersible Pump	2

The selected sewage pumps for the system had a discharge pump capacity of 26 l/s and a maximum head of 13m. The sewage pump sizing had to correlate with the station's peak flow values. Two pumps were recommended for the system with one being a standby pump in case the other one develops a fault.

Table 12: Vacuum Pump Details

Vacuum Pump Capacity (l/s)	Pump Down Time (m)	Type of Pump	No. of Pumps
261	1	MM1402AV	3

In this study, three vacuum pumps each having a capacity of 261 l/s were selected. The pump downtime is 1 minute which is within the stated limits as stated in Airvac's design manual (2018). It is very important to make sure that the pump's downtime is within range as failure to achieve this requirement results in a pump failure.

Table 13 shows the power consumption values of both the vacuum and sewage pumps.

Table 13: Power Consumption Details

Type of Pump	Power Consumption (KWh)	Minimum Daily Running Time (h/d)	Daily Electrical Current Consumption (KWh/d)
Vacuum Pump	1,191	0.22	262.02
Sewage Pump	196	0.32	62.72
Combined Pumps			325

The calculated daily electrical current consumption is 262.02 KWh/d and 62.72 KWh/d for the vacuum and sewage pumps respectively. The combined daily electrical current consumption is 325 KWh/d.

3.3 Financial appraisal

3.3.1 Investment cost

Figure 8 compares the investment costs of the two sewer systems.

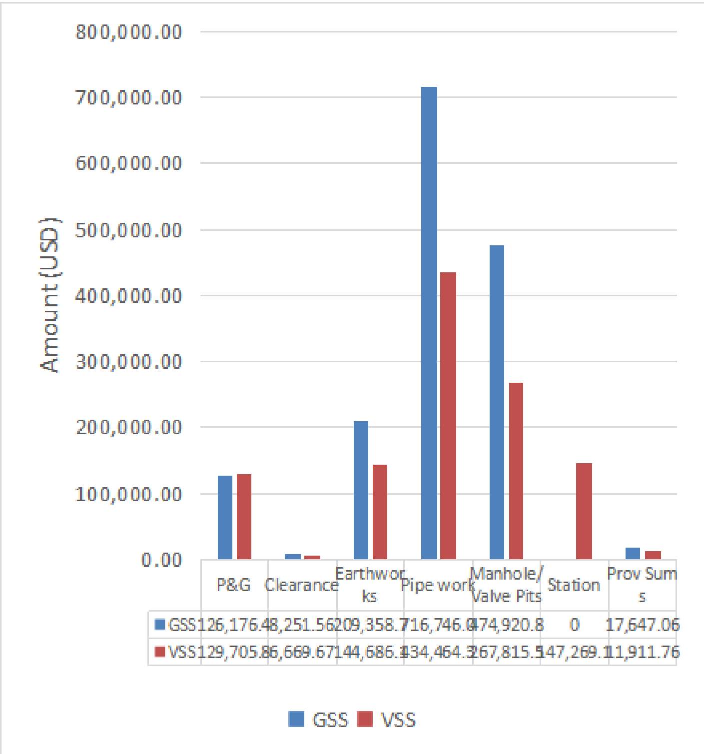


Figure 8: Investment Cost Comparison

The VSS is marginally more expensive (USD 129,705.88) on preliminaries and general costs as compared to the GSS (USD 126,176.47). The difference is emanating from the fact that the mobilization of materials for the VSS, especially on the collection chambers and vacuum station equipment, will be sourced from outside Malawi unlike the for GSS in which most of the materials will be sourced locally. However, the cost for the GSS (USD 8,251.56) is more expensive than that for the VSS (USD 6,669.67) on site clearance because the total area to be cleared to allow for pipework excavation for the GSS is more compared to the VSS. The costs for the pipework for the GSS (USD 716,746.08) is also more than the costs for the VSS (USD 434,464.32). As already indicated, the total pipework network for the GSS is 8.968 km more than that for the VSS.

The earthworks volume for the GSS which turn cost more (USD 209,358.75) than the cost for the VSS earthworks (USD 144,686.10) is also due to the difference in pipe distance. The differences in cost for both the earthworks and pipe work are in tandem with the findings of Islam (2016) and Gurtler (2014) as in their separate studies they found out that both the costs for the GSS were more than those for the VSS. The only differences are on the percentages, as for example Islam (2016) found out that the earthwork cost for the VSS was 25.60% less than the cost for the GSS, whilst in this study the VSS earthworks cost is 69.1% less than the GSS earthwork cost. For the pipework, Islam (2016) found that the VSS pipework cost was 93.48% less than the GSS pipework cost, Gurtler (2014) found that the VSS pipework was 31.25% less than the GSS pipework whilst in this study the findings show that the VSS pipework cost is 60.6% less than the GSS pipework cost. The differences in cost for the values obtained in this study and those values in the study done by Islam (2016) were inevitable as the terrain in this study is slopy whilst the terrain in the other study is almost flat. This can be backed by the use of a pump station for the GSS in the study done by Islam (2016) whilst in this study the whole GSS relied on the flow due to gravity for the whole GSS. The same can also be said of the study by Gurtler (2014) as he studied an area in Middle East (Fuhairah) that has a flat terrain. In addition, conditions for different projects are site specific so differences in either pipe or earthworks percentages will always be present.

In summary, the total investment cost of the VSS (USD 1,342,275.44) is 26.4% less than the investment cost of the GSS (USD 1,824,893.42). This is in line with findings of other studies. Islam (2016) found that the VSS was 30% economical than the GSS. Gurtler (2014) found out that the VSS was 59.36% more economical than the GSS. However, the VSS studied by Gurtler (2014) was more economical since the GSS was designed to use 5 pumping stations due to the flat terrain of the area. The introduction of sewage pumps for the GSS increases the investment cost as the pumps are expensive.

3.3.2 Operational and maintenance costs

Figure 9 compares the operation and maintenance costs of the VSS and GSS. The operational and maintenance cost in VSS is consistently higher compared to GSS. The material cost for the GSS and VSS are USD 20,467.39 and USD 407,395.57 respectively. The big difference in material and tools cost is because the VSS has a lot of electromechanical equipment whilst the GSS and especially in this study will only need a few tools for the cleaning of the system in case of blockages. For example, the vacuum and discharge pumps need to be replaced at least after 20 years of being in use (Fraunhofer, 2016; Islam, 2016). According to the findings in this study, the cost of purchasing and installing 2 discharge pumps and 3 vacuum pumps at the investment stage is USD 68,235.29. Since the system has a design life of 40 years, it will require the pumps to be replaced after 20 years and at such a time the prices will have gone up due to inflation.

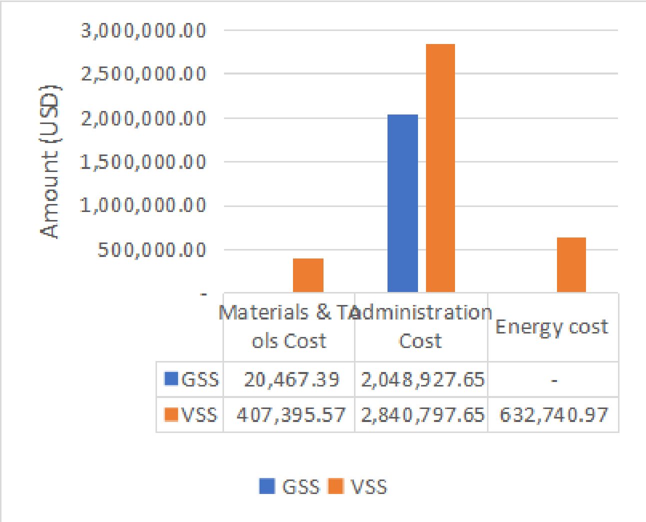


Figure 9: Operation and maintenance cost comparison

The administration cost for the VSS sewer system (USD 2,840,797.65) is USD 791,870.00 more than the GSS cost (USD 2,048,927.65). The differences largely emanate from the fact that the VSS requires more trained technicians and who will require more money than those for the GSS. For example, there will be a need of an electrician at the vacuum station whilst there will not be such a need for the GSS since there is no pump station.

In terms of energy requirements, the GSS in this study will not need any since there is no pump station. However, the energy requirement cost for the VSS is USD 632,740.97.

3.3.3 Project appraisal comparison

Figure 10 compares the project appraisal results of the VSS and GSS.

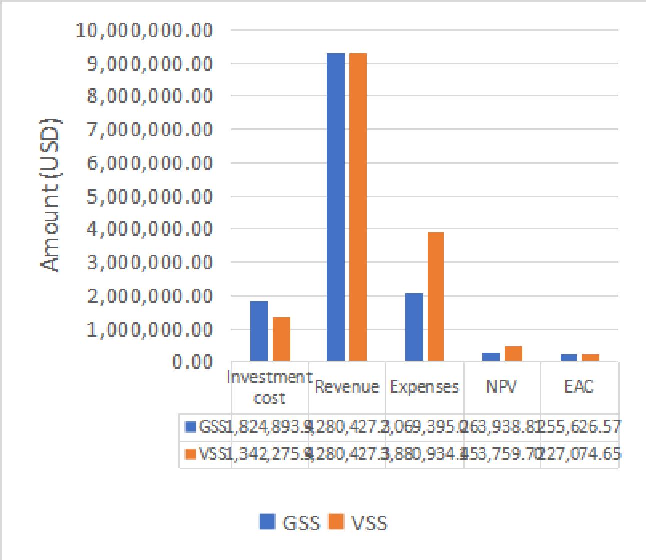


Figure 10: Project appraisal comparison results

The investment appraisal for the VSS project calculated a positive NPV of USD 453,759.70, a DPP of 13.8 years with a profit index of 1.34. The investment appraisal for the GSS project obtained a positive NPV of USD 263,938.81, a DPP of 13.9 years with a profit index of 1.18. From the analysis, the overall performance makes the two projects financially viable. Even though both projects are financially viable, the VSS is more recommended than the GSS on the basis that it has proved to be more viable in all aspects. The NPV value for the VSS is higher than that for the GSS in spite having lower operating cost. The VSS has proved to quickly pay back the investment cost within 13.8 years which is a month less than the GSS which will be able to pay back the investment cost at 13.9 years. The VSS has proved to have a lower EAC than GSS with an EAC of USD 227,074.65 and USD 255,626.57 respectively which makes it more cost effective than the GSS.

4. Conclusions and Future Work

The main objective of this study was to carry out a cost-benefit analysis between the VSS and GSS. The VSS is in the category of pressurised type of sewer systems and is not very common in most developing countries especially in Africa. On the contrary, the GSS is the most popular and tried sewer system. Considering the uncertainty surrounding the VSS in terms of functionality and project costs, the study applied the two systems in a common area for comparative purposes.

Results show that:

- The two sewer systems are technically feasible for the study area.
- The pipe material cost for the VSS is USD 434,304.01 whilst for the GSS is USD 716,746.08.
- The investment cost for the VSS is USD 1,342,893.4 whilst that for the GSS is USD 1,824,893.4
- However, the operational and maintenance costs for the entire design life of the (USD 3,880,934.19) are more compared to the GSS costs (USD 2,069,395.04)

Overall, both systems are financially viable. However, the VSS is economically a better system compared to the GSS. This is supported by all financial appraisal indices used; NPV (USD 453,759.70 > USD 263,938.81), DPP (13.8 years < 13.9 years), PI (1.34 > 1.14) and EAC (USD 227,074.65 < USD 255,626.57).

The recommendations of the study are as follows:

- More research should be done on the two systems especially by accounting for social and environmental benefits and costs of these systems.
- More research should be done in a flat terrain by extending the work that other authors have done in comparing the two systems. The research should conduct a financial analysis as previous research has only evaluated the investment costs.
- Governments especially of developing countries should embrace the VSS as an alternative to the GSS. There should be capacity building of the engineers or any other technocrats working in the wastewater engineering section.
- The Malawi Engineering Institution should spearhead the formulation of Sewer Design Standards by also including other new sewer system technologies like the VSS.

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Paper 4: Assessment of the use of remote monitoring in water supply systems

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Abstract

Sustainable rural water supply has been a challenge in Malawi as monitoring of the various parameters associated with it have been hard to track in the life cycle of projects. Data generation, availability, management and usage are key components of sustainability of water supply system, it provides key performance indicators to a water supply scheme. While it is not easy to completely do away with the manual collection and management of data with the advancement of technology it has become increasingly essential to have data readily available, at the fingertip of those who require to use it. This paper discusses the impact of remote monitoring of water supply schemes on parameters such as production, water level and turbidity, an approach adopted by Water Mission Malawi. The production data indicates the uptime of each system that water was readily available with an uptime of 95%. Borehole water level data provided seasonal variations of the water table and the change in dynamic water level which is crucial for monitoring and long-term planning in borehole life-span, last but not least is the turbidity data which on average was not more than 5 nephelometric units (NTU), citing that the water is clean. Five systems were selected, with two focused on remote monitoring of the parameters and the remaining three focused solely on water production.

Keywords: remote monitoring, water mission, water quality, water supply, solar power.

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1.0 Introduction

Water Mission is a Christian engineering non-profit organisation that builds safe water, sanitation and hygiene solutions in developing countries and disaster areas. Water Mission has several country offices around the globe, one of which is located in Lilongwe, Malawi. The organisation was established in Malawi in 2009 to primarily provide safe water solutions in rural and peri-urban areas in Malawi, hence designing and installing solar powered water supply schemes, also known as safe water projects.

Water Mission Malawi has installed over 80 solar powered water supply schemes. With the increase in the number of operational schemes, it became crucial for the organization to identify a reliable method of collecting and storing data for water supply schemes. As a result remote monitoring was introduced and made part and parcel of the water supply schemes lifecycle.

1.1 Literature Review

Remote monitoring can be applied in numerous sectors such as water supply, irrigation, agriculture [3], water resources management [8] and forestry [6]. This section will look at past works that were undertaken in remote monitoring, their application, sector/field and the year the works were published.

Remote Monitoring Key Works

Author	Application	Field	Year
Dasgupta & Darshan	Water quality Water quantity	Agriculture	2014
Dongare et al	Modelling pressure and flow Leak detection	Water supply	2023
Chawla, Karthikeyan & Mishra	Water quantity Water quality	Water resources	2020
Sun et al	Water quality	Water resources (basin management)	2021
Adjovu et al	Water quality	Water resources	2023
Le, Harper & Dell	Water quantity/stress	Forestry	2023
Thomson	Water availability Utilization	Water supply	2021
Karthikeyan, Visu & Raja	Water quality	Water supply	2023

	Theft detection Water quantity Lead detection Billing

Table 2: Key past works in remote monitoring

1.2 Problem Statement

The sustainability of every system requires data to be readily available for analysis, without available data it is difficult to control and manage failure rates and downtime [9]. Though conventional methods such as manual data collection are useful, they have a limitation when it comes to being readily available, as they are time-consuming and do not offer the efficiency and readiness of providing real-time data when need arises [5].

Remote monitoring is essential in ensuring that water quality is protected and restored by calling for management strategies that promote the sustainability and usability of water resources [1]. By analysis and rethinking management approaches, a balance between water development and water usage can be reached to ensure that groundwater stress is decreased.

Therefore, there remains a need to find a better method of recording and storing. Remote monitoring offers that alternative.

1.3 Objectives

The aim of this study was to evaluate the impact of remote monitoring on water supply schemes as adopted by Water Mission.

Specific Objectives

a) To assess the water availability of each scheme using remote monitoring
b) To determine the utilization of each scheme based on data transmitted by remote systems
c) To identify borehole water level changes using remote monitoring
d) To analyse water quality with respect to turbidity by applying remote monitoring

2. Materials and Methods

Five schemes were randomly selected from 60 schemes for this study. Three schemes have a focus on water production data. While the remaining two schemes transmit borehole water level and turbidity in addition to water production. Table 2 indicates a summary of the same information.

The first three projects were funded by the McKinnon Family (USA), whose works involved design and installation of the water supply scheme including the installation of a water production monitoring sensor. The last two were funded by UNICEF Malawi where Water Misson was engaged to install remote monitoring system encompassing water production, borehole water level and turbidity.

Table 3: Project locations and details

Name of Site	District	Population	Sensors	Year
Bua Safe Water Project	Kasungu	4,816	Water production	Feb-21
Malembo Safe Water Project	Mangochi	1,000	Water production	Feb-23
Mphomwa Safe Water Project	Kasungu	10,000	Water production	Aug-20
Goneko Children's Centre	Lilongwe	400	Water production, Borehole water level, Turbidity	Jul-22
Mchoka Primary School	Salima	850	Water production, Borehole water level, Turbidity	Jul-22

Figure 1. Shows a conceptual framework for this study. Linking remote monitoring back to water resources management. That water is essential to mankind cannot be overemphasized [4], yet as a resource it needs to be managed and taken care of.

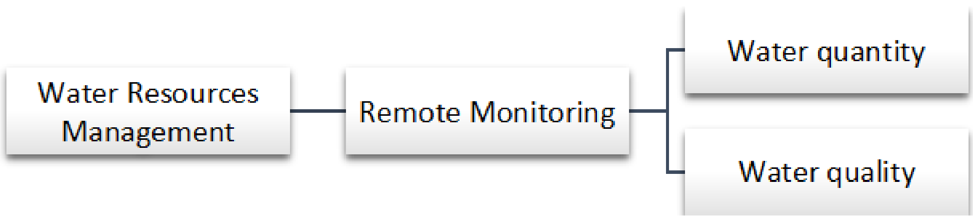

Figure 3: Conceptual framework (adapted from Chawla et al)

2.1 Sensors

This section explains the installation process of all the three sensors and their working principles. The three sensors namely water meter (flow meter), water level sensor (probe) and turbidity sensor (turbidimeter) are all satellite based meters linked by a communicator (data logger). The meters are installed in the water supply system as below:

a) Satellite water meter (installed in the pipeline)
b) Water level sensor (installed in the borehole)

c) Turbidity sensor (installed in the pipeline)

For water production, two remote monitoring devices are installed, a flow meter and data loggers. Each time water flows through the flow meter, it sends a pulse to the data logger which then send the information to the Monitoring and Alerting Platform (the MAP). A pictorial working flow is shown in Figure 2. The MAP is an in-house remote monitoring tool that was created by Water Mission. The flow meter is primarily installed before the storage tank, to record daily water production; the data logger sends various alerts to the monitoring platform such as production, no production and missing transmission alerts. The input information required for the remote monitoring system to function accordingly are serial numbers (for both the flow meter and data logger) and the meter reading for the flow meter. The flow meter is powered by non-rechargeable Energizer lithium AA batteries, which need to be replaced from time to time, the period varies from site to site.

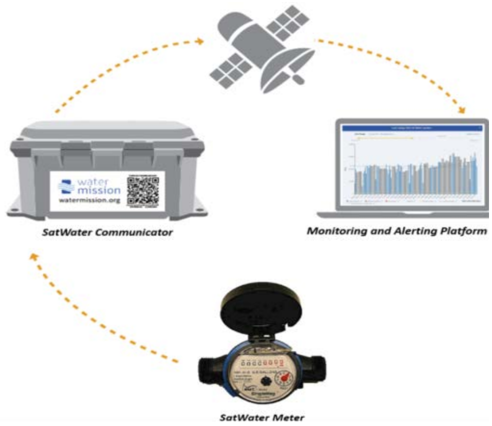

Figure 4: Remote monitoring flow chart for water production

The water level sensor is installed in the borehole just a meter above the pump to send data of the static water level (SWL) and dynamic water level (DWL) in the borehole. Information such as initial SWL is taken before installing the water level sensor, the water level sensor depth and pump depth are also useful for the remote system for accuracy and triangulation. A turbidity sensor is installed in the pipeline to collect samples and send turbidity reading to the data logger. Following the addition of two more sensors, the data logger and the turbidity sensor both require an additional power from an auxiliary power box which proved 24V of power, supplied by a 350W solar panel.

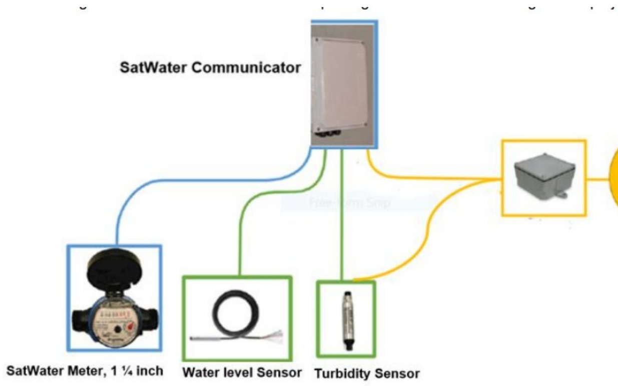

Figure 5: Remote system with three sensors

During the installation of the remote monitoring systems, several test messages were sent to the monitoring platform (portal) to check the accuracy of the data being sent. Daily production would be compare with manual meter readings, the turbidity reading would be compared with the handheld/mobile turbidimeters.

3.0 Results and Discussion

The heart of this study is to evaluate the impact of remote monitoring on water supply systems with a focus on three parameters: water production, borehole water level and turbidity.

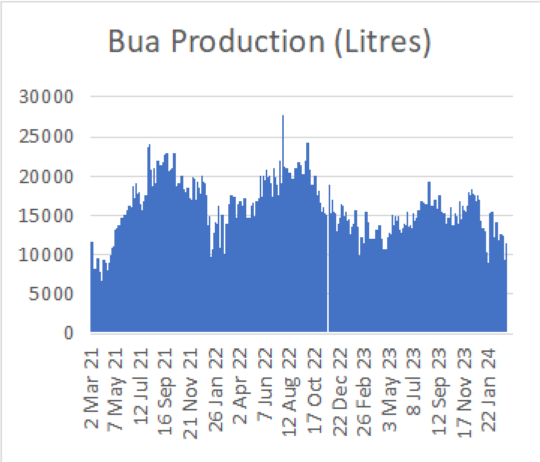

Figure 6: Bua Production Graph

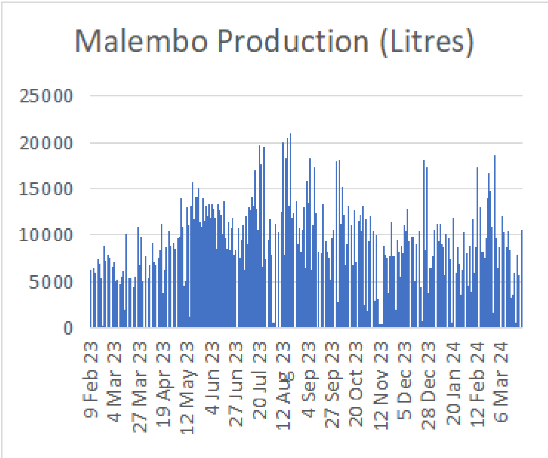

Figure 7: Malembo Production Graph

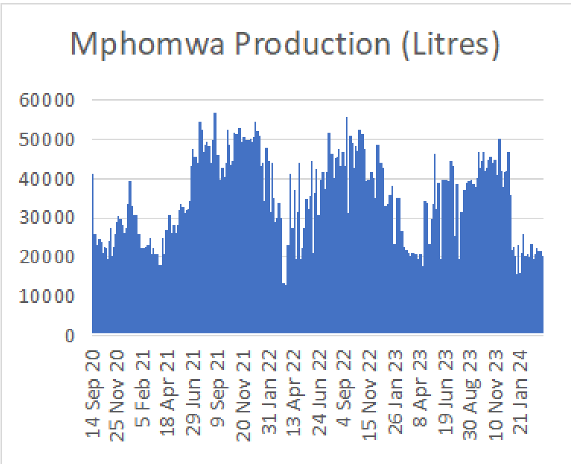

Figure 8: Mphomwa Production Graph

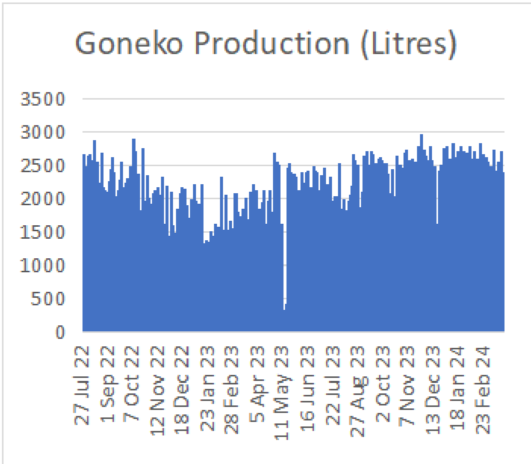

Figure 9: Goneko Production Graph

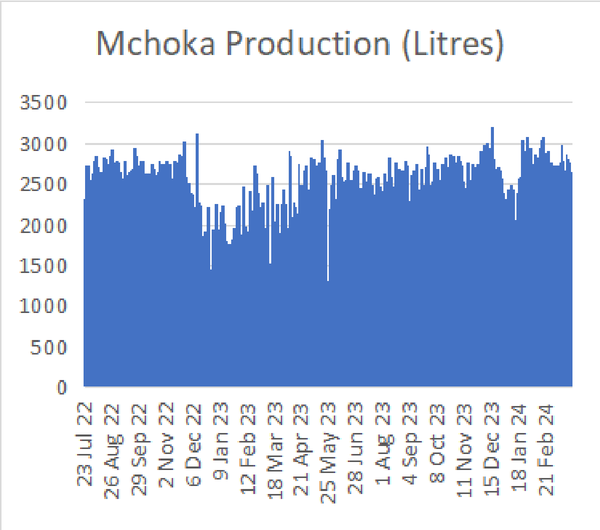

Figure 10: Mchoka Production Graph

3.1 Water Production

Each of the five graphs (Figure 2 – 6) indicates the daily production for each site. The monitoring period under consideration ranges from 12 months to 42 months. Table 2. summarizes the main findings of the study. It should be noted that for Goneko and Mchoka sites Water Mission was engaged to only install remote monitoring systems, hence the design demand and utilization were not part of this study.

Table 4: Summary of water production data for sites

#	Name of Site	Population	Uptime	Design Demand (l/d)	Average Demand (Actual) (l/d)	Utilization	Storage Capacity (L)	Operation Period (months)
1	Bua Safe Water Project	4,816	100%	20,670	13,434	65%	10,000	36
2	Malembo Safe Water Project	1,000	82%	15,600	7,372	47%	10,000	12
3	Mphomwa Safe Water Project	10,000	100%	31,200	29,031	93%	20,000	42
4	Goneko Children's Centre	400	94%	N/A	1,733	N/A	30,000	20
5	Mchoka Primary School	850	100%	N/A	2,466	N/A	10,000	20

<u>Water availability (uptime)</u>

All five sites had water available, with the lowest site registering 82% uptime and the highest registering 100% indicating an average uptime of 95%, which is a positive indication that people were able to access water as the minimum target for uptime is 90%.

Malembo registered an uptime of 82%, however this does not mean that people were not accessing water on a daily basis, due to low demand there were days when water did not flow through the water meter, but people still used water because the storage tank had sufficient water, an extension to this will be highlighted in the utilization section.

Missing transmission may occur if there is a problem with satellite positioning or overhead interference and even when batteries powering the data logger no longer have power. Since the data logger still retains the production data from the water meter, this is sent to the portal, the collection portal then makes an estimated production based on previous data. Estimating how much water was or should have been produced assuming production data went through, as evidenced on Bua on 6 days.

No production may be a scheduled stop by the users of the water system in case of low usage as already alluded to in the case of Malembo where water did not flow through the water production meter, but people still accessed water from the buffer of the storage thereby indicating that the system did not pump any water

Manual readings are sometimes used in the event that the production sensor indicates missing transmission, this is verified by calling the system operators on site who confirm whether the water system is functioning or not, if it is functioning manual readings are then input into the data collection portal, as evidenced on Mphomwa, which had about 6 days of manual readings.

System Utilization

Bua, Malembo and Mphomwa indeed indicate water availability. Comparing the design demand against the actual average daily demand the results indicate the utilization percentage of each site. Even though the utilization is at the lower end, it shows that there is still capacity of the water systems to serve more people, than are currently being served.

Mphomwa is the only site with a utilization percentage of 93%. The low utilization for the other two sites, depicts that the population has not been fully saturated, with the main reason that others use alternative water sources such as handpumps and individuals' wells, and only use the water from system sparingly for drinking purposes as there is a small system sustainability fees averaged at MK1.00 per litre consumed that they have to meet.

The rain season also registers low production, due to the main reason that people prefer to use rainwater for other domestic uses, and only use water from the water system for drinking and cooking purposes.

3.2 Borehole Water Level

Borehole water level sensors were installed in the borehole, just within a meter or less from the pump position. The aim of the water level sensor is to provide groundwater regime data, two parameters are recorded, namely, static water level (SWL) and dynamic water level (DWL). Static water level is defined as the level of water when it is at rest in the borehole, on the other hand dynamic water level is defined as the water level during pumping after an equilibrium has been reached. Both the SWL and Dynamic water level are measure with reference to the ground level.

Table 5: Upper and lower limits for SWL and DWL

Name of Site	Initial SWL	SWL		DWL	
		Lower	Upper	Lower	Upper
Goneko	5.2	2.39	6.95	0.12	36
Mchoka	3.38	3.79	7.78	6.07	10.06

NB: All numbers are in metres.

The initial SWL for Goneko during installation was 5.2 metres, the range for the SWL based on the data collected is 2.39 – 6.95 metres. Whilst the DWL as seen from the data, at the beginning of the installation fluctuated a lot with a wider range of 0.12 – 36 metres. Several months after installation the data improved. This data indicates that the SWL has not changed much. The DWL has improved but is still not stable, this may be attributed to intermittent pumping, as the storage capacity is larger. As a result based on this data, the water table keeps changing based on the pumping.

Mchoka had the SWL on 3.83 metres during installation, and the range of the SWL is 3.79 – 7.78 metres, whilst the DWL is between 6.07 – 10.06 metres. Mchoka stable data for both SWL and DWL. It also indicates that there has not been much change in the water table for the past 20 months.

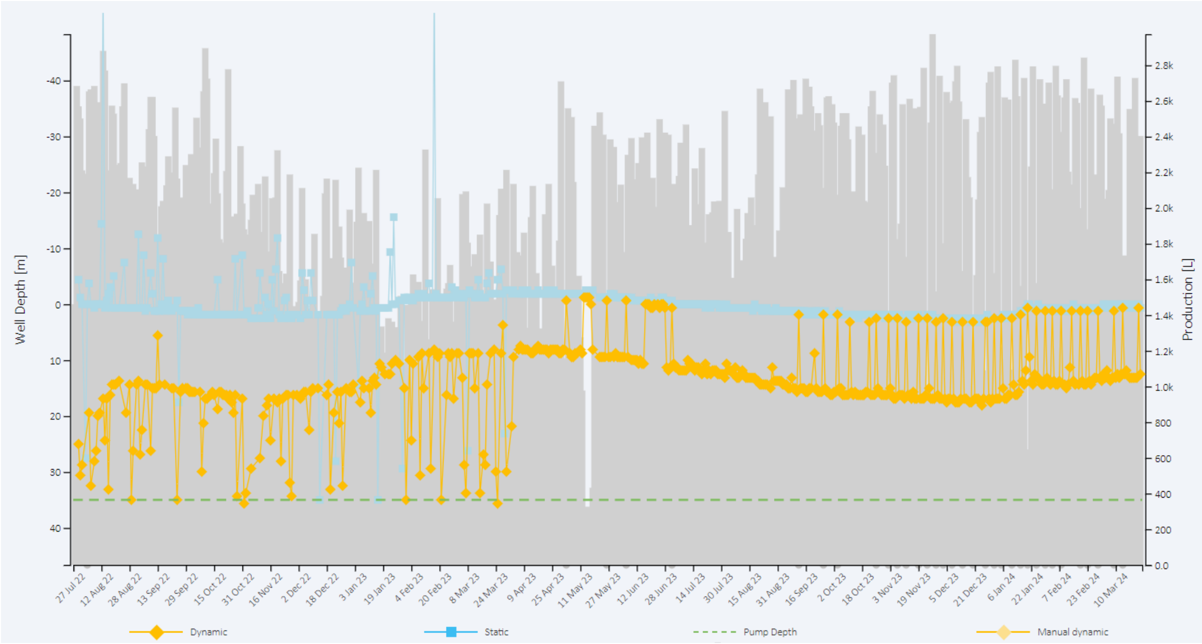

Figure 11: Borehole level data for Goneko

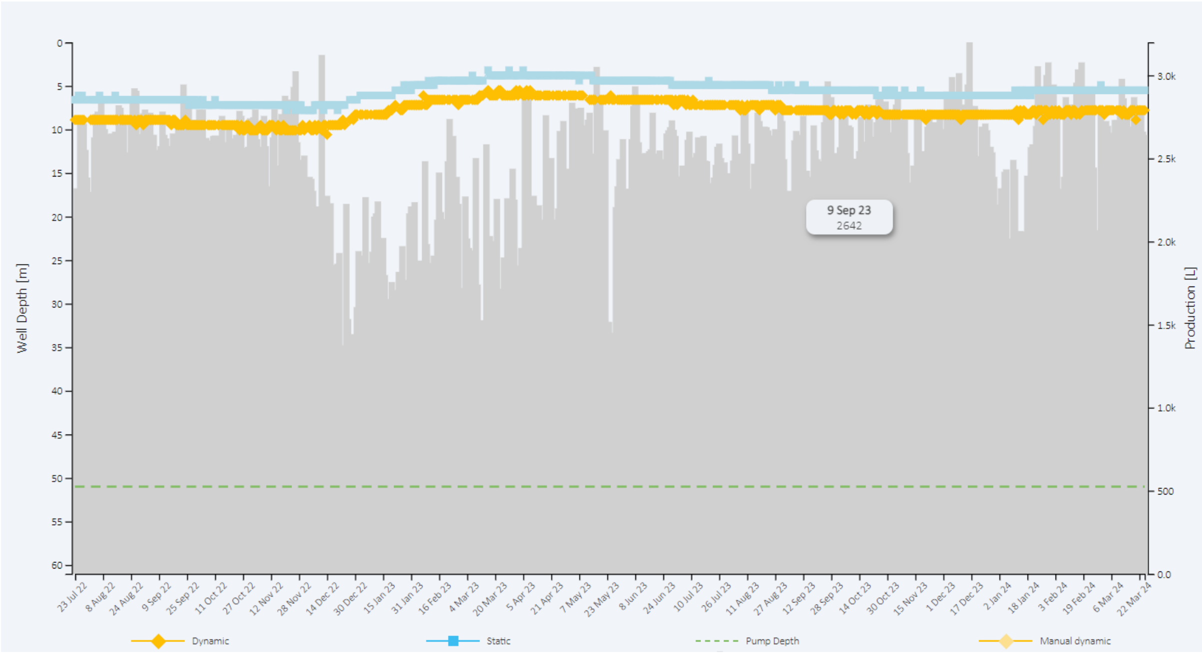

Figure 12: Borehole level data for Mchoka

For both sites, since the DWL is well above the depth of the pump, it is safe to conclude that there isn't over-abstraction as there is no major drop in the water table. It also indicates that the pump is operating in a safe environment with very low risk of dry pumping at all times. This points also to the designs and the installations that they were done in a professional and considerable manner including pump tests for the given boreholes.

3.3 Turbidity

Turbidity sensors were installed on two water systems, the same systems which had borehole water level sensors. Generally, the turbidity readings were within the World Health Organization recommendation of 5 Nephelometric Units (NTU) [10].

On a daily basis, the turbidity sensor records 8 readings that are sent to the portal. Some readings may be out of range, the aim of recording 8 readings is to come up with an average that is a reflection of the water quality regarding turbidity. In the early days of the installation of Goneko, the data in Figure 11 indicates that they were some outliers attributed to similar faults that may occur when a new device is installed in any system. Later on, the data improved because the sensors had stabilized. The Malawi Government water quality standards recommend a maximum reading of 25 NTU [7]. 9 outliers were identified on separate days, indicating an outlier percentage of 4%, the rest of the reading were well within 25 NTU. Within a period of 7 months, 43 outliers were identified which were above 5 NTU but below 25 NTU, representing 20% of reading above 5 NTU in that period. The next 8 months indicate the readings to be well within 5 NTU confirming that the water is clean. This points to the borehole development being done in a professional manner where enough time was given for flushing out any suspended particles.

Just as with Goneko, Mchoka also registered outliers (Figure 12), but these outliers were within 10 NTU, all identified outliers were 3, and these were above 5 NTU, representing an outlier percentage of 0.6%. Whilst the rest of the readings were within 5 NTU. Generally, water produced at Mchoka is clean.

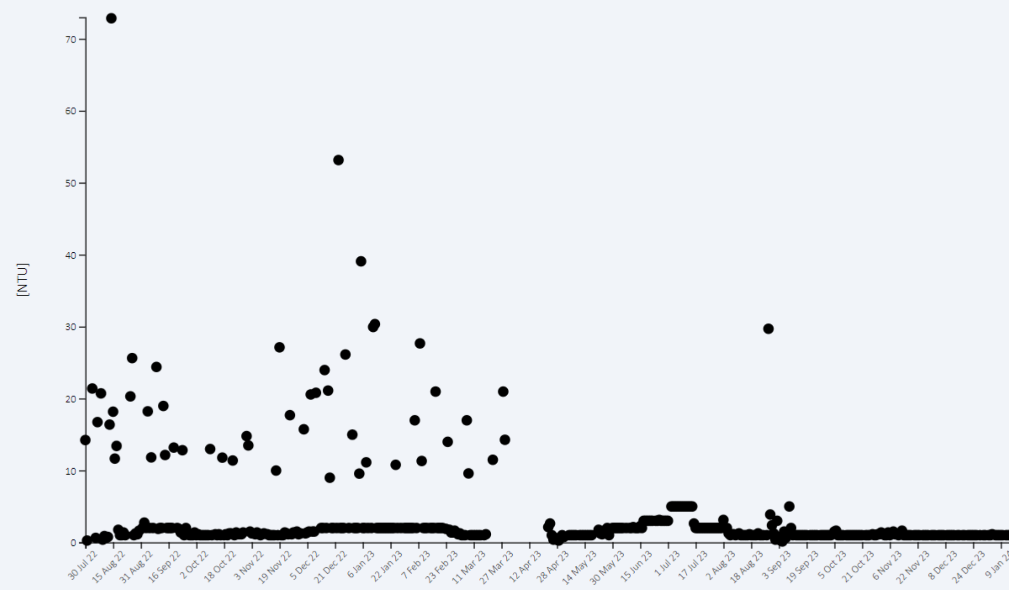

Figure 13: Turbidity data for Goneko

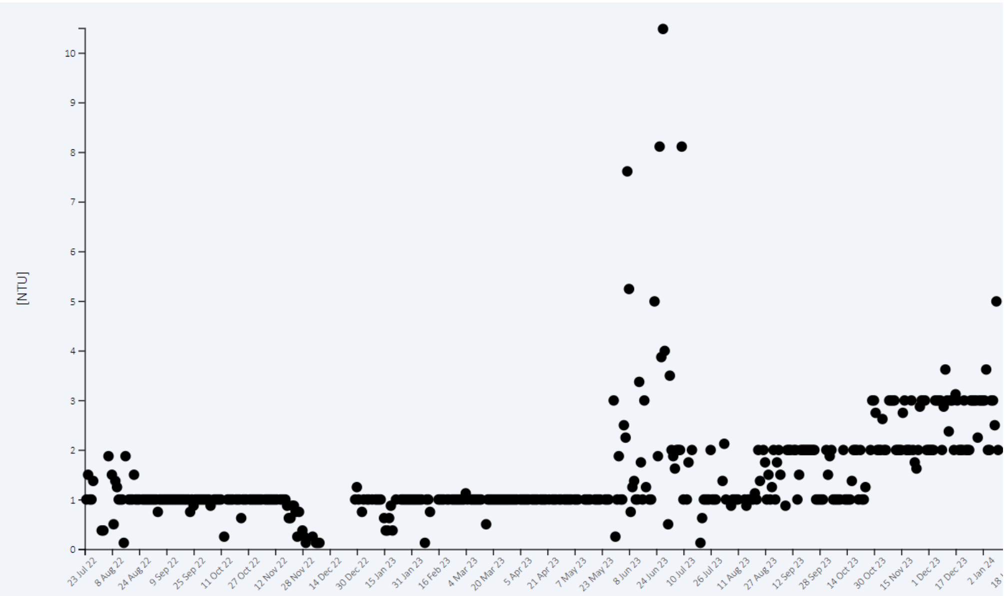

Figure 14: Turbidity data for Mchoka

4.0 Conclusion and Future Work

The two challenges were no production when water hasn't flowed through the flow meter, and missing transmission or no data availability due to flat batteries. Water Mission is working to bring another version of the data logger, to tackle these issues. The new data loggers that are in development will have an in-built rechargeable solar battery and a small panel will also be installed on the data logger to ensure that power is available at all times. Secondly, the data logger will have a provision to install two flow meters, the first meter will be installed to record the volume of water produced by the pump, and the second meter will record the volume of water released by the storage tank. Such that in circumstances where no water is extracted by the pump, consumption is still recorded if water has been released from the storage tank.

Remote monitoring ensures that data is readily available, this data is useful for corrective measures, appreciation of a scheme's status and capacity, and the data is also useful for decision making and long-term planning for water supply schemes. If sustainability of water supply schemes is to be enhanced, remote monitoring is the way to go.

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Paper 5: Developing an Asset Management Framework: A Roadmap to Improving Performance of Water Boards in Malawi

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Abstract

There is global recognition that physical asset management (AM) frameworks help to improve performance in asset-intensive enterprises through enhanced decision-making and proper utilisation of resources. The dearth of knowledge and lack of policy may have hindered AM framework development at Water Boards in Malawi. Thus, this study aimed to develop a framework to support the effective management of physical assets at Water Boards (WBs) in Malawi. A questionnaire that sought to discover and examine AM practices and drivers was applied to 141 water supply experts drawn from all WBs in Malawi, and data was analysed using SPSS V 20.0. The results from the survey, literature reviews, and experts' opinions were used to postulate the AM framework which was later validated by potential users. The substantiation generally revealed that the proposed framework guides management and other key players, areas to be considered to best utilize and sustain AM for the utmost performance of the WBs in Malawi and beyond. The study has not been done before hence it raises public awareness but also provides insights to top management on areas they need to prioritize to develop or maintain a high level of excellence in AM. Furthermore, the framework may be utilised by policymakers as a guide to influence the development and implementation of AM practices across WBs in Malawi. A future study on how each stage of asset life affects the performance of WBs is proposed so that constrained enterprise resources are channelled appropriately.

Keywords: Practices, asset-intensive, life cycle, drivers, strategic goals,

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1. Introduction

Modern businesses are competitive in nature and hence their success largely depend on super-efficient and cost-effective processes. Business processes are supported by different types of assets. It should be noted that assets are delineated differently across the fields and businesses depending on the domain of use. For example, global asset standard defines an asset as anything that has the actual or potential value for an organisation [1], while [2], define engineering assets or physical assets as objects that have legal status and value. [3] terms an asset as "any physical core, acquired elements of significant value to the organisation, which provides and requests services for this organisation" p. 27. Also, [4], defines physical asset as an entity that is capable of creating, sustaining or destroying value at any stage in its life cycle. Although all these definitions agree that value must be derived from these assets for an organisation, [5] point out that there are differences from one enterprise to the other as to how value is perceived (p. 31). This is so because of different business processes, environment, and goals that each organisation operates. Nonetheless, these definitions illustrate how each organisation must justify ownership of these assets with respect to their business objectives. Assets are also classified as real estate and facilities, plant and production, mobile assets, infrastructure, information technology and human asset [6, 7]. Notwithstanding, these assets are fundamental in driving the strategic goals of any asset-intensive enterprise and as pointed out in literature, their main aim is to benefit the organisation [8, 9]. This suggests that by optimally utilising the assets owned by any asset-intensive enterprise, the performance of the business improves, and this puts the business at a better competitive edge over others. For physical assets to continue registering sustained good performance, effective decision making is crucial, and this is supported by asset management frameworks (AMFs) which act as a guide. Literature reveals that apart from financial significance, asset management (AM) is driven by a number of factors such as the aging of assets, changing stakeholder and service level requirements, amplified emphasis on public health and safety, and increasing stringent requirements set by regulating bodies [10]. Unpredictable natural disasters and climate change will also continue to pose a great challenge in AM. [11], point out that AM was born as a response to the poor state of maintenance of infrastructure due to resource constraints and the complexity of infrastructures. [12], argue that for complex organizations, traditional approaches in strategic planning, asset management, and decision making cannot adequately solve growing problems in these organizations, as a result a new approach was prompted as a response to the challenge.

Literature reveals that different AMFs have been developed and adopted globally, but most organisations continue to apply AM without linking to organisational strategy [13, 14, 15], this is a nonconformity to what the developed frameworks promote. This may mean that the developed AMFs have gaps but also may mean that organisations are not aware of the benefits associated with alignment with business strategy. This points to the need for public awareness in asset-intensive enterprises, policy makers and all duty bearers on the requirements of AM and associated benefits. Studies indicate that most approaches to AM are centred on either technical or financial aspects, rather than being multidisciplinary [16, 17]. Furthermore, the attention is often limited to certain parts of the lifetime of the assets [18], or solely on the estimation of the remaining useful life of the assets [19]. Literature reveals that in most cases planning doesn't consider probable variations in the working environment such as regulations [20]. Of particular importance, both the literature and ISO 55000 standard [1] on AM do not offer guidance as to how to do AM in a way that fulfils the aforementioned five characteristics. The aforementioned gap in AM creates an opportunity for further studies that would make the practice more beneficial and appealing. According to studies done by [20], it was found that the limited availability of data, the distribution of information throughout the organization and the limited time available for long term strategic issues results in a limited understanding of the remaining lifetime of assets. This was also echoed by [21] and [22].Thus, there is that need to ensure that all stages of asset lifecle have adequate data to facilitate effective decision making. [23], concludes that adopting AMFs can lead to sustainable value creation from assets. The study by [24], clearly indicates how AM practices positively influence the performance of asset-intensive enterprises. As AM benefits are being revealed, it is important to note that business enterprises are facing competing priorities and scarce resources such that the development of AMF does not guarantee success, unless other factors in an organisations are taken on board [25]. Therefore there is that need to ensure that other areas of the organisation are holistically considered for sustained success. AM has earned attention, especially in asset-intensive organizations, and will continue to be a key player affecting the performance of businesses [22, 26]. This is true, because of the critical role assets play in the realization of business objectives. Physical assets are fundamental to the success of both current and future growth of any enterprise [10]. Studies reveal many AM goals such as cost efficiency, capacity matching, meeting customer needs, and market leadership [27], each of these goals is needed for the success and sustainability of an asset-intensive enterprise. Therefore, it is important to base AM practices on the strategic objectives of the business in line with available resources, with customers in mind, and in the best interest of stakeholders.

It is generally noted that success of an asset intensive organisation is based on adoption of high-quality asset management practices and systems [28, 23], yet many organisation are still lagging behind on adoption of AM strategies. Furthermore, [28], observes that strategic AMF ties an asset management organisation from end to end, and is targeted at improving efficiencies, effectiveness and overall performance whilst meeting the business objectives. This should be enough to trigger development and implementation of AM practices especially in asset-intensive enterprises to reap these potential benefits. [13], proposes a holistic framework for the AM system so that managers in capital intensive organisations can better understand how to manage assets lifecycles and deal with their stages in practice. Water Boards in Malawi are asset intensive as well as capital intensive organisations with clearly defined objectives that need to be fulfilled, regulations that need to be complied, and most of these require AMF to register meaningful and continued success. Most of these Boards have aging infrastructure, and this make asset managers increasingly face change in both the goals of their assets and the context in which the assets operate [29]. For example, the aged infrastructure is one of the major causes of high non-revenue water (NRW) [30], which is a big concern to the Water Boards as it drains their prime resources and adversely affect service delivery. [31], argues that Asset Management has five important characteristics; it is a multidisciplinary practice; the whole life cycle of a physical asset should be taken into account; the goal is to achieve certain specified objectives; within acceptable limits of risk and relevant regimes; and it should determine the allocation of resources. This is also supported by other researchers [27]. According to [20], Asset Management that fulfil the five requirements are termed Asset Life Cycle Management (ALCM). The multidisciplinary practice of AM means that diverse stakeholders are involved, and this poses another challenge due to their different requirements and expectations [32]. Nevertheless, this requirement yields more benefits, and the expected challenges call for excellent leadership skills such as collaboration, teamwork, delegation, and creation of participatory environment. The whole life cycle consideration requires that each stage of asset life is given due attention to make sure that there is longevity and return on investment. The alignment of specified objectives with asset activities facilitates corporate budgeting and attracts executive support. Assets pose risk and therefore the need to define the level of risks the organisations can bear is crucial. The allocation of resources assures the implementation of AM practices and facilitates effective planning. [33], point out that AM is characterized by the adoption of an integrative approach, defining service levels and performance standards and limiting them to strategic planning objectives, an optimized investment decision-making approach, adopting a long-term (lifecycle) approach to asset management and demand and risk management (RM). All this characterization shows the multi-disciplinary and holistic nature of AM. [22], suggest that the definition should generally be flexible and accommodative since research work and practice are not fully matured, hence ongoing. AM in this study adopts the definition by [34], as the process of utilizing physical assets from creation to disposal in order to strike the right balance between performance, cost, and risks in pursuing the enterprise goals.

AM core practices are progressively maturing on the ground. Literature reveals; strategy and planning, risk management, life-cycle delivery, asset information, and asset review as AM core practices [10, 35, 36, 37, 26]. While literature is generally showing a number of studies regarding AM globally [24, 2, 26], very little is known to the best of the authors' knowledge, research that addresses AM core practices and their link to operational performance in water utilities. Recent studies on AM core practices concentrated only in organizations located in Europe and mostly in the manufacturing industry with less than 1% data in water utilities [24, 26]. For water supply systems which are usually asset-intensive in nature, a deliberate effort to strengthen asset management practices is a must in order to support and sustain the provision of better services to the communities in a sustainable manner. Broadly, AM is regarded as maintenance with just a fraction of 5% to 40% of major production or processing costs of an enterprise and therefore over the years it has not drawn any strategic attention in the board rooms [38]. This line of thinking regrettably views maintenance as insignificant when compared to other costs in an enterprise and therefore not of major concern in the boardroom. Although this is the perception, unfortunately by only looking at costs, this line of thinking is one-dimensional, and it excludes other important benefits such as the value maintenance delivers to the business. For example, if there is a breakdown of water main transmission pipeline, apart from the cost of repairing, there are other forms of cost to the business that should be considered. There is loss of water sales, customer satisfaction will be compromised, some employees will be idle lowering productive time, and a myriad of problems ranging from risks to environment and legal threats. These but few examples should make every meaning business enterprise consider AM as one of the key areas to discuss from the boardroom. Also, there is worldwide recognition that AM practices allow water utilities to serve customers more effectively by encouraging better financial, social and environmental responsibility [39].

Certainly, there are more benefits asset management brings to any asset-intensive business such as enhanced production capacity, sustained lowest and affordable risk, and extended equipment life which reduces future capital expenditure. [40], earlier on outlined efficient and effective systems, accountable and auditable enterprises, increased asset portfolio, and improved quality of servises as opportunities in public asset management (40 p. 1). Literature also reveals many other benefits of AM, according to studies done by [41], [42], [43], and [44], for example; improved financial and safety performance, reduced environmental impacts and improved ability to demonstrate socially responsible and ethical business practice. Moreover, studies reveal that AM practices positively influence the sustainability performance outcomes, namely, economic, environmental, and employee-related social performance [24]. Also, there are many benefits associated with AM when aligned to business objectives are reported in literature such as improving the quality of decision making, and hence reduce risk of asset failure, protection and enhancement of asset value, improved reliability and performance, financial, social and environmental sustainability [45]. Although literature highlights a number opportunities when asset management is introduced in organisations, many challenges to the introduction of AM are also inexorable. For example, many governments and enterprises have no clear institutional and legal frameworks to guide AM, non-entrepreneural attitude towards public assets, multiple jurisdictions in public assets, complexity of objectives in an organisation, and absence of data to manage public assets [40]. Nevertheless, the strides in AM are evident as main industries aim to create an integrated and holistic methodology to manage physical assets [46]. AM provides the basis for improved organisational performance and sustainability, therefore, no business oriented organisation would opt to miss the AM associated opportunities and benefit from the expected returns.

Although there is growing world-wide interest on this subject, many developing countries including Malawi are not capitalising the opportunities in this area and therefore the potential benefits associated with effective AM are not earned. This anomaly can be attributed to lack of awareness and absence of policies to guide its practice. Therefore this study contributes to the existing literature by analysing the AM practices in the study area in relation to global practice and formulating AM framework to provide the line of sight for its practices at Water Boards (WBs) in Malawi and beyond.

2. Materials and Methods

This study used mixed research methods because of its exploratory nature as depicted in Figure 1.

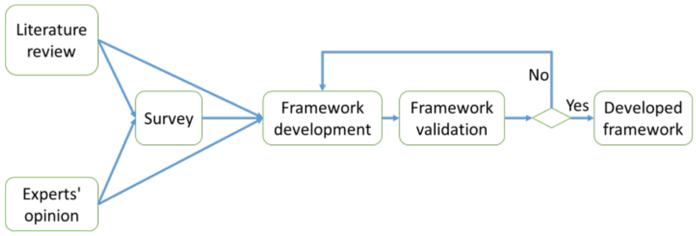

Figure 1: Framework development process

Firstly, a comprehensive literature review was conducted to identify AM core practices, preliminary list of AM drivers and success factors to be analysed and utilised in the study area. The search in science-cited journals, conference proceedings, white papers, books and book chapters, magazines, and PhD dissertation works, based on the keywords containing AM, and maintenance of assets were done, and the final list of papers were selected for the review.
Secondly, based on the literature analysis and experts' opinion, a survey was conducted in the study area to respond to three objectives of the study i.e. to assess the AM practices, to examine factors that promote AM, and to analyse critical success factors for AM at WBs in Malawi. A questionnaire was used to collect data, it was preferred because it was suitable, easier, rapid, uniform, and economical

to collect data, and the main objective of its use is to obtain relevant information in the most reliable and valid manner [47, 48]. The objectives of the research and the pattern of the questions were explained in detail to the respondents. All questionnaire items were subjected to validity and reliability tests. Validity explains how well the collected data covers the actual area of investigation, while reliability concerns the extent to which a measurement provides stable and consistent results [49]. Respondents were asked to rate according to the aggregated experience in their company on a 5-point Likert scale, to what extent their enterprises were implementing AM core practices, rank AM drivers, and critical success factors. The mean score of 3 and above was considered as an indication that AM core practices were fairly adopted in the study area. To identify key factors in the study, the natural cut-off point was used [50] i.e. all factors whose average scores are above the average of the upper and lower mean score of the sample. This was preferred as opposed to other methods presented in literature such as average of the ranking scale in the questionnaire [51, 52] i.e. for a 5-Likert Scale, (1+2+3+4+5)/5 equal to 3, therefore all factors with average score above 3 are considered critical. Other researchers have used relative importance index (RII) to rank the success factors [53]. The cut-off point method was opted due to its simplicity and relatively good quality results that one can get. Exploratory factor analysis (EFA) and Confirmatory Factor Analysis (CFA) were both done to condense and analyse data into few variables and establish common themes applicable to the study area [54, 55]. Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy and Bartlett's Test of Sphericity were used, a KMO value over 0.5 and Bartlett test significance level below 0.05 were considered suitable [56]. A principal component factor analysis with Varimax rotation was conducted on the shortlisted factors. The factor extraction was based on eigenvalues (quality scores) greater than 1(common rule of thumb). The rotation was done to reduce the number of factors on which the variables under investigation have high loadings, which makes interpreting the analysis easier [57]. [58], state that a minimum factor loading of 0.50 was acceptable, while [57] and [59], promote 0.40 and above; this study adopted 0.40. The analysis of data was done using SPSS V 20.0. It should be pointed out that different researchers recommend different minimum sample size for EFA. For example, a 150 to 300 sample size is perceived necessary [60] while others recommend a minimum size of 50 [61]. This study had 106 sample size which suits the latter condition. As pointed out by other researchers, although the condition was met, even a far lower sample size was applicable provided certain conditions were met [61].

Thirdly, the output from the literature review and the survey results were supported by the experts' opinion to define a framework appropriate to the study area. This is termed retroductive strategy in literature and has been applied by other researchers in the same field [23]. This was favoured because it combines research approaches and eliminates some flaws in other research processes [62], this also suits well with the exploratory nature of the study.

Finally, the postulated framework was subjected to validation process. Face to face interviews were conducted in the study area targeting water supply experts to offer their candid views, explore evidence and testing the relevance of proposed framework. The substantiation was similar to what other researchers used [17, 63, 64].

Results and Discussions

This section provides results and discussion of the survey and framework development.

2.1 The analysis of the questionnaire and the study population

This was regarded as the first step under results and discussion which concerns the analysis of the sample composition by specifically observing the distribution according to which WB they belong, the position, and level of education the respondents have. The demographic data is central in that it helps to understand the implication of the participants of this research on quality of the results and also maintaining and providing justification regarding sample accuracy. A total of 120 questionnaire items under seven themes was developed. The developed questionnaire was subjected to pilot test by administering to 10 water utility professionals followed by a questionnaire review. This was done to improve face validity. Out of 141 questionnaires distributed to all water utility professionals managing water supply systems in all five WBs in Malawi, 106 were completed and were declared valid representing a 75% response rate. This reflected the importance the respondents put on the research area. The sample size was considered sufficient to carry out an analysis and was within what was provided in other studies [65, 66]. All factors had 2-tailed significance values of less than 0.05, therefore valid, and also, had Cronbach's Alpha above recommended reliability [67].

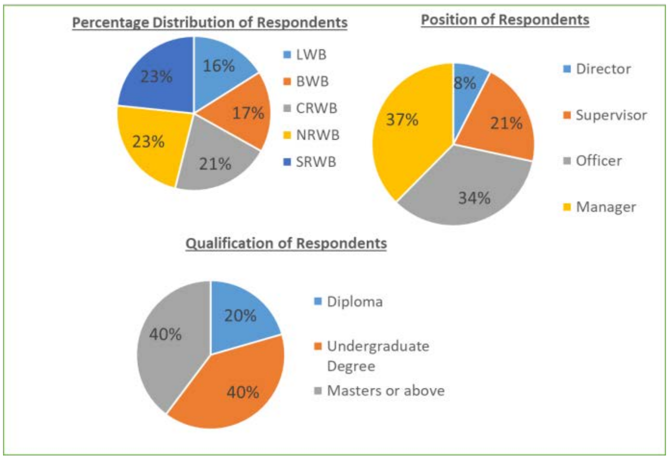

Figure 2: Characteristics of the sample

From Figure 2, 16% of the respondents work with Lilongwe Water Board (LWB), 17% with Blantyre Water Board (BWB), 21% with Central Region Water Board (CRWB), 23% with Northern Region Water Board (NRWB), and 23% with Southern Region Water Board (SRWB). There is a minor difference in the percentage distribution of respondents across WBs in this study, this shows that the results fairly represent all the five WBs in Malawi. The majority of the responses were from managers (37%) and officers (34%), supervisors (21%), and directors (8%). Furthermore, respondents with a master's degree and above represent 40% of the responses, with an undergraduate degree representing 40% and with a diploma representing 20%. The results in Figure 2 show that all the respondents possessed diplomas and above but also were at supervisory level and above. Therefore, it would be expected that such respondents could understand the contents of the questionnaire and interpretation of the results, and have considerable knowledge of water supply and AM. The level of education is also crucial in integrating new knowledge and implementation of AM projects.

2.2 The AM core practices at WBs in Malawi

Table 1 shows ranked descriptive statistics and bivariate correlations for AM core practices in this study. The means for the 5 core practices range from 1.909 to 2.865, which is low and indicates low application of core PAM practices in the study area. This can be attributed to lack of awareness and absence of policy to promote its practices. The standard deviation (SD) varies from 0.291 to 0.549, which is generally low, and this shows some kind of consensus among professionals on the assessment of PAM practices in the water supply. The standard error mean varies from 0.028 to 0.053, which is small, this shows that the sample means closely represent the true population mean. All five core practices show that they have a statistically significant positive linear relationship among themselves (correlation is significant at the 0.01 level (2-tailed)). It is also observed from Table 1 that asset information at 0.681, is the strongly related factor to life cycle delivery, and asset review at 0.445 is the lowest related factor to asset information. Generally, all these core practices tend to increase together.

Table 1: Descriptive statistics and correlations of AM core practices

PAM Core Practices	Mean	SD	Std. Error Mean	Correlations				
				(1)	(2)	(3)	(4)	(5)
(1) Strategy and planning	1.909	0.291	0.028					
(2) Risk management	2.853	0.549	0.053	.529**				
(3) Life cycle delivery	2.865	0.517	0.050	.495**	.648**			
(4) Asset information	2.654	0.462	0.045	.491**	.666**	.681**		
(5) Asset review	2.388	0.510	0.049	.564**	.550**	.583**	.445**	

**. Correlation is significant at the 0.01 level (2-tailed)

Life cycle delivery

Life cycle delivery was rated first in this study with an average score of 2.865. AM involves all stages of asset life i.e. from creation to disposal, hence it impacts every stage of the asset lifecycle. It is observed from this study that utilities are putting more emphasis on life cycle delivery practices which are also under the exploitation phase possibly because the stage commands daily activities of the business and this easily attracts customer reaction but also huge operational and maintenance costs are involved, yet most of these costs were already factored in during the creation and establishment phase [4, 68], hence each of the stages in asset life cycle must be seriously managed for total utilization of asset management system.

Risk Management

Risk management (RM) with an average of 2.853, was rated second in this study. Although respondents acknowledged that some practices in the study area relate to RM, many of those practices are mandatory i.e. as a result of regulatory and other financial global standards other than AM. It should be emphasized that RM is a crucial element of AM [36], hence it should be vigorously promoted. Apart from reducing risks, RM sustains a competitive advantage to enhance performance and has a direct impact on business success [69]. RM is best known to reduce the possibility of many threats such as financial uncertainties, legal liabilities, accidents, and natural disasters, hence top management must place RM at the heart of AM and promote its practices.

Asset information

Asset information with an average of 2.654, was rated third in this study. Although it was rated third, portfolio intelligence is very key to the success of

AM. This is well supported in literature that access to quality information is one of the main critical success factors for AM application and effective decision making [70]. This is true in the sense that any form of data in asset management system can create chain effects that eventually affect many activities in the process and hence the need for an organization to emphasize the quality of data at different asset management levels of the business [71]. There is an old adage that says 'what you cannot measure, you cannot improve'. With the increasing complexity of asset systems and technology, having established an asset register there is a need to continuously capture asset information in operation to assist in decision making. It is not every asset data that is needed, the quality of the asset data provides foundation for effective AM [72, 71]. For an organization to have quality asset data, processes must be put in place which should be supported by multiple stakeholders, technology and systems for effective AM. As pointed out by [73], to improve quality of data is to take note of the areas that affect its quality which I point out as use of skilled personnel that are properly aligned to their assignments and utilization of appropriate technology. Effective communication throughout the strata of the organization also improves quality of data in an enterprise. There are several packages on the market that can be utilized to capture, analyze and display asset information in operation. The organization must facilitate training to multiple stakeholders on data collection process and how the collected data affects AM and performance of the institution. Top management has a duty to support AM information systems to support executive decision-making.

Asset review

Asset review with an average of 2.388, was rated fourth in this study. Having knowledge of asset base and their performance, it is vital that reviews are carried out which would help to provide feedback to management and trigger necessary action on the asset management system. Based on what data is captured in the asset system, an asset review must come in to process the data and give direction on the possible course of action. Top management needs to support recommendations from the asset review to fully optimize the asset performance.

Strategy and planning

Strategy and planning with an average score of 1.909, was rated fifth in this study yet this practice is very crucial in facilitating AM practices from asset creation to disposal. Although it was rated the least, item 9 (we create strategic asset management plans including costs estimation) at 3.302, was the highest rated of all the factors in the analysis. Most WBs are good at asset creation and establishment phases of the asset lifecycle in what is commonly termed infrastructure development projects hence the high rating. All AM definitions point to a multi-disciplinary and holistic approach with linkage to organizational strategy [22, 1], therefore, it is expected that executive management supports the establishment of AM policy, objectives, and plans which should be part of the strategic goals of the organization. Studies show that policy and strategy are positively related to AM [24]. Also, there is great emphasis on the linkage between business objectives and asset performance measurements [74]. Therefore, it is expected that as strategy and planning in AM is prioritized, asset performance is enhanced.

2.3 Factors that promote physical asset management

Table 2 shows ranked descriptive statistics and a one-sample T-Test of survey results. The means for the 15 drivers range from 2.594 to 4.651, hence the cut-off point for key drivers in this study was (2.594+4.651)/2, i.e. 3.623 [50]. The similar method would have given a cut-off point of 3 i.e. (1+2+3+4+5)/5 [51, 52]. Therefore, all factors with mean scores above 3.623 in Table1 are considered key in this study. The standard deviation varies from 0.393 to 0.743, which is generally low, and this shows some kind of consensus among water supply experts on the assessment of PAM drivers in the water supply. The standard error mean varies from 0.038 to 0.072, which is small, this shows that the sample means closely represent the true population mean.

Table 2: Descriptive statistics and factor analysis for AM drivers

Descriptive Statistics and EFA for PAM Drivers					
PAM Drivers	Descriptive Statistics				EFA
	Mean score	Std. Dev.	Std. Error	Rank	Factor Loading
Local context (1)	**3.201**			**4**	
Under-investment in PAM	3.387	0.489	0.072	10	0.765
Decentralisation	3.019	0.743	0.050	14	0.746
Accountability to public sectoe	3.198	0.723	0.071	12	0.649
Entrepreneural (2)	**3.413**			**3**	
Need to optimise value of assets	3.868	0.731	0.048	5	0.743
Necessity to recognise business value	3.406	0.714	0.046	8	0.732
Need for an integrated approach to PAI	3.057	0.715	0.069	13	0.588
Advances in ICT use	3.292	0.647	0.069	11	0.460
Need to reduce business risk	3.443	0.518	0.063	7	0.421
Globalization (3)	**3.578**			**2**	
Publication of international standards	2.594	0.493	0.048	15	0.730
Response to incidents	4.651	0.479	0.047	1	0.676
Investor attitudes towards PAM	3.670	0.473	0.048	6	0.649
Advances in the maintenance market	3.396	0.491	0.070	9	0.603
Compliance (4)	**4.305**			**1**	
Regulation and legislation gy Govt.	4.189	0.393	0.038	4	0.811
Increasing system demand	4.340	0.476	0.048	3	0.769
Financial constraints	4.387	0.489	0.046	2	0.665

Response to incidents or high-profile events.
This result from the perception of respondents in the study area was expected and is in agreement to what is reported in literature. Regrettably, many organizations are reactive when it comes to AM. They tend to bring an intervention following an accident or incident. For example, literature reveals that the real acceleration of modern AM in the UK was due to the Piper Alpha disaster and oil price crash in the late 1980s [75]. Also, Hatfield train accident in the UK in 2000, the 'Black Saturday' bushfires in Australia in 2009, the Deepwater Horizon incident in the Gulf of Mexico in 2010, and the Grenfell Tower fire in London in 2017 [68], as some of the examples globally where the organizations began to respect AM practice so that further asset risks associated to their businesses are managed. Unfortunately, this type of approach is costly to any business, can be fatal, and also can bring irreparable damage to the asset and environment due to its reactive approach and hence it should be avoided. Although this factor continues to influence introduction and implementation of asset management practices in many industries, the consequences far outweigh the benefits to the business. Reactive approaches to asset management need to be avoided.

Financial constraints.
This result was also expected as many organizations are currently facing insufficient financial resources to realize their business goals. Economic hardships and the need to realize profits are forcing organizations to look into areas where they can realize savings. AM, for every asset-intensive organization, is being prioritized for such savings. Successful AM implementation in any asset-intensive enterprise and as pointed out in literature can lead to improved financial and safety performance, reduced environmental impacts, and improved ability to demonstrate socially responsible and ethical business practice [41, 44, 42, 43].

Increasing system demand for maintenance, reconstruction, performance, and management.
Water supply systems and indeed many other systems because of the sudden boom in technology, are increasing in physical asset and asset system complexity. This is compounded by ageing of the assets which is a long-time challenge and the asset deficit in many enterprises due to lack of financing [76]. The AM which was traditionally known as 'maintenance' was effective to a certain level of asset integration with business success. As demand for the assets increased, there was a clear need for AM that could match complexity, technology, and business demands. This stimulated the need for an improved level of asset care which is predominantly known as asset management.

Regulation and legislation by the government
This plays an important role in the development of AM practices. The ever-increasing costs of renewing or rehabilitating aging infrastructure assets and systems require more transparent ways of justifying these costs and this has become increasingly important for regulators and governments. For example, in RSA, public institutions must include in their annual reports how assets have been managed in the year [16], this gives stimulus to AM practices. Regulations, pieces of legislation, and policies are being introduced to improve decision-making and transparency around investments in critical infrastructure, as well as to generate better outcomes from limited resources [68]. Therefore, governments must deliberately introduce AM regulations, legislation, and policies that should make AM practice mandatory for asset-intensive institutions.

The need to optimize the value of assets throughout their life cycle.
Asset-intensive organizations face pressures to sustain the performance of assets, pay back asset investment loans, meet institutional targets, and improve service delivery. This is accelerating the need to optimize the value of assets throughout their life cycle and consequently forcing companies to place AM among the key areas that need attention.

Investor attitudes towards AM.
Financiers consider physical assets as reliable long-term investments hence they are putting up measures and conditions on enterprises regarding their investment. Apart from requiring organizations to

receive certification in AM, some financiers are assessing the asset management maturity of businesses they invest in and then setting challenging targets to improve this and show better control and management of costs and risks [68]. In short, the conditions financiers are putting on asset-intensive organizations to fulfil in order to access funds are stimulating AM practices as non-compliance results in failure to access finances.

Publication of international standards in AM such as ISO 55000 and BSI-PAS 55

Although this factor was rated the least in this study, it has contributed substantially towards introduction and implementation of AM across the globe especially in developed countries [68]. The low rating of this factor in the study area may be attributed to lack of industry awareness on AM practices which this study intends to address. The contribution of global standards on AM is not only the mere introduction and compliance requirements but the public awareness it brings to key stakeholders and the opportunity to benchmark within and outside the various industries. Many enterprises have developed and improved their AM frameworks and practices based on these standards and therefore there is need to widely populate their existence to benefit various enterprises.

Component 1: local context

Of the four components in the analysis, this component has the highest eigenvalue of 3.247 with a variance loading of 21.647%. Under-investment in AM, at 0.765, was the highest loaded variable in this component. This indicates that local context aspects are strongly affected by under-investment in AM as per the perception of the respondents. This variable can help to explain the other two variables in component 1. Adoption of AM practices is affected by AM maturity level of an organisation [77, 78, 79]. The local context component reflects how AM is organized and practiced in the study area.

Component 2: an entrepreneurial approach

This component has an eigenvalue of 2.343 with a variance loading of 15.622%. The need to optimize the value of assets throughout their life cycle, at 0.743, was the highest loaded variable in this component. This indicates that entrepreneurial aspects are strongly affected by this variable as per the perception of the respondents. This variable can help to explain the other variables in component 2. Currently, every business is looking for survival and any opportunities that could bring savings such as those in AM are being implemented. AM ensures that all assets owned by businesses are fully utilised in their entire lifecycle. For example, entrepreneurial approach in water supply means that every drop is accounted for and that business-as-usual attitude is eliminated.

Component 3: globalization

This component has an eigenvalue of 1.548 with a variance loading of 10.323%. Publication of international standards in AM such as ISO 55001, BSI-PAS 55, at 0.730, was the highest loaded variable in this component even though it was ranked the least in the study area. This indicates that globalization aspects are strongly affected by this variable as per the perception of the respondents. This variable can help to explain the other three variables in component 3. The low ranking of publication of international standards in the study area may mean that AM practices at WBs are at its infancy level and may also reflect lack of awareness in the field. Globally, many enterprises are implementing AM practices because of the availability of international standards [68].

Component 4: compliance and demand

Although this component had the least eigenvalue of 1.330 and a variance loading of 8.870%, it was the most dominant. Regulation and legislation by government, at 0.811, was the highest loaded variable in this component. This indicates that compliance and circumstances aspects are strongly affected by this variable as per the perception of the respondents. This variable can help to explain the other two variables in component 4. As previously pointed out, for state-owned enterprises such Water Boards and other asset-intensive enterprises in general, deliberate introduction of policies, regulations and legislation by governments that emphasize on AM would help accelerate the practice and bring much needed gains in asset-intensive industries [16].

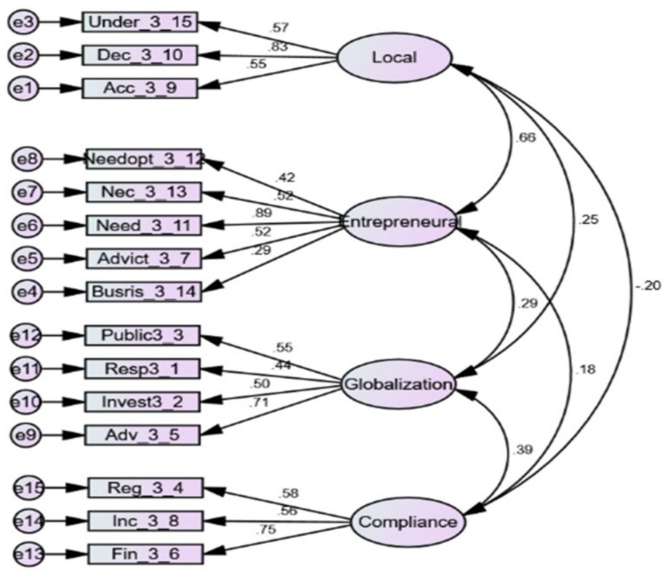

Figure 3: PAM promoters

The results of confirmatory factor analysis show that the model had good fit statistics including p = 0.357, x^2/df = 1.062, TLI of 0.982, CFI of 0.987, PCFI of 0.718, RMSEA of 0.024, and PCLOSE of 0.78 which were above the recommended thresholds of $p \geq 0.05$, $x^2/df \leq 3$, TLI ≥ 0.9, CFI ≥ 0.95, PCFI ≥ 0.6, RMSEA ≤ 0.05, and PCLOSE > 0.05 respectively [80, 81, 82, 83, 84]. Therefore, these factors were fit to be utilised further in the framework development

2.4 Critical success factors for AM practices at Water Boards in Malawi

Table 8 shows the descriptive statistics and one-sample test of survey results in descending order. The means for the 40 success factors range from 2.368 to 4.575, therefore the cut-off point for CSFs in this study was (2.368+4.575)/2, i.e. 3.472 [50]. Therefore, all factors with mean scores of at least 3.472 in Table 8 are considered critical in this study. The standard deviation varies from 0.409 to 0.905, which is generally low and shows some kind of consensus among water supply experts on assessing CSFs for PAM. The standard error mean varies from 0.040 to 0.088, which is small, this shows that the sample means closely represent the true population mean.

Exploratory factor analysis (EFA) was used to reduce the number of factors into common themes [54, 55]. In order to carry out EFA, as pointed out in the study methodology, Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy and Bartlett's Test of Sphericity was done. The condition of KMO value of over 0.5 and Bartlett test significance level of below 0.05 were achieved [56], a KMO of 0.752 and Bartlett's Test of Sphericity with a significance value of 0.000 were realised. This showed that the correlation matrix was statistically different from an identity matrix as required. Therefore, all conditions to conduct factor analysis were met. From Table 3, four themes with eigenvalues greater than one from the data were generated using SPSS, accounting for a substantial amount of variance toward what the instrument purports to measure.

Discussion

From Table3, there are 8 top-ranked CSFs whose averages are at least 4, and these are top management support, availability of financial resources, portfolio intelligence, recognizing budget constraints, utilization of strategic plan of the organization, adequate team members with high competence and expertise, entrepreneurial approach, and ownership. These results are in line with similar studies of CSFs for various disciplines found in the literature [85, 25, 86, 29, 87, 54, 88, 50, 89, 90]

Table 3: Descriptive statistics and factor analysis on critical success factors

Descriptive statisticsand EFA for critical success factors (CSFs)					
	Descriptive statistics				EFA
CSFs	Mean score	Std. Dev.	Std. Error	Rank	Factor loading
Technical	4.017			2	
Strategic asset management competencies	3.660	0.742	0.072	11	0.780
Coherent, self-organizing team-work	3.575	0.675	0.066	14	0.677
Recognizing budget constraints	4.274	0.448	0.044	4	0.592
Portfolio intelligence	4.377	0.506	0.049	3	0.582
Effective performance monitoring	3.642	0.807	0.078	12	0.507
Top management support	4.575	0.497	0.048	1	0.441
HR and org. culture	3.675			4	
Participative environment	3.660	0.755	0.073	10	0.733
Adequate team members with high competence and expertise	4.028	0.762	0.074	6	0.723
Presence of regulation to enhance accountability	3.509	0.502	0.049	16	0.703
Existence of supportive organization culture	3.613	0.751	0.073	13	0.689
Accurate AM data	3.566	0.704	0.068	15	0.501
Strategic planning	4.031			1	
Availability of financial resources	4.566	0.498	0.048	2	0.743
Utilization of strategic plan of the organization	4.057	0.688	0.067	5	0.671
Defined contracting criteria	3.472	0.830	0.081	17	0.535
Managerial	3.906			3	
Excellent management of existing physical assets	3.698	0.719	0.070	9	0.813
Ownership – someone to control and monitor	4.000	0.816	0.079	8	0.663
Entrepreneurial approach	4.019	0.743	0.072	7	0.590

Top management support

This result was expected and is in line with what is populated in literature. Top management support is central, this is supported by [91], [33], that effective leadership is critical in ensuring successful development and implementation of asset management. A recent similar study also revealed that management commitment significantly influences achieving a successful world class manufacturing [92], this further reveals that for any successful system or practice in any organisation, executive support is crucial. Physical asset management need resources (physical, financial, and human), and without executive support, these will be scarce. As pointed out by [3], "to ensure effective utilization of asset, one has to make effective decisions regarding the asset lifecycle", p. 25, and top management are key when it comes to decision making. Physical asset management should be driven from the boardroom and not in the engine room hence senior management must endorse and support AM integration into the business processes and strategic business plan for its success.

The availability of financial resources

The availability of finances to support and invest in AM activities are critical for its success. This ranking agrees with what was recently published in literature regarding factors affecting effective facilities management practices in South Africa [93]. Management must ensure that budget lines for AM activities are supported. Financial resources are very critical to the successful implementation of AM practices. Planning and budgeting of AM activities should be in line with budget limitations. A deliberate budget allocation to AM practices is essential to kick-start and sustain its implementation.

Portfolio intelligence

Many enterprises are oblivious of the need to know with a high level of confidence the assets they own including their location, performance, and condition, and sadly they do not even have the appetite to do so. It is rewarding to have the knowledge of the asset base which organizations own, this is key to the success of AM, and it is the first major step that ensures effectiveness of any AM program. It is implausible that one can succeed in managing something that one does not know. There is an old industry parlance that says, 'what you do not know doesn't exist'. Organizations need to develop the asset register which lists and verifies all the enterprise assets, establish and configure physical asset hierarchy and their criticality in line with organizational strategic goals [94]. Finally, develop and implement a process that ensures future changes to the assets are properly evaluated and recorded. For example, for every project that brings physical assets into the business of WBs in Malawi, there must be a 'close' that binds a consultant during procurement to ensure that all new assets are properly documented, located and submitted with manufacturers recommended operation and maintenance instructions in place. This would facilitate efficient and effective update on the asset register. It would also simplify consolidation of new assets with the existing. Similarly, every new asset that is procured internally should be documented, located and updated in the asset register.

Recognizing budget constraints

Most businesses in the world are facing financial difficulties and budget lines are frequently trimmed leaving a very small amount to spend, especially during utilization phase of the assets. Traditionally, asset management has always been considered as an expense by organizations in their financial records. There is little attention to it during budgeting because its cost compares less with other cost lines in the books of accounts, hence commanding little interest. This is particularly aggravated when asset management is considered haphazard maintenance, non-value adding, and enormous operational errors resulting in high-risk exposure of the business. Unfortunately, this is one dimensional thinking but also failure to recognize the value AM brings to the business. As already pointed out, availability of financial resources is significant. When AM activities are aligned according to budget lines of the institutions, implementation of its programs is assured especially proactive AM. Executive management must know that although cost-cutting often wins, it is at the expense of deferred proactive asset management and inadequate skills for asset managers, engineers, technicians, and operatives. In agreement with what literature reveals, the approach to be considered where budget lines are constrained is to prioritize the most critical assets or practice risk-based asset management [95].

Utilization of strategic plan of the organisation.

Strategic business plan is a roadmap to success for every organization. Embedding AM programs into strategic business plans attract attention from senior management and wins the allocation of budget lines for its implementation. This ranking was expected in this study as all the Water Boards in Malawi draft and implement a 5-year strategic business plan for their enterprise. Although this is the practice in the Water Boards, without proper inclusion of AM drivers and practices in the strategic plans their visibility would not be there. Each WB is expected to ensure that all key requirements for AM are entrenched in their strategic plans. It is suggested that duty bearers should ensure that policies or regulations are put in place that ensures that AM practices are embedded into the strategic plans of the institutions to trigger their use.

Adequate team members with high competence and expertise

Human resource is critical in any enterprise. All processes and technologies in an organisation are made possible because of human resource. A competent team is significant during the planning and implementation of AM activities especially when prioritization is a must due to budget constraints. A highly motivated team is essential for the successful implementation of AM practices. The required numbers, competence and expertise of team members is achieved through effective recruitment, training, organisation culture and the presence of effective leadership.

The entrepreneurial approach

Nowadays, many organisations are facing financial hurdles leading to constrained budget lines in most of the activities. This has made organisations look for alternatives in accomplishing their goals. The entrepreneurial approach promotes value for money; therefore, WBs must account for every process in AM so that the constrained resources are fully utilised. This requires identifying bottlenecks and finding ways of rectifying them in a cost-effective manner. This tactic discourages a business-as-usual approach in WBs and is promoting a commercial business culture which for a long period was less practiced due to WBs statutory organisational setting.

Ownership – someone to control and monitor.
Sustainability of many initiatives in organisations are a flop due to many reasons, one of the major reasons is lack of ownership as the established processes are orphaned. When there is no ownership it means there is no one to monitor progress, evaluation, and provision of necessary communication to the companies' different strata, in fact it means the introduced practices lacks accountability and support. Moreover, performance and sustainability of physical asset management activities without ownership would be a failure, someone must be identified to track activities and provide necessary feedback especially to top management for support and also bridging AM communication gaps that may exist among diverse stakeholders. The proposed personnel to own this responsibility must be someone who is capable to deal with a multi-disciplinary team.

Component 1
This was identified as technical, had the highest eigenvalue of 5.801 with a factor loading of 34.121%, and was ranked second, at 4.017 average means of the factors in the component. Strategic asset management competencies, at 0.780, is the highest loaded variable in this component. This indicates that technical aspects are strongly affected by strategic asset management competencies as per the perception of respondents. This variable can help explain the other five variables in component 1. WBs must ensure the availability of strategic asset management competency across technical teams for the success of AM. As already pointed out, there is growing complexity of asset and asset systems due to technological advancement and market demands which require matching competencies for proper management and delivery of asset objectives.

Component 2
This was identified as human resource and organizational culture, had an eigenvalue of 1.910 with a factor loading of 11.234%, and was ranked fourth, at 3.675 average means of the factors in the component. The participative environment, at 0.733, is the highest loaded variable in this component. This indicates that human resource and organizational culture aspects are strongly affected by a participative environment as per respondents' perception. This variable can help explain the other four variables in component 2. WBs must ensure that a participative environment is nurtured for the success of AM. A participative environment also promotes teamwork, innovation, and creativity.

Component 3
This was identified as strategic planning and budgeting, had an eigenvalue of 1.555 with a factor loading of 9.145%, and was ranked first, at 4.031 average means of the factors in the component, hence most dominant in the study. Availability of financial resources at 0.743, is the highest loaded variable in this component. This indicates that strategic planning and budgeting aspects are strongly affected by adequate financial resources as per the perception of respondents. This variable can help explain the other two variables in component 3. WBs must ensure the availability of financial resources for the success of AM.

Component 4
This was identified as managerial, had an eigenvalue of 1.156 with a factor loading of 6.802%, was ranked third, at 3.906 average means of the factors in the component. Excellent management of existing physical assets at 0.813, is the highest loaded variable in this component. This indicates that managerial aspects strongly affected by excellent management of existing physical assets as per respondents' perception. This variable can help explain the other two variables in component 4. WBs must ensure excellent management of existing physical assets for the success of AM.

2.5 AM framework development and validation

The alignment of AM practices with the organisation's strategic business plan (SBP) is strongly populated in literature as one of the key requirements for an effective asset management framework. Therefore, the proposed framework, refer Figure 4, identifies the SBP as a starting point. Water Boards must ensure that the SBP is in place and should be guided by the following themes and as pointed out in Chapter 4; local context, entrepreneurial approach, globalization, and compliance and demand in order to incorporate AM practices. It should be pointed out that these themes align well with global requirements for what needs to be incorporated in business strategy [1], and these are;

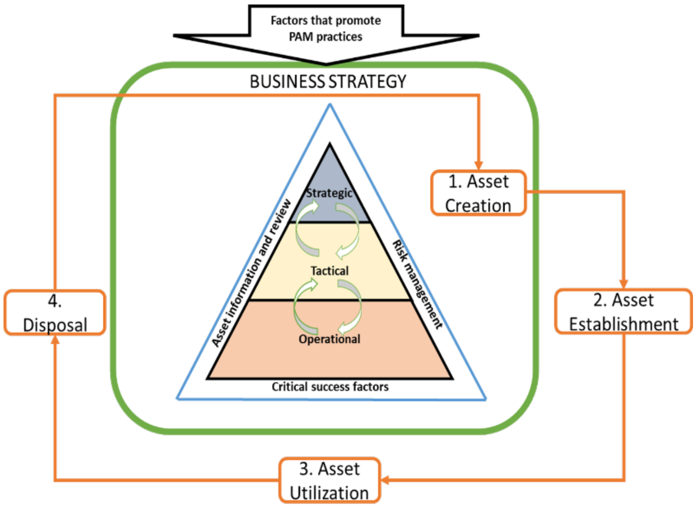

Figure 4: The simplified physical asset management framework (SPAMF)

Stakeholder needs – Water Boards as statutory corporations have the Government of Malawi as a major stakeholder, investors, customers and many other groups and individuals whose interests must be considered during development of SBP. For example, as regards to assets and as previously presented in Chapter 2 and Chapter 4 on factors that drive AM practices, investor attitudes towards AM are very critical and therefore should be highlighted during the planning stage.

Applicable legislation – Laws and other regulations pertinent to the business especially from Government that are generally mandatory in nature affect decision making and general conduct of the business. These laws and regulations must all be known, planned, and complied during formulation and implementation of the SBP. For example, disposal of assets in public institutions in Malawi is guided by Public Procurement and Disposal of Public Assets (PPDPA) Act of 2017 and Public Procurement Regulations of 2020. This Act should be applied during development of SBP of each utility. Another available Act to be considered is the Public Finance Management Act of 2022.

Business environment – The SBP should consider operational, financial, and customer performance reviews of the business for the immediate past 5 years. The reviews will reveal a number of areas such as business growth, profitability, challenges, and opportunities surrounding the business which need to be considered.

Risk management – All external and internal threats of the business need to be recognised and considered in SBP development so that appropriate measures are employed. In Chapter 4 under AM core practices, risk management is featured and correlates positively with other asset management core practices.

The proposed framework is in line with what is populated in literature that the responsibility of setting strategic corporate goals rests with top management. These broad goals serve as guidelines to the development of asset policy and strategy, performance level of assets, and risks the organisation is prepared to accept.

2.5.1 Asset creation

Asset creation denotes the beginning of physical asset life and life cycle cost (LCC) [96]. This stage involves strategy and planning. The requirement of an asset is established i.e. gap analysis, based on the evaluation of existing assets and the business environment. Traditionally, in Water Boards, this stage involves analysis of existing systems and identifying bottlenecks or areas of intervention, feasibility studies, preliminary designs and cost estimates, preparation and submission of project proposal up to a point where financing becomes effective. For externally funded projects, which is dominant in the study area, Water Boards submit their funding proposals to the Ministry responsible for water supply which in turn submits the proposals to the Ministry of finance who link up with potential financiers. For asset-intensive enterprises, strategic business plans are critical during this stage. For example, the performance and condition of assets from trend and data analysis for the existing assets and business performance are critical at this stage to allow decision-makers to identify the need for the asset and what value it will bring to the business. From the strategic perspective, the values of asset management must be deeply grounded on the alignment and fitness of the business resources in order to best meet the needs of the customer within the environment in which it is required to compete in order to maximize returns to stakeholders. For instance, an overseer of the organization's asset resource must fulfil the need to align the goals of the assets with those of the strategic business goals as defined in the SBP so that it can achieve long-term stakeholder value enrichment. Hence, the asset manager needs to understand the goals of asset management that can support the broader organization's business goals.

2.5.2 Asset establishment

This phase involves procurement and deployment of assets based on the set plans and availability of funding. Under this stage, procurement of consultants, contractors, and actual purchasing of the asset based on the approved design, budget and guidelines is done using recommended procurement methods. Procurement facilitates ownership of the asset, for public institutions in Malawi, the process is guided by Public Procurement and Disposal of Public Assets (PPDPA) Act of 2017 and Public Procurement Regulations of 2020, the needs of the financier and other stakeholders, and generally the nature of the assets to be procured. Typically, the following procurement methods are used.

- International competitive bidding
- National competitive bidding
- Restricted tender
- Request for proposals
- Request for quotation method
- Single sourcing; and
- Single sourcing in an emergency

The deployment phase under asset establishment is the state where all the action takes place before the asset is finally used. In water supply, designs are confirmed and modified accordingly and typically, consultants ensure that contractors work according to the approved plan within the budget. Under this stage, the physical asset is assembled, installed, and tested to ensure it conforms to the design and compliant to available regulations and guidelines. The inspection is done to check for physical defects as well as design and engineering problems, whether the asset is installed correctly and safely or not. Also, tests are performed to confirm any emerging issues worthy noting for tracking purposes. It should be pointed out that asset creation and establishment phases are under what is traditionally called project management at Water Boards in Malawi. Project management is under infrastructure development departments where planning and execution of water infrastructure projects that bring water supply assets are done.

2.5.3 Asset utilisation

This stage involves operation and maintenance and is aimed at putting asset to good use for which it was planned. The initial stages of this phase for newly established assets are termed defects liability period. Under this stage, all problems that arise as a result of introducing this asset outside the approved performance levels are ironed out by the contractor including all agreed modifications. The utilisation phase is the longest stage in the AM life cycle. As pointed out in the literature review, this stage accounts for about 80% cost of owning the asset even though it is stated that the same percentage was already factored into the asset during asset creation and establishment through wrong designs, compromised procurement and errors during installations. The stage is characterised by revenues and returns earned on the investment. The performance of an asset is continuously checked for issues that might arise unexpectedly during its use. The primary focus during this stage is to get the most output from the asset. Some activities done under this stage are periodic monitoring and evaluation, modifications and upgrades, proactive and reactive maintenance, compliance and license management, and asset depreciation calculations. A well designed and established asset system must have provisions or systems put in place to capture sufficient, reliable and timely asset performance data that should be analysed and used for decision making. As pointed out by [72], asset data facilitates control of assets and therefore critical to successful AM, the quality of data is vital when it comes to effective operational, tactical, and strategic decisions and management of business risks. Modifications and upgrades are done to align the assets with the changing needs of the business but also to improve efficiency and effectiveness leading to improved quality of work and services. Maintenance is a necessary requirement under this stage that is aimed at addressing wear and tear which the asset is exposed to due to continuous use and fatigue. Maintenance prolongs life of an asset and sustains its productive life.

2.5.4 Asset disposal

This stage involves retiring assets from the system based on service deliverables and signifies the end of its useful productive life. Furthermore, it symbolizes the last phase of the public procurement process [97]. In financial terms, this involves elimination of the asset from the organisation's financial records. There are many reasons why assets are retired by different enterprises and these include the following: inadequacy for the activity; limit of its useful life; obsolete due to technological advances; and availability of alternative solutions that are more economical [98, 99]. Each enterprise has the duty to ensure that every anticipated asset replacement is well planned and the disposal decision is supported by the asset information and reviews, availability of new technologies or innovation, compliance with safety standards or any other mandatory standards, availability of spares to support operation and maintenance, and obsolescence that may limit the asset's use [98, 99]. In water supply systems, the asset disposal decisions may lead to rehabilitation, upgrading, extension, or indeed total introduction of water supply system which is the creating stage of an asset and hence a cycle is complete.

It should be pointed out that several calculation methods exist that support the decision to replace an asset. In these calculations, several variables are taken into account and include the following:

acquisition value, assignment value, operating costs, maintenance costs, running costs, inflation rate, and capitalization rate. As pointed out by [99], the values of most of these variables are obtained through historic valuation, with the exception of the assignment value. Therefore, it is important that periodic valuation of assets is done to facilitate calculations in order to make informed decisions on the assets. Furthermore, the market value for each specific piece of equipment is needed and this makes the exercise challenging. In response to this hurdle, several devaluation techniques provide an alternative and hence can be simulated, and include the following [98]: Linear method of depreciation - the aging of the value of the equipment is constant over the years; Sum-of-digits method - annual devaluation is non-linear; Exponential method - the annual depreciation charge decreases over the life of the equipment. Also, there is an additional method which involves using the "useful life", which defines that the life of an asset ends when its maintenance costs exceed the maintenance costs plus the capital amortization of equivalent new equipment. In this regard, there are several methods for determining the economic cycle of replacing equipment. The most common ones are the following: the Uniform Annual Income Method; the Total Average Cost Minimization Method; the Total Average Cost Minimization Method with Present Value Reduction [99].

The actual discarding activities involve demolition, recycling, relocation or selling. Before disposing of the asset, everything is checked, treated, and processed to ensure that it should not harm nature or society. For this, depending on the type, all the data must be wiped from the asset. It is then dismantled piece by piece, all the parts which can be used further are stored and those with no use are sent in scrap. If the asset consists of any part that can cause an environmental hazard, they are to be eliminated and disposed of as dictated by the applicable environmental laws of that geographical area. Typically, in utilities, most of the buried assets such as pipes are abandoned underground and it is good practice to ensure that all such assets are completely cut off from the system in operation to avoid water loss but also manage all other related risks.

Generally, the validation process revealed that the proposed framework guides the executive, managers, engineers, technicians, and operatives to improve AM. Those interviewed recognized the potential of the proposed framework, its structure, and the guidance it provides to improve asset utilisation which should result in sustained business performance once fully implemented especially across asset-intensive enterprises.

3. Conclusions and Future work

This study used literature analysis, a survey, and expert opinions to develop AM framework for WBs in Malawi. Literature analysis revealed that AM evolved to address the needs of the society in transportation, agriculture, banking, business processes and warfare. The practice is understood differently depending on how the assets support each business or process, hence multidisciplinary. The study has revealed that strategy and planning, risk management, life cycle delivery, asset information and review as core asset management practices widely reported in literature, are decimally applied in the study area. This is attributed to lack of awareness and policy to guide in planning and execution of AM practices. Local context, entrepreneurial attitude, globalization, and compliance/demand are the four thematic factors that emerge that influence AM practices in the study area. Regulation/legislation by government loaded highly on a dominant theme of compliance/demand and hence it should be prioritized. This emphasizes on the need to have policies and acts that compels institutions to implement AM practices in their respective enterprises. Technical, HR and organizational culture, strategic planning, and managerial are the four thematic critical success factors for AM in the study area. Availability of financial resources loaded highly on a dominant theme of strategic planning and budgeting and hence it should be prioritized.

The proposed framework was based on literature analysis, survey results, and experts' opinions. The novel input into the proposed framework are asset management drivers pertinent to the study area which should be incorporated into the strategic plan of the institution and the physical asset management success factors that should be considered along the entire asset's life cycle. Synonymous with other frameworks across the globe are risk and information management, people and technology which should be optimised for efficient, effective, and sustained asset management practices and hence must be placed at the centre of the framework. The framework validation was done by interviewing potential users of the proposed framework in the study area and then incorporating their feedback into the final framework. Generally, the potential users who were water supply professionals indicated that the proposed framework provides a pragmatic method for improving the management of water supply physical assets. The framework provides a simplified yet structured and objective presentation of physical asset practices that should enable Water Boards to address their asset management proactively. Given that the optimised physical asset management for an asset-intensive organisation is a proven and significant success factor for organisational performance, Water Boards that are generally asset-intensive are likely to benefit from the study, since no known framework to the knowledge of the researcher was available in the study area. The framework provides systematic guidance that establishes essential understanding and knowledge about relevant strategic physical assets. The application of this proposed framework in the study area would support both development and change to ensure sustained improved performance of the respective Water Boards in Malawi. Future studies need to consider analyzing how each stage of the physical asset in the framework affects the performance of WBs in Malawi, this would help to plan ahead but also utilize limited resources accordingly.

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SESSION 2B: Energy, Mining and Industry

Paper 6: Enhancing power asset reliability by application of stochastic and probabilistic techniques

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Abstract

Sustainable Development Goal 7 (SDG7) and Malawi Vision 2063 (MW2063) drive the agenda to increase access to energy and expand its infrastructure to accelerate economic growth. Energy infrastructure assets are capital-intensive and to operate sustainably, techniques for both predicting and eliminating failures must be deployed. These range from the well-known preventive, through condition-based to advanced ones that employ continuous Markov processes and artificial intelligence (AI). In recent years there has been a surge in application of AI in fault finding and providing early warning of power system components' deterioration. On the other hand, augmentation of Markov processes with inferential statistics are promising to offer very long-term predictive capabilities, but their penetration has been slower than expected and require large data that may be hard to obtain. This paper uses a multi-method approach, where numerical methods, parametric probabilities and inferential statistics augment Markovian models to predict levels of reliability of power network assets during their lifecycle, and to determine the optimal timing of life extension strategies based on 12MVA transformer and 500kV reactor failure data. Results show that the multi-method approach combines strengths of various methods, namely: the Least Squared Method and the Maximum Likelihood Estimation for large uncensored data sets and small censored data sets, respectively, to compute lifecycle modeling parameters which are then used for simulation and decision-making. The results can help managers of power grid assets to determine the best timing of lifecycle treatment options such as refurbishment and renewal; thereby extending and optimizing returns on the assets.

Keywords: Failure management, Lifecycle modelling, Markov models, Parametric probabilities, Reliability-enhancement

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1.0 Introduction

Sustainable economic growth of any country largely depends on development of its energy or power infrastructure. Sustainable Development Goal 7 (SDG7) drives the agenda for ensuring universal access to affordable, reliable and modern energy services; and for expanding its infrastructure. The Malawi Government has articulated its vision to turn Malawi into an inclusively wealthy and self-reliant industrialized upper middle-income country by the year 2063 in its Vision 2063, the Malawi 2063 (MW2063). In the MW2063, energy is identified as an enabler number 6 of Malawi's economic infrastructure (NPC, 2020, p. 39). In the advent of adverse climate change effects, most countries globally have moved to seek alternative energy supply options that can support industrialization in the wake of explosive population growth. However, absence of strategies for security of energy supply can render efforts for affordable energy supply ineffective. Power system reliability is a key facet of security of supply. Power infrastructure assets, for example, substation transformers, are among the most capital-intensive physical assets in industry hence the need for establishing measures for enhancing their reliability through optimal timing of lifecycle treatment options [2, pp. 1193-1195]; and their optimal operation and maintenance scheduling require an intricate trade-off analysis of costs, risk and performance while considering several deterioration mechanisms [3]. Increase of reliability raises costs and reduces failure risks and improves performance. Modelling of failure risk and/or hazard rate [2], optimization of lifecycle management strategies [3] and maximization of availability [4] require an assortment of mathematical models, multi-method, and/or multi-criteria approaches because of the complex nature of engineering systems and the varying conditions under which these systems exist and operate.

Multi-method and multi-criteria approaches are most applicable when there is a need to strike a balance between properties and performance metrics in product selection or between cost and benefit within asset planning problems to optimize decision making in complex processes [5].

Artificial Intelligence (AI) techniques have been very instrumental in locating faults and providing early failure warning, but their major flaw is the lack of field specialists to train machines, and their case-specificity. Attempts have been made to overcome this weakness through the application of reinforcement learning, deep learning, and their combination-deep reinforcement learning; but the complexity, data-intensive nature, and lack of interpretability of the later still pose a major challenge to their implementation in industry [6]

In recent years, multi-criteria and multi-method approaches have proved very useful in holistic management of physical assets; because there is no single method that can cater for all scenarios pertaining to planning of investment in electrical generation, transmission and distribution systems [7]. Neither is there a single method that can optimize the management of remaining life of existing machines that can be possibly envisioned, because some methods work well within certain thresholds and not so well in others [4].

This paper demonstrates how to leverage benefits of multi-method, and multi-criteria approaches to enhance system reliability management and to lengthen the life of physical assets, thereby maximizing returns on the assets. It applies a multi-method approach where a two-parameter Weibull failure model is combined with some statistical models to trend the failure risk and estimate the optimum timing of lifecycle treatment options such as refurbishment, renewal, retrofit and overhaul in critical power infrastructure assets.

2.0 Materials and Methods

2.1 Problem formulation

The electric power grid is a capital-intensive business venture. The grid normally has numerous machines which makes tracking and obtaining data for statistical analysis very hard; and when coupled with poor historical record keeping in firms, the problem gets exacerbated. Power grid machines are not only capital-intensive but also have long lifespan, which means there is a high probability that some of the equipment's historical data would get lost along the way. In this case, several scenarios arise which would call for a multi-method approach, namely: 1) where complete and adequate or non-censored data is available, making sample size fit for statistical analysis; 2) where incomplete (censored) data is available which could render it untenable to statistical inference, and 3) where there is a combination of cases 1 and 2. What renders the data to be censored could be failure to capture all of it due to loss of the same with passage of time or poor historical record keeping. For the scenario of large non-censored data sets the Least Squared Method (LSM) would yield accurate statistical parameters; whereas for censored data and small sample sizes the Maximum Likelihood Estimation (MLE) would produce accurate results for power infrastructure assets such as substation transformers [2, p. 1191].

This paper uses data from transmission transformers and electrical reactors to demonstrate the applicability of the multi-method approach in modelling life cycles of power grid equipment to aid in optimizing the timing of treatment options like major maintenance and refurbishment. MATLAB is used to generate life-distribution parameters from numerical methods and to simulate life patterns and failure trends. It focuses on the multi-method approach where probability distributions and Markov (stochastic) processes augment each other.

2.2 Mathematical formulation

The solution to modelling of the lifecycle of physical assets is a stepwise one involving the following:

1. Modelling the power grid as a system in state transition from being 100% reliable through various intermediate deterioration states until failure takes place; hence applying Markovian models to determine the states, estimate mean times to failure, and estimate costs.
2. Determining parameters that portray the lifecycle phases using statistical models.
3. Selecting appropriate methods for determining the parameters in (1) and application of numerical methods like Newton Raphson to compute the parameters. For censored data and small sample sizes, MLE should be used; and for non-censored data involving large sample sizes, the LSM should be applied.
4. Fitting the parameters in (2) into mathematical models to assess the remaining life and the associated risks, and to predict failure trends.

2.2.1 Modelling of a power system

A power system can be modelled as system in transition from operating states to failed states using discrete or continuous Markovian methods where failure and repair rate data is used to define deterioration and restoration processes, respectively. Consider, for example, the system presented in Figure 1; where, λ_1 and λ_2 are failure rates 1 and 2, respectively; whereas μ_1 and μ_2 are repair rates 1 and 2, respectively; notation i stands for the initial state, and j the final state, also known as the absorbing state; and k_1, k_2, represent intermediate states, respectively.

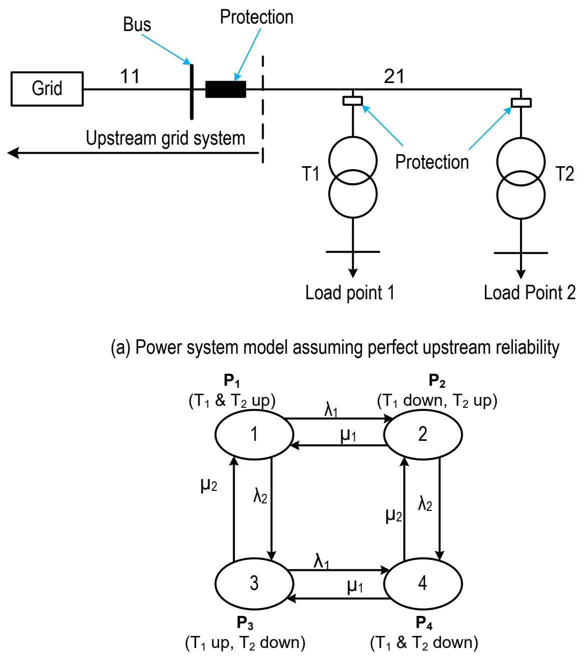
A Markovian process assumes conditional probabilities of events, where the transition from i to j can be generalized by [8]

$$p_{i,j}(x) = P(Z(t+x)) = j \mid z(t) = i ; 0 \le p_{ij} \le 1 \qquad (1)$$

$$p_{i,j}(t+x) = \sum p_{ik}(t) p_{kj}(x) \qquad (2)$$

$$\sum_j p_{ij}(x) \le 1, \text{ for all } i \text{ and } j. \qquad (3)$$

where t = time, x = incremental time and notations i, j, k_1 and k_2 are as defined in Figure 1.



(a) Power system model assuming perfect upstream reliability

(b) State-space transitions

Figure 15: Power system model

From Figure 1(b), a state transitional probability matrix is obtained as in equation 4 and the state probabilities as in equations 5 to 7.

$$P = \begin{array}{c|cccc} & P_1 & P_2 & P_3 & P_4 \\ \hline P_1 & 1-\lambda_{1\to k1}\Delta t-\lambda_{2\to k2}\Delta t & \lambda_{1\to k1}\Delta t & \lambda_{2\to k2}\Delta t & 0 \\ P_2 & \mu_{1\to i}\Delta t & 1-\lambda_{2\to j}\Delta t-\mu_{1\to i}\Delta t & 0 & \lambda_{2\to j}\Delta t \\ P_3 & \mu_{2\to i}\Delta t & 0 & 1-\lambda_{1\to j}\Delta t-\mu_{2\to ki}\Delta t & \lambda_{1\to j}\Delta t \\ P_4 & 0 & \mu_{2\to k1}\Delta t & \mu_{1\to k2}\Delta t & 1-\mu_{1\to k2}\Delta t-\mu_{2\to k1}\Delta t \end{array} \qquad (4)$$

$$P^{(n)} = P(0)P^n \qquad (5)$$

$$\lim_{n \to \infty} P^{(n)} = \alpha \qquad (6)$$

$$\alpha P = \alpha \qquad (7)$$

Where $P^{(n)}$ is the probability of being in each state after n time steps, $P(0)$ is the initial state vector, and α is the limiting probability vector, *[P_1 P_2 P_3 P_4]*

For a transient set of states S_k with matrix H obtained by truncating P, the mean number of times the process is in S_j before absorption, if it started in S_i, yields the *MTTFF* as [9]:

$$MTTFF = S\left(N_{ij}\right) = n_{ij} \le \left| S \in S_k \right. \qquad (8)$$

$$N = (I - H)^{-1} \qquad (9)$$

where n_{ij} are the elements of N and I = identity matrix.

Alternatively, the MTTFF is given by [7]:

$$MTTFF = e^{-\eta t^{\beta}} dt = \frac{\Gamma\left(1+\frac{1}{\beta}\right)}{\eta^{1/\beta}} \qquad (10)$$

Where β = shape parameter and η = scale parameter of a Weibull distribution, t = operating time, and Γ is a gamma function.

The expected failure cost per year can be presented in terms of the MTTFF as [9]:

$$C_F = \frac{F_C}{T_R + MTTFF} \qquad (11)$$

where C_F is the expected failure cost per year, F_C is the failure cost, and T_R is the repair time.

In a study to evaluate effects of aging failure in power system reliability, [10, pp. 236-242] presented a classical method for incorporating aging failures in power system reliability evaluation. His viewpoint is that the aging failures are usually ignored in the evaluation of an aged system, and in so doing, reliability indexes are greatly underestimated. This in turn most probably leads to misguided conclusions in system planning. He further alludes that "the traditional probability theory has provided a method of calculating reliability to an aging failure in a given time period, however, the probability is transitional and does not have a consistent concept such as unavailability which is applicable to repairable failures". The study is limited to incorporation of aging failures in reliability modelling using Normal and Weibull distribution models for unavailable failures, and to implementation in reliability evaluation. It applies probabilistic models and contributes significantly to the enhancement of traditional reliability evaluation models which generally exclude aging; yet has a significant impact on the system reliability, especially for an aged system. Li [10] advances that to avoid underestimation of system risk and the most definite misleading conclusion in system planning, aging failures should be included in reliability evaluation.

This study models ageing failures with a two-parameter Weibull Distribution, which incorporates the shape and scale parameters, assuming that there is no failure free life. The two-parameter Weibull Distribution is widely used for analyzing most lifetime data [11]. It is a good mathematical model for determining deterioration trends and risks associated with components because it incorporates parameters that can distinguish various phases of the lifecycle of electric power system components [3].

The problem then can be expressed parametrically using the Weibull Probability Density Function (PDF) and Cumulative Density Function (CDF) as [2, 3]:

$$PDF = f(t;\beta,\eta) = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} \exp^{-\left(\frac{t}{\eta}\right)^{\beta}}, \quad t > 0 \quad (12)$$

$$CDF = F(t) = \int_0^t f(t;\beta,\eta)\,dt = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \quad (13)$$

where β = shape parameter, η = scale parameter, t = random variable; and $F(t) = 1 - R(t)$; $R(t)$ = reliability function.

The likelihood function of a Weibull distribution is given as [11, p. 271]:

$$L(t_1,\ldots,t_n,\beta,\eta) = \prod_{i=1}^{n} \frac{\beta}{\eta}\left(\frac{t_i}{\eta}\right)^{\beta-1} \cdot \exp\left[-\left(\frac{t_i}{\eta}\right)^{\beta}\right] \quad (14)$$

The risk of failure can be expressed by the hazard rate $h(t)$ which represents the probability that an item that has survived up to time, *t,* will fail after that time.

$$h(t) = \frac{f(t;\beta,\eta)}{R(t)} = \frac{f(t;\beta,\eta)}{1-F(t)} = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \quad (15)$$

The β is associated with aging. As the component age increases so does the β [13].

2.2.2 Modelling data

Two sets of failure data are used for simulation and modelling, namely: for 12 MVA substation transformers in Tables 1 and 2 [2, p. 1192]; and for 500 kV reactors in Table 3 [10]. From Section 1.0, considering that the sample size is small, and the data is censored, the MLE was used to compute Weibull parameters by taking a natural logarithm of the Weibull likelihood function, equation 14, and partially differentiating it with respect to η and β.

Table 6: Failure data for twelve retired 12 MVA transformers

Times to failure for 12 MVA transformers, t (x10^5) [hrs.]					
1.892	1.971	1.971	2.182	2.31	2.418
2.365	3.715	3.925	4.03	4.188	4.366

Table 1 presents raw data from which the Weibull parameters in Table 2 are derived.

Table 7: Weibull parameters for retired 12MVA transformers, derived from Table 1

Parameter	**Value**	**2.5% confidence Interval**	**97.5% confidence interval**
β	3.430	2.190	5.390
η (x10^5)[hrs.]	3.290	2.760	3.920
η [yrs.]	37.557	31.507	44.749

Table 3 presents parameters computed by [10].

Table 8: Data for twenty retired 500kVA reactors

Description	**Parameter value**
Mean life	29.723 yrs.
Standard deviation	3.909 yrs.
Shape parameter, β	9.407
Scale parameter, η	31.361 yrs.

In the next section, data in Tables 1 to 3 is applied to model the lifecycle of power system equipment for decision making.

3.0 Results and Discussion

Markov limiting states arising from equations 4 to 7 for λ_{T1}= 0.017123, λ_{T2} =0.01146, μ_{T1} =0.068493, and μ_{T2} =0.08333 [13, p. 476] are presented in Figure 2.

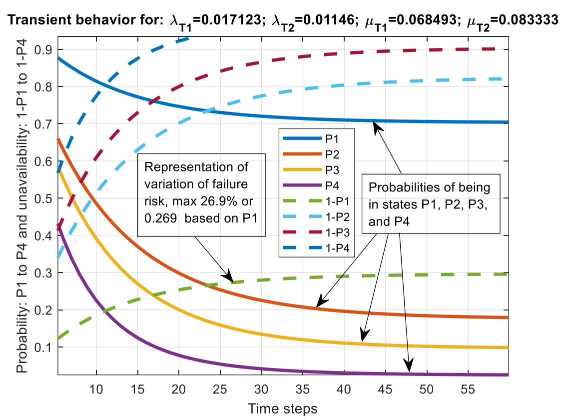


Figure 16: Markovian limiting state probabilities for transformers T_1 and T_2 in the power grid model of Figure 1.

Where P_1, P_2, P_3, and P_4 in Figure 2 are obtained by making *Δt* in equation 14 implicit and applying Laplace Transformation to it as follows:

$$P_1 = \frac{\mu_{T1}\,\mu_{T2}}{(\lambda_{T1} + \mu_{T1})(\lambda_{T2} + \mu_{T2})} \quad (16)$$

$$P_2 = \frac{\lambda_{T1}\,\mu_{T2}}{(\lambda_{T1} + \mu_{T1})(\lambda_{T2} + \mu_{T2})} \quad (17)$$

$$P_3 = \frac{\mu_{T1}\lambda_{T2}}{(\lambda_{T1} + \mu_{T1})(\lambda_{T2} + \mu_{T2})} \quad (18)$$

$$P_4 = \frac{\lambda_{T1}\lambda_{T2}}{(\lambda_{T1} + \mu_{T1})(\lambda_{T2} + \mu_{T2})} \quad (19)$$

Results from the analysis of Markov process also show that the failure risk or the complement of P_1 (i.e., $1-P_1$) in the limit as the age of the transformers tends to their retirement or disposal is 26.9% or 0.269.

By applying cost data provided in [13], Figure 3 is generated, showing the relationship between transformer maintenance costs and the MTTFF.

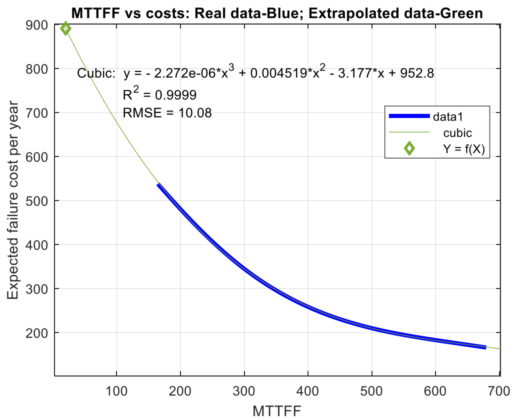


Figure 17: MTTFF and cost model for actual (blue) vs. extrapolated (green) data

Results in Figure 3 show that the relationship between MTTFF and costs is governed by the following equation at a R^2 value of 0.9999:

$$y = -2.272 \times 10^{-6} x^3 + 0.004519\, x^2 - 3.177\, x + 952.8 \quad (20)$$

Where x is the MTTFF.

The R^2 value shows that the model predicts the relationship between the MTTFF and costs very accurately. Therefore, the regression model, equation 20, can be used to accurately predict maintenance costs of power transformers on the grid when the value of the MTTFF is known.

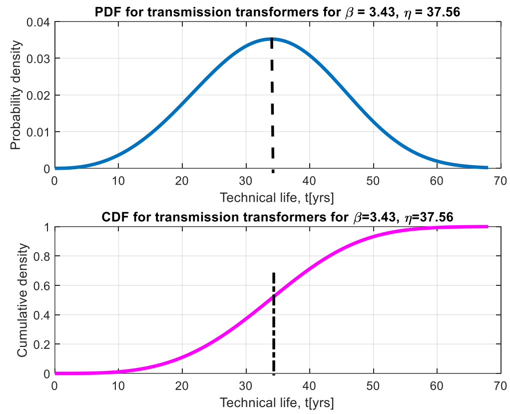


Figure 18:PDF and CDF for 12 MVA transmission transformers

Equation 20 is referred to as the regression model relating maintenance costs to the MTTFF.

Figure 4 shows that, based on the computed parameters β and η, the lifecycle patterns of components can be modelled. For the 12 MVA transmission transformers on which the Figure is based, their mid-life is 34 years and their lifespan is estimated to be 68 years and the life distribution is fairly normal. From the CDF, they portray a failure free life of approximately 5 years, i.e., when the CDF=0. Furthermore, Figure 4 shows that for power transformers with a lifespan of 68 years, lifecycle treatment options like refurbishment, renewal and retrofit should be implemented after mid-life.

On the other hand, Figure 5 indicates that for reactors which have a lifespan of 40 years, the treatment options should not start at mid-life (i.e., 20 years) but at around 31 years which is at 77.5% of their lifespan.

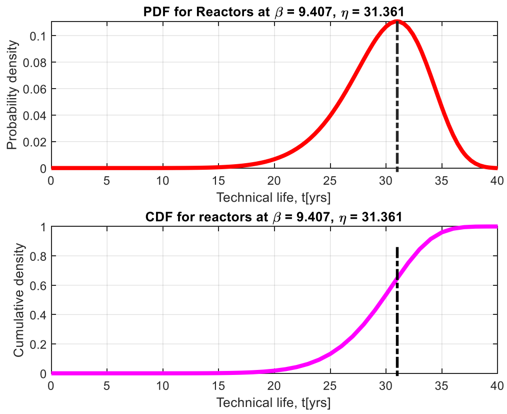


Figure 19: PDF and CDF for 500 kV reactors

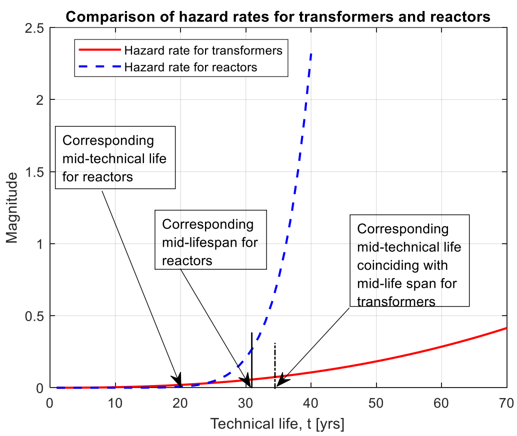


Figure 20: Comparison of hazard rates-transformers vs reactors

Additionally, the life distribution for reactors, Figure 5, is a flipped log-normal skewed to the left. From the CDF and hazard rates, they have a failure free life of about 15 years.

Figure 6 presents hazard rates, based on equation 15, for the transformers and reactors, illustrating that the two types of machines have unique characteristics; hence the need to apply life cycle management strategies differently. This observation is very important as the appropriate timing of these treatment options can save costs and enable firms to maximize profits. Figure 7 further shows the major differences in deterioration mechanisms by comparing the hazard rates to PDFs and CDFs.

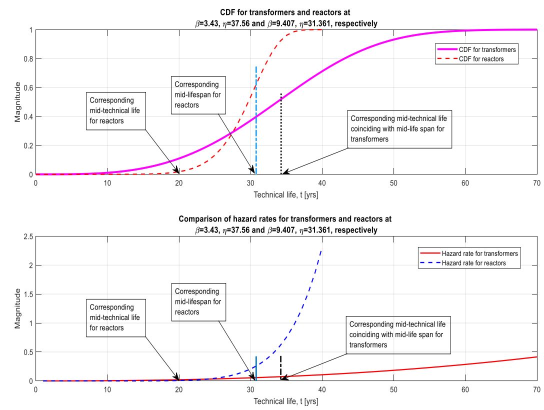


Figure 21: Comparison of PDFs, CDFs and hazard rates

Energy, as an economic infrastructure enabler in the MW2063, cost-savings realized can be reinvested in reliability improvement drives, and subsequently aid in the attainment of the SDG7. The appropriate timing will also improve operation and maintenance efficiency.

By using the MLE, it was possible to obtain statistical inferences with very few data sets.

Figure 8 summarizes the multi-method approach used in the study. The figure shows that there is a need to review the data and methods to improve the accuracy of results. On the bottom right-hand side of the figure, the loop between the lifetime parameters, and the evaluated PDFs and hazard rate boxes signifies that multiple sensitivity analyses should be conducted at that stage to weigh the impacts of various options.

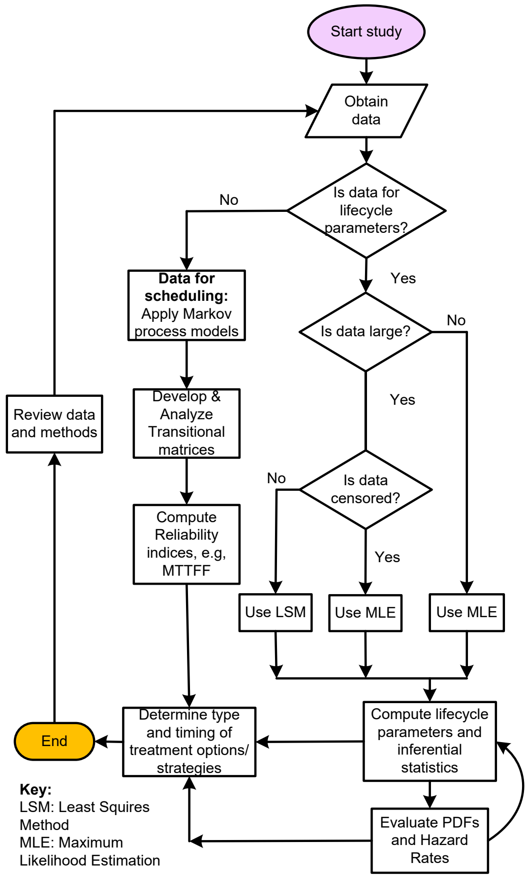


Figure 22: Summary of the multi-method approach

4.0 Conclusion and Recommendations

The study has revealed that there is a tendency in industry to carry out refurbishment, major overhauls and retrofits in the middle of the technical life which in most cases is assumed to be the same as the mid-life. Results have shown that the middle of technical life may not always be the same as the mid-life. For example, in the case of the 500kV reactors, the mid-technical life is 20 years; whereas the mid-life is 31 years, and their retirement is at 40 years. For the 12 MVA transformers, the mid-life is the same as the mid-technical life because the plot of failure data is a Normal Distribution. Therefore, it is advanced that the determinant of the optimal or appropriate timing of end-of-life treatment measures should be the failure patterns that the assets portray when their PDFs, CDFs and hazard rates have been generated. Furthermore, the study shows that the Markov process can model state transitional probabilities from the uptime to the downtime or absorption state. The study has demonstrated that by applying a multi-method approach in formulating and solving problems in the power infrastructure, a set of methods can be tailored to specific hierarchical levels or stages of the problem to exploit the strengths of those methods; because there is no single method that can solve all power grid reliability enhancement problems optimally. Furthermore, the optimal timing of strategies that extend the lifecycle, for example, refurbishment, should be based on evidence from data analysis as opposed to the traditional way of assuming that the mid-technical life is equal to the mid-life of equipment, because various types of equipment have different deterioration mechanisms. Plots of hazard rates and PDFs are the best way of revealing deterioration mechanisms, the criticality for executing major overhauls, refurbishments, and retrofits. A regression model for relating transformer maintenance costs to the MTTFF has been determined. Optimized timing of life cycle management strategies can improve reliability and enhance cost effectiveness, which in turn can save money for reinvested in energy infrastructure expansion. Energy, being a constituent of the economic infrastructure in the MW2064, must be reliable; and this study has addressed that through the multi-method technique that has been advanced. The results can be used by industry practitioners and academicians in formulating and deploying lifecycle management strategies. Future work should attempt to use data from live machines as opposed to failed ones.

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Paper 7: Household Socio-economic Status and Prospects of Biomethane Cooking Fuel Adoption at Lizulu Market in Ntcheu, Malawi.

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Abstract

The study was conducted at Lizulu Market to investigate socio-economic barriers that can potentially affect the adoption of biomethane for cooking. The study adopted a household survey design, where a pre-set questionnaire was administered among the members representing their households. Data collection was done using the KoboCollect mobile application, and a random sampling technique was used to identify the households. The Cochran's formula was used to calculate the sample size (i.e., 385). The study findings showed that with the low education level (only 2% attaining tertiary education), most of the households are dependent on petty trading (37%), casual labor (22%), and farming (22%). Such income-generating activities bring households about $67.00 per month on average. The majority of households (i.e., 99%) depend on biomass as their first cooking fuel option. Regardless of whether unprocessed biomass is considered dirty fuel, 90% of households considered it reliable, which could be attributed to a lack of awareness. For instance, it was observed that 62% of the households are not aware of biomethane, 79% of them have never used biomethane, and 94% of households were interested in learning more about biomethane. After educating the respondents about biomethane, 99% of the households showed willingness to transition to biomethane fuel, which costs 0.30 USD/m3, enough for one day for a household size of 4.5. Therefore, the study indicates that households, regardless of their poor socio-economic status, are willing to try biomethane, and what is needed is increased awareness and enhancing the availability of the fuel at Lizulu Market.

Keywords: Energy choice, awareness, income, biogas, biomass.

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1. Introduction

Lizulu is a rural area that is in Ntcheu District of Malawi, where most of the people are involved in agricultural activities as their main source of livelihood (Eales, 2018; GoM, 2009; World Bank, 2019; Deloitte, 2017; Innovate UK & UKAID, 2020). This is a common characteristic of rural areas in Malawi, where 80% of the people live (MoNREM, 2018; Deloitte, 2017; Innovate UK & UKAID, 2020). Lizulu, as one of the rural areas in Malawi, is faced with the challenge of access to electricity (Coley et al., 2020; Eales, 2018; Kachaje et al., 2017; MoNREM, 2018). In general, it is estimated that access to electricity in rural areas is less than 4% (World Bank, 2019; Taulo et al., 2015; Deloitte, 2017). Therefore, most of the households are not connected to the grid. The Government of Malawi (GoM), through the National Energy Policy and the Sustainable Energy for All (SE4ALL) National Action Agenda, seeks to achieve universal access to modern, affordable sustainable energy by the year 2030 (Eales, 2018; MoNREM, 2018; GoM, 2009; Taulo et al., 2015; Deloitte, 2017; Innovate UK & UKAID, 2020). However, with only seven years remaining, it is impractical for the country to achieve this ambitious goal by 2030.

Due to a lack of alternative sources of energy, many people in rural areas are forced to rely on dirty and unsustainable fuels, such as, fuelwood, charcoal, and agricultural waste (Eales, 2018; GoM, 2009; MoE, 2023; GoM, 2009; MoNREM, 2018; Deloitte, 2017; Tetra Tech, 2020). It is estimated that 9.2 metric tons and 1.7 metric tons of fuelwood and charcoal, respectively, are consumed annually (MoE, 2023; Deloitte, 2017). The charcoal and fuelwood supply chain also employs many people who are involved in different activities, such as, transportation and retailing (GoM, 2009). The unsustainable use of fuelwood and charcoal is blamed for contributing to deforestation and land degradation (Tetra Tech, 2020). In addition, due to high rates of deforestation, fuelwood and charcoal have become less affordable (Kambewa & Chiwaula, 2010; GoM, 2009; Tetra Tech, 2020). Recently, the government of Malawi, through the Malawi Energy Regulatory Authority (MERA), has been promoting the use of Liquefied Petroleum Gas (LPG) to improve access to clean cooking energy. However, this imported LPG is proven not to be affordable in the country (MoE, 2023; GoM, 2009; MoNREM, 2018). The costs of the imported LPG cylinders are very high, thus creating a major obstacle to the adoption of LPG as cooking fuel (Eales, 2018; GoM, 2009). It is observed that an increase in LPG consumption in North Africa and Kenya is a result of long-term government support and subsidies (Tetra Tech, 2020). Therefore, the options for cooking energy are limited, especially for rural areas without government support, and as a result, many households are turning to cheaper yet dirty cooking and heating fuels.

Biogas is emerging as a viable option for addressing cooking energy poverty in urban as well as rural areas. Biogas is a clean fuel generated through a process called Anaerobic Digestion. The fuel can be produced from any biodegradable material. For markets that produces huge amounts of vegetable waste, such as, Lizulu Market in Ntcheu District, it becomes a natural choice to adopt the technology as it helps to solve multiple challenges including energy and waste management challenges. Responding to the community these, the Malawi University of Science and Technology (MUST) in partnership with the Green Impact Technology (GIT) with funding support from the United Nations Development Programme and Environmental Affairs Department (EAD) developed the Lizulu Commercial Biogas Plant. The plant is 40m3 in size producing 14m3 of biogas per day. The plant uses vegetable waste (i.e., potato peels, cabbages and tomato waste) restaurants food waste and cattle manure generated from the market animal slaughterhouse as feedstock. The biogas produced is supplied to households and restaurants at Lizulu Market. The biogas generated is not purified nor bottled. Therefore, 1m3 biogas backpacks are used to transport the biomethane to the end users.

As biogas starts its operations, it is vital to understand the socio-economic bottlenecks to the adoption of commercial biomethane. It should be noted that the socio-economic status of rural households plays a critical role in accessing clean and modern energy services (Coley et al., 2020; GoM, 2009; Practical Action Consulting, 2017). In Malawi, poverty levels remain very high, regardless of some improvements. Most of the people in rural areas are dependent on agriculture as their main source of livelihood. However, climate change and rising costs of inorganic fertilisers negatively affect agriculture, and as a result, many are experiencing food insecurity (GoM, 2009; World Bank, 2019). Therefore, to reduce expenditure, most households are forced to rely on any cooking fuel that can be sourced for free (Practical Action Consulting, 2017; Tetra Tech, 2020). The other important thing to be considered in relation to cooking energy options is the awareness (Coley et al., 2020). Some people, especially in rural areas, may lack knowledge regarding the available clean cooking technologies (MoNREM, 2018). Findings from different studies show that indoor emissions cause respiratory diseases among women and children (MoNREM, 2018; GoM, 2009; Practical Action Consulting, 2017; Deloitte, 2017). This has become the basis for promoting clean cooking energy, where stakeholders are arguing households to transition to LPG, biogas, and other clean fuels (Innovate UK & UKAID, 2020).

2. Materials and Methods

2.1 Study Area.

This study was done in areas surrounding Lizulu Market in Ntcheu District of Malawi. The geographical coordinates of Lizulu are 14° 31' 0" south and 34° 28' 0" east. This is an area where most of the people are dependent on agriculture as their main source of income. The area was chosen because has the potential for economic growth, considering that the market presents many business opportunities to both Malawians and Mozambicans. The economic transformation of the area may contribute to changes in lifestyle, where, among others, the need for modern cooking energy services may rise. Therefore, sustainable energy supply becomes an important area for consideration by local authorities and other key stakeholders.

2.2 Sample Size.

The researcher used Cochran's formula for calculating sample size, which is suitable when the population considered is deemed to be infinite.

$$n_0 = \frac{z^2 \times pq}{e^2}$$

Where n_0 is the sample size, z is the selected critical value of the desired confidence level, p is an estimated proportion of an attribute that is available in the population, *q* is equal to *1-p* and e is the desired level of precision. Therefore, using the formula a sample size of 385 was calculated.

2.3 Sampling Method

The study used the random sampling method, which allows every member of the population to have an equal and independent probability of being chosen using this method. The design of the experiment enables the researcher to select components from the population by creating member numbers at random (Nanjundeswaraswamy & Divakar, 2021).

2.4 Data Collection Methods and Analysis.

A household survey method was adopted, where a pre-set questionnaire was administered among the members representing their households. The questionnaire required the respondents to provide information regarding household demographics, socio-economics, cooking energy options, and the reliability of the cooking energy sources used. A random sampling technique was used when identifying the households, and in total, 385 households were sampled for this study. The data was analyzed using the statistical package Excel, which enables users to manipulate, analyze, and visualize large amounts of data very quickly and with ease.

3. Results and Discussion

Discussion section consists of three parts: addressing the hypothesis, problems and limitations. The purpose is to highlight the major findings from the results section and interpret them.

3.1 Education Level of the Household Heads.

The study findings showed that the family heads who attained primary education, secondary school education, vacation diplomas, and university diplomas/degrees accounted for 56%, 31%, 1%, and 1%, respectively. In addition, 10% of the respondents have never been in school, and 1% of the respondents attended adult literacy education. The education level statistics of Lizulu also help to understand that many people are not dependent on formal employment, which demands someone to have the required education qualifications. Malawi's weak economy generates few jobs for the growing population, where many young people compete for the few opportunities available. Therefore, it can easily be predicted that many people in Lizulu have limited sources of livelihood. Economic opportunities are limited, and eventually, this will affect their income generation and cooking energy choices. Figure 1 shows the education status of the respondents in Lizulu.

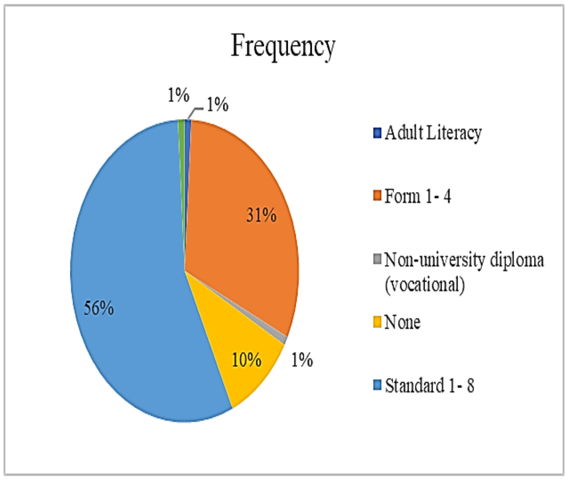

Figure 23: Education Level of Respondents in Lizulu.

3.2 Household Sources of Livelihoods at Lizulu Market.

Petty trading, casual labour, and farming at 37%, 22%, and 22%, respectively, remain the major sources of livelihoods in Lizulu. The area is known for agriculture and has a market that is located along the major road (i.e., M1 Road) that connects two major cities in Malawi, Lilongwe and Blantyre. The market is known for trading fresh vegetables, such as, tomatoes, Irish potatoes, sweet potatoes, and cabbage. Therefore, farming, trading vegetables and other crops, and casual labour, such as, transporting goods for traders, remain the major sources of income generation for most households. The concern for most people is to generate adequate income that can support their families in terms of accommodation, food, clothing, and energy, regardless of the type of economic activity in which they are involved. Figure 2 shows the household sources of income in Lizulu.

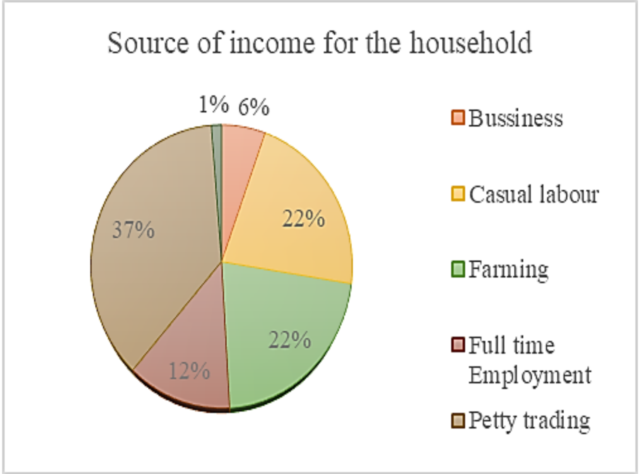

Figure 24: : Source of Income for the Households in Lizulu, Ntcheu District.

3.3 Households Income Generation at Lizulu Market.

The income of the household is one of the important factors that can affect cooking energy options. Usually, households will settle for a cooking energy source that is available for free or at an affordable price (Practical Action Consulting, 2017). It is for this reason that Sustainable Development Goal Seven (SDG 7), Sustainable Energy for All (SE4ALL), and the 2018 National Energy Policy focus on energy affordability as a means for improving energy access. Simply put, this means energy accessibility is incomplete without consideration for affordability. Households in Lizulu, too, are expected to settle for cooking energy options that they can afford. In this study, the average income per month for the 320 households that were sampled was determined to be 67.00 USD (i.e., equivalent to 70,098 Malawi Kwacha). Lizulu is mostly rural, where the cost of living is expected to be lower when compared to urban settings. However, rising costs of farm inputs, such as, fertilizer, contribute to food insecurity in Malawi. Eventually, a high inflation rate affects both urban and rural areas. An average income of 67.00 USD per month for households with an average occupancy of 4.6 people in Lizulu is not adequate to support basic needs, such as, housing, food, water, and energy. Therefore, households are expected to have limited cooking energy options. For instance, a user who seeks to transition to LPG for cooking in Malawi initially is supposed to spend about 60 USD, which is almost equal to what households earn per month in Lizulu. In this case, regardless of increased awareness about the advantages of cooking with LPG, it will be difficult for most households to transition to such a clean cooking fuel (Coley et al., 2020; GoM, 2009; Tetra Tech, 2020). Table 4 shows the monthly incomes of the households in Lizulu.

Table 9: Households Income.

Average Income/month				
Variable	n	Mean	Min	Max
Income (USD)	320	67.00	4.78	1,145.40

3.4 Current Household Cooking Fuel Choices at Lizulu Market.

To identify the cooking energy choices of households, the study pre-identified the cooking energy sources mostly used in Lizulu. The identified cooking energy sources were charcoal, electricity, firewood, and maize cobs. Each respondent (i.e., member of the household) was requested to identify the first, second, third, and fourth cooking energy options for the household. The study findings show that charcoal remains the most preferred cooking energy option for 75% of the sampled households in Lizulu. Firewood was determined to be a cooking fuel that is regarded as the first option for 24% of households. Therefore, biomass in the form of fuelwood and charcoal is regarded as the first cooking option for 99% of the households in Lizulu, which is in line with the findings of many similar studies (Coley et al., 2020; Eales, 2018; Kambewa & Chiwaula, 2010). However, charcoal is easier to transport, store, and use when compared with firewood. Only 1% of households' regard electricity as the first cooking energy option. In rural areas, access to electricity is low, estimated to be at only 4% (World Bank, 2019). Therefore, it remains inaccessible to most rural households, including in Lizulu (Coley et al., 2020). Findings from many studies have also shown that the use of electricity for cooking is very low in rural as well as urban areas in Malawi (GoM, 2009). This low usage can be attributed to both inaccessibility and unaffordability for most low-income households (Coley et al., 2020; Kachaje et al., 2017; Practical Action Consulting, 2017). On the other hand, the use of maize cobs for cooking is regarded as the last option for all the sampled households. Figure 3 shows household cooking fuel choices in Lizulu, Ntcheu District, Malawi.

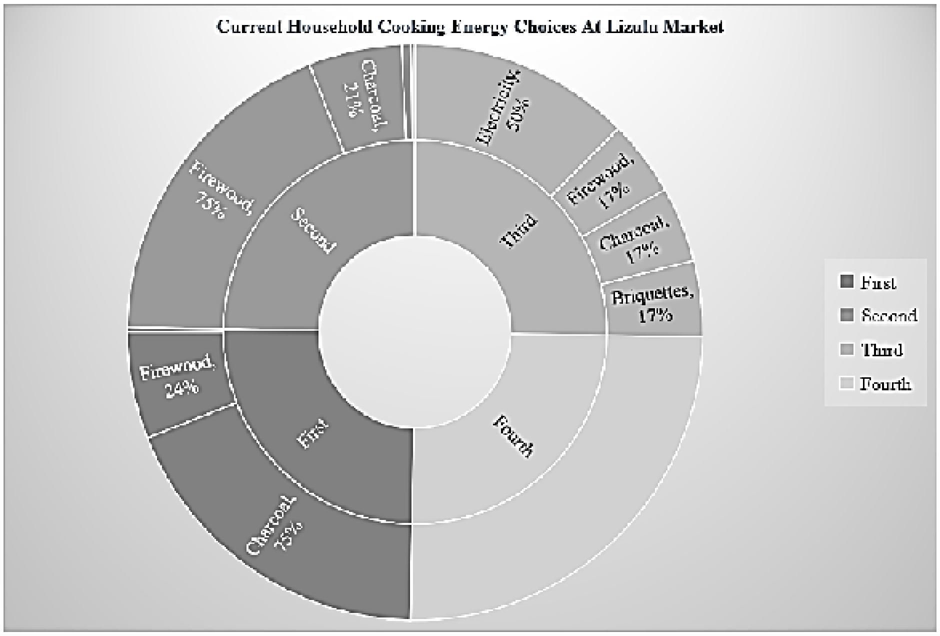

Figure 25: Households Cooking Fuel Choices.

3.5 Households' Satisfaction Regarding the Cooking Energy Currently Being Used.

Reliability refers to cooking fuel availability at all times and the ease with which it can be used for cooking. It should be noted here that charcoal and firewood cooking fuels are regarded as the first cooking energy options for 99% of households. Therefore, it can be concluded that household responses address the reliability of charcoal and firewood cooking fuels. The study findings showed that 52% of households thought the cooking fuels that they currently use were the most reliable. About 25% and 13% of the households respond that the cooking fuels are moderately reliable and partially reliable, respectively. On the other hand, only 10% of them responded that the cooking fuels they use are not reliable. The high level of household satisfaction with the cooking fuels currently being used (i.e., mainly fuelwood and charcoal) can be attributed to many local factors. For example, regardless of high rates of deforestation (Taulo et al., 2015), a few existing forests continue to supply the much-needed fuelwood and charcoal supply. Therefore, these biomass-based cooking fuels (i.e., charcoal and fuelwood) are easily accessible in rural areas when compared with electricity and other alternative cooking fuels, such as, LPG and briquettes (Coley et al., 2020; GoM, 2009). In addition, households may not have been exposed to alternative cooking fuels that are cleaner and easier to use use (GoM, 2009; Practical Action Consulting, 2017). Therefore, they were unable to compare the performance of the dirty fuels with modern cooking fuels. However, transitioning to modern energy services is inevitable at a time when fuelwood supply is declining due to deforestation (Coley et al., 2020; Eales, 2018; Kambewa & Chiwaula, 2010; GoM, 2009; Tetra Tech, 2020). Figure 3 shows the reliability of the cooking fuels mostly used by the households at Lizulu (i.e., charcoal and fuelwood account for 99% of the cooking fuels used).

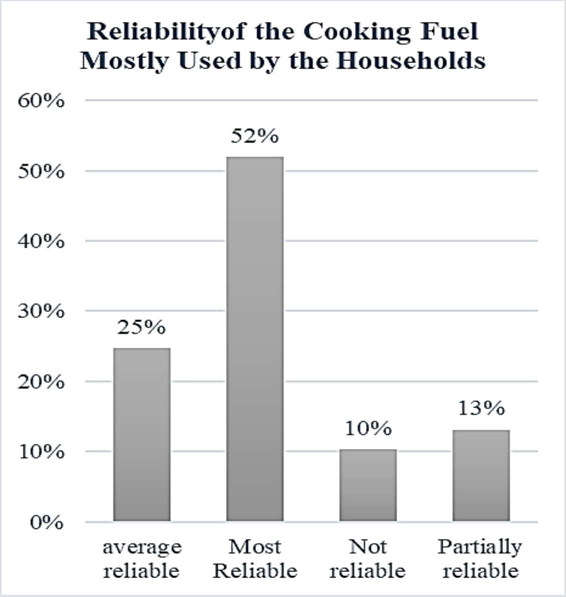

Figure 26: Cooking Fuel Reliability.

3.6 Households Biomethane Awareness and Willingness to Use.

Of the 385 households interviewed, the study findings showed that only 62% of them were aware of biomethane at Lizulu Market, 79% of them have never ever used biomethane for cooking, 99% of the households are interested in using biomethane for cooking, and 94% of them are interested in learning more about biomethane. These statistics show that a lack of awareness regarding alternative cooking energy options, such as, biogas, has the potential to affect their adoption. Therefore, project implementers and other stakeholders must consider putting much effort into education and raising awareness in the communities. Regardless of the socio-economic status of the communities, it is vital that awareness programs be designed in such a way that households are able to get the message so that they are able to compare different cooking energy options available in their communities.

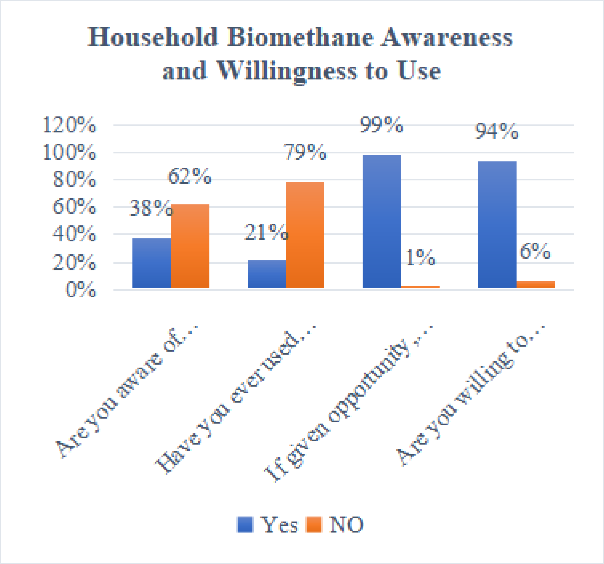

Figure 27: Biomethane Awareness and Willingness to use.

3.7 Reasons for the Household Transitioning to Biomethane.

The study findings also showed that households had other reasons for transitioning to biomethane apart from socio-economic issues. For instance, the majority of the households (i.e., 49%) wanted just to try the new cooking technology, whereas 31% of them cited their economic status, which can allow them to buy biomethane for cooking. Note that the price for biomethane was 0.48 USD/m3. This amount of biomethane is enough to last 2 days for a household (i.e., the household size on average is 4.6 at Lizulu), based on the study findings for Lizulu Biogas Plants. The others cited technological and environmental benefits associated with the use of biomethane for cooking.

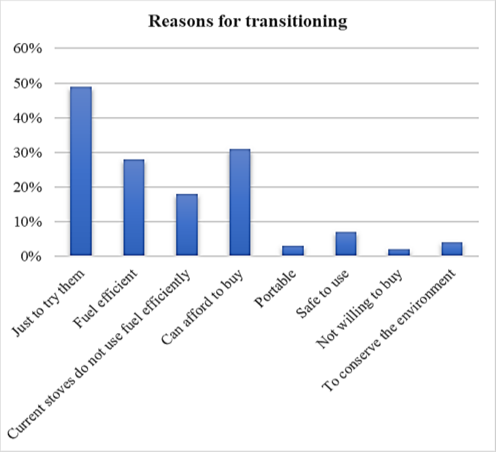

Figure 28: Reasons for Households Transitioning to Biomethane at Lizulu Market.

4. Conclusions and Future Work

This study was undertaken to investigate the socio-economic status of the households at Lizulu Market and the potential for the adoption of biomethane cooking fuel. Quantitative data was collected through a household survey. Findings showed that most of the people at Lizulu are involved in agriculture, petty trading, and casual labor. Low levels of education and limited employment opportunities contribute to high unemployment levels in the area. Therefore, households are characterized by low income, which may influence their energy choices. In addition, the area may not be attractive energy investment because of a weak market. Therefore, households have limited cooking energy options. Currently, clean and modern cooking energy options, such as, LPG and electricity, are less affordable for households, apart from being inaccessible. Dirty fuels, such as, firewood and agricultural waste cost less or almost nothing; therefore, they are widely used by households. High levels of satisfaction with the use of fuelwood and charcoal (solid or dirty fuels) for cooking were observed during the study, which could be attributed to a lack of knowledge and the inaccessibility of modern cooking energy options that are clean, efficient, and easy to use. Increased awareness and investment in modern cooking energy technologies can help increase their uptake.

Acknowledgments

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Paper 8: Optimizing Factory Performance

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Abstract

The industry in Malawi today is striving to minimize costs in all aspects of operations. Maintenance managers are often asked to drive costs down while maintaining maximum productivity. However, whilst doing this, standards should not be compromised, and regulations should be followed. With limited resources managers are required to maintain high efficiencies and employ low-cost maintenance programs. Some organizations attempt a strict systems approach at the expense of practical relevance, while others consider the various parts of the maintenance systems in isolation with little reference to the overall objectives of the organizations. This research aims to come up with a maintenance model that best fits Malawian industries to increase reliability. It looks at the performance of industries with the current methods and identifies gaps that need to be closed to achieve maximum performance and reliability.

In this research, the approach was to observe various maintenance practices currently being practiced and data on plant stoppages. Using statistical analysis, reliability growth was measured and compared to best industry practices. A look at practices high performance industries was studied and the results compared to Malawian industries. It has been shown that there are differences that account for reduced reliability. Possible interventions have been outlined that can effectively improve reliability growth.

Keywords: Reliability, probability density function, maintenance, management, methods, growth,

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1. Introduction

Malawi is a landlocked country, and its economic activities are cantered on agro-business activities. The major crops grown in Malawi are maize, tobacco, sugar cane, soya beans, cassava, wheat flour, tea, coffee, ground nuts, pigeon peas and cassava. Of these, major operations that the country relies on for income are sugar, tobacco, tea and coffee. The cotton market fluctuates greatly while maize is mainly produced for domestic consumption. Very few agricultural products are exported for income and very little is realized from this produce.

Lately, the country has been struggling to achieve meaningful exports and shortage of foreign income has been the order of the day. Industries have been struggling to survive and some industrial operations have shut down (Sabola, 2020). For industries to survive, strict measures are being put in place to control expenses. Maintenance has been affected in almost all industries. This has seen employees being retrenched, productivity going down, standards deteriorating, and substandard practices being implemented. In turn, revenue turnover has decreased, and integrity risks have been experienced. One of the common operations that have been affected across all industrial functions is asset management maintenance (Rasmussen, 2018) as it is deemed as one of the most expensive operations in industry hence the need to relook at how management models can be improved to sustain businesses.

Literature Review

Maintenance has been defined in several ways. (Dekker, 1996) defines maintenance as the combination of all technical and associated administrative actions intended to retain an item or system in, or restore it to, a state in which it can perform its required function. In the recently released (European, Standards, 2001) regarding maintenance, maintenance is defined as the combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function. The (British Standards Institution, 1984) BS 3811 defines maintenance as a combination of technical and administrative actions undertaken to restore an asset to perform its intended function.

Processing factories in Malawi have adopted the use works order system to manage workflow. In the works order system, requests that are generated or initiated are sent to supervisors who assign personnel to do the works. Completed works are signed off by supervisors and managers and the works orders are closed.

Fig 1: Work Order System

Complete overhaul of equipment is done when factories shut down (January to April). This is referred to as off-season maintenance or annual shut down maintenance. The cost of annual overhaul is between $ 1,600,000 and $2,500,000 per individual factory. (Proverbs, Holt, & Cheok, 2005) estimate the maintenance costs to be between 30% and 60% of operational costs.

In-season Maintenance is done when production starts. It is scheduled at intervals in such a way as to maintain factory performance.

Scientific approaches to maintenance management date from the early 1950's (Pintelon & Van Wassenhove, 1990). During this period, the focus was on preventive maintenance which was seen as a means of reducing failure and unplanned downtime (Dekker R, 1996). Preventive maintenance is time-based scheduled maintenance program which does not require actual failure and often draws schedules from equipment manufactures or from operator experience.

Condition monitoring surfaced in the 1970's with the idea in mind to detect potential likelihood of failure before the actual failure occurs. Techniques such as lube oil analysis, vibration monitoring, infra-red thermography were introduced to determine actual state or condition of equipment or machinery. This was a better approach and outsmarted preventive maintenance (Dekker, 1996).

Although reliability centred maintenance (RCM) was introduced in the 1960's, it was mainly applied in the aeronautic industry for airplanes and not in ordinary production facilities. Maintenance efforts were focused on the critical areas of reliability to maintain functionality without causing risks (Vesely & Goldberg, 1980).

Computerized maintenance systems followed condition-based maintenance in the 1980's. There was attention being paid to maintenance management processes, administrative process and building management information (De Felice, Patrillo, & Autorino, Maintenance Strategies and Innovative Approaches in Pharmaceutical Industry: An Integrated Management System, 2014).

In Maintenance management, (Dekker, 1996) notes that there are two aspects; first, maintenance faces an inherently stochastic deterioration and failure process. Secondly, maintenance is a collection of different activities. These activities could range from few tasks to many tasks.

Maintenance optimization models are mathematical models that aim to find an optimum balance between costs and benefits of maintenance with all constraints taken into account. (Sherif & Smith, 1981) classified the models into two: – Deterministic Models and Stochastic Models. These were based under risk and under uncertainty. The systems are sometimes simple and sometimes complex. The models employed are linear and nonlinear programming, dynamic programming, Markov decision methods, decision analysis techniques, search techniques and heuristic approaches.

There is a gap between theory and practice. Maintenance models are difficult to understand and interpret. Engineers traditionally focus on deterministic approaches which hamper effective reliability concepts. This is because many researchers lean for mathematical purposes. This means they have been central to the models rather than providing optimal policies. Companies tend to also keep records under control and do not wish to have them published.

There are various approaches to optimizing maintenance methods. The choice really depends on the flexibility and familiarity of the user with a particular method. However, the Markovian method has reached maturity hence preventing researchers to gaining more insight (Jiang & Cheng, 1995). Besides it is limited by computational complexity and modelling efficiency.

Interesting models were suggested by (Honkanen, 1997). He proposed UML knowledge model, a Garry-Morton, Stochastic, Dynamic Maintenance systems and Dynamic supply chain models. However, the limitations with these models are based on assumption rather than actual data.

Models utilizing Weibull distributions have been found to be more practical and provide accurate failure analysis and are user friendly (Martinez, 2007). In trying to answer the research question posed, the belief is that the Weibull distribution, Markov and Duane will provide a desirable answer be done.

2. Materials and Methods

The research was conducted in the flowing way:

1. Examining literature on maintenance methods and management.
2. Examining relationships that are available on maintenance methods
3. Understanding management methods and practices
4. Select key a factory that fall in the category of seasonal processing
5. Examining CMMS data base and doing reliability analysis.
6. Compare with theoretical reliability trends
7. Select maintenance management and methods that will improve reliability.
8. Summarize all results and discuss them.
9. Propose reliability models and methods
10. Recommendations

Most organizations operate with confidentiality policies and do not wish to share strategies with competitors. That was the greatest drawback in conducting this research despite being for academic purposes and non-disclosure agreement.

Secondly, there is a lot of conflicting ideas on what effective maintenance programs are and how they should be designed and executed. Most methods and management practices are derived as company visions and objectives. Since the study samples a factory out of different processing industries, this could not be a fit for all purpose models but suffice to bring the much-needed difference to maintaining factories.

Thirdly, data correlation was a challenge because of data input into CMMS. Some data has had to be taken out because of wrong descriptions. This may influence the overall results. However, the error this could bring can be regarded as too minimal to give improper results.

The subject of maintenance is very wide and so sticking to one position, the results would probably not be very significant. Hence several areas must be considered simultaneously. When looking at maintenance and management methods, they usually overlap in many ways. Hence the approach taken in this research is multi-dimensional.

In this research the performance parameters being observed are the productivity and reliability. Both ontological aspects have been used in this research. Firstly, objectivism to establish baseline and followed by subjectivism to see optimal intervention to produce desired results.

Maintenance being a wide field of study, the epistemological stance is based on the research question. In this research, positivism and realism have been adopted. Realism, because the outcome of maintenance functions is a reality that can be observed. Realism has as well been adopted because introduction of several management and maintenance methods have direct or in-direct effects on the system performance and output.

Again, maintenance is very broad. While freeway seems easier, the results of the outcome could be biased as they are meant to fit into what final outcome is being sought. This is typical for theoretical research. In this research, real activity is being analysed hence the value laden approach has been adopted.

Again, maintenance is very broad. There is a wide literature available covering various aspects of maintenance. As this research is specific to seasonal industries in Malawi, it is necessary to establish what literature is available, what data can be accessed, and what phenomena can be observed. Hence the design is a bit complex. Archival, survey formed the backbone of the design with partial action considering that the researcher is a practitioner in the same field.

This research used a combination of qualitative and quantitative data. Several maintenance managers have been interviewed to establish what maintenance and management methods are being used and their opinion on the effectiveness. Data bases have been used to collect data for analysis. Mixed sampling methods have been used.

Secondary data has been used in this research. The primary data comes in form of surveys and observable events.

The content analysis method was adopted for this study. According to (Barbour, 2014) content analysis is the approach used for analysis of qualitative data in which responses are clustered and or coded basing on emerging themes. Responses were clustered and coded by grouping similar themes. These were discussed as findings of the study. The knowledge gap was then established in the responses from the interviewees. Links were then established, and similarities defined using the content analysis to determine baseline for maintenance and management methods. (Blumberg, Cooper, & Schindler, 2008) says qualitative data needs to be categorized to create a focussed argument during discussion of results.

The probability distribution functions probabilistic approaches that will be used in this research are the Weibull distribution and Duane reliability growth model.

The validity of the study was based on questions that were open ended to determine patterns and similarities.

3. Results and Discussion

A weekly breakdown trend has been prepared. Graph 1 below shows the weekly breakdown comparison.

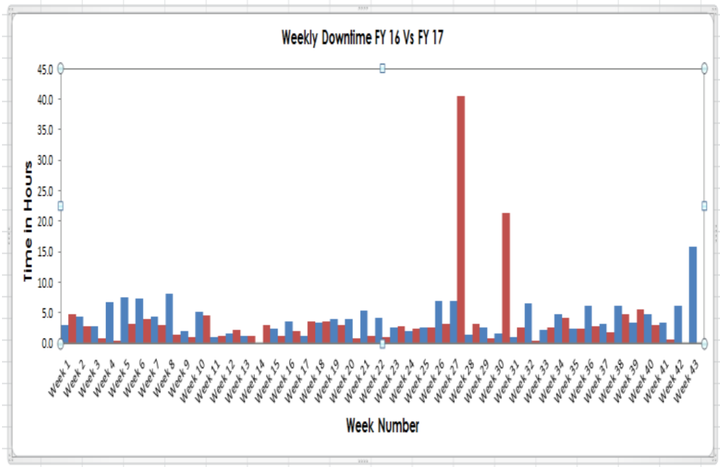

Fig 2: Weekly Down Time

Taking week 27 and week 31 as outliers (FY17), a periodic trend can be seen. The downtime starts to shoot and then falls again. Roughly a four-week cycle can be seen where on the first week is low and then increases the second week, peaks on the third week and falls on the fourth week. The pattern is not a coincidence. There should be a reason why this is periodically happening.

Data for FY16 is organized and a graph is similarly done. This is mapped against 2017 data.

Again, this can be approximated to a periodic trend. The question is why is this happening?

A closer look at the calendar shows that the downtime is low at the beginning of the month and steadily rises in the second week and peaks in the third week and falls again in the fourth week. It is reasonable to assume that this is a monthly trend. The low downtime is attributed to the amount of work done following the maintenance. More work is done in week 1 because focus is on reducing downtime hence needed to do more preventive and corrective works. Then the focus comes to maintenance expenses and the amount of preventive and corrective work orders are downsized only prioritizing what are assumed as critical works. As a result, failures begin to increase and prompt action to do more work again to keep downtime low.

The oscillating trend shows system instability. The balance between downtime and cost is not being achieved and this is the problem that needs to be addressed. There is now a need to define a model that keeps downtime low and costs to a minimum. Costs however are a function of number of spares being used for maintenance. Maintenance depends on performance of the factory. Bearing in mind the need to optimize production, maintenance methods have to be put in place to keep the factory in good operating condition. These include condition monitoring – vibration analysis and infra-red thermography, lubrication schedules, checklists, and heat gun. The outcomes from these reliability inspections determine the maintenance activities to be done. The challenge is to determine what constitutes as critical and priority works.

Critical works are all works that if not attended to will cause downtime. Priority works are also necessary works that must be done to ensure continuity of operations.

From CMMS data, frequency of equipment failure has been analysed.

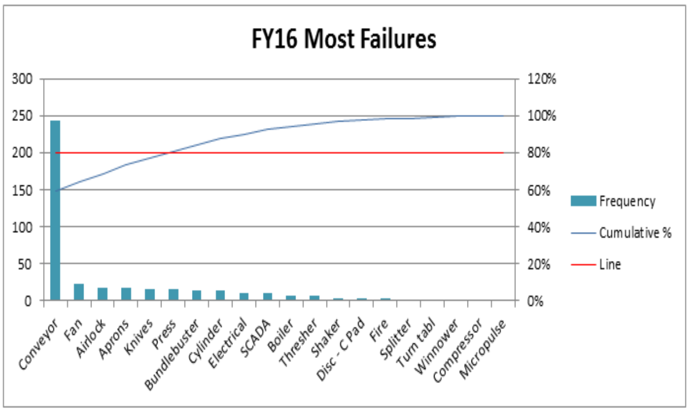

Fig 3: FY 16 Pareto analysis by Failures

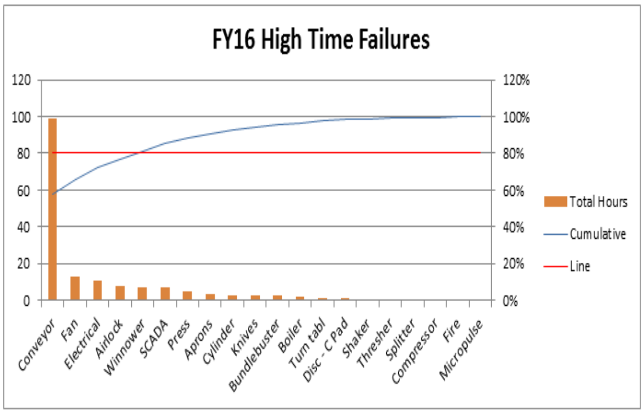

Fig 4: *FY 16 Pareto analysis by Time*

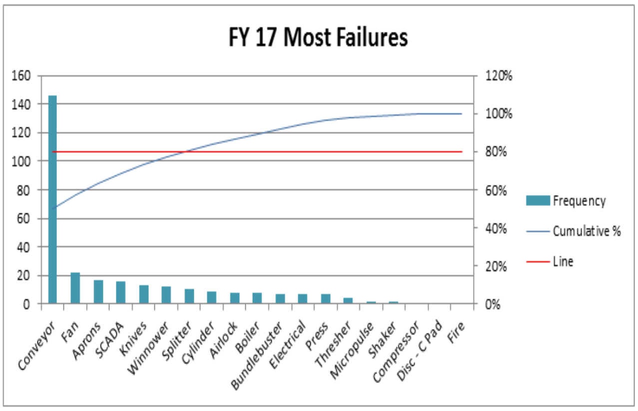

Fig 5: FY 17 Pareto analysis by Failures

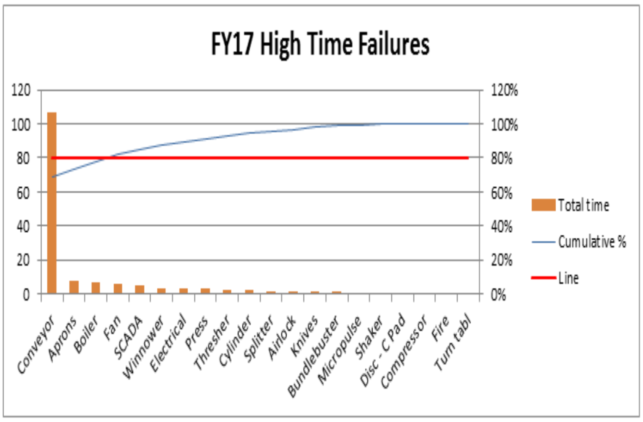

Fig 6: FY 17 Pareto analysis by Time

From above charts high failures and high downtime arises specifically from conveyors, fans, airlocks, knives, presses, electrical faults, winnowers, aprons, boiler and SCADA. To achieve optimized performance attention should be drawn to these areas especially the conveyors. This would take away the most problematic areas costing time, materials and loss of production.

In FY16 topping the failures are conveyors. Aprons, airlocks, and fans come second, aprons, segments and fans come second, knives come third, presses come fourth and bundle busters come fifth.

In FY17 conveyors top the failures, fans come second, aprons come third, SCADA comes fourth, knives come fifth and winnowers come sixth.

Conveyor failures reduced significantly in FY17 probably because much attention was given to them following a troubled season but still topped the failures. Fans and aprons are the next equipment accounting for the second and third downtime items in both years. Apron failures reduced while fan failures increased. The reduction in apron failures is minimal while the increase in fan failures is significant. Probably a consistency in apron maintenance could be the reason but an increase in fan failures could be a result of an oversight while paying attention to conveyors.

Press failures are reduced but a new entrant SCADA takes up the place. It may not be apparent as to why SCADA failures came to spot, but it is tempting to think that this can be a result of ageing. Knives maintain similar spot also probably due to consistency of maintenance program.

Zooming in more, it can be seen than belts have a high failure rate. These are followed by trips. Trips can be a result of restrictions or resistance resulting into higher than designed loads. This makes the drive to stall. Then there are v-belt failures. These often result from belt slippage due to worn out pulleys, under tensioning and sometimes overloading. VSD failures in FY16 are high. These are attributed to voltage fluctuations but in FY17 these were corrected through installation of AVS. The other persistent failures are on rollers, chains, motors, and bearings. Rollers fail mainly due to wear and so are chains. Wear comes because of time of operation and environment in which they are operating. In clean environments, the life is longer while in rough and dirty conditions life is short. Bearings also fail due to wear. However, wear in bearings can be mitigated by lubrication. So many failures occur due to over or under lubrication. Motors on the other hand fail for numerous reasons that lead to winding failure or bearing failures. In other cases, motor bases fail or terminal box may have dry leads.

Now, a summary is made by category on the failures. These are classified as mechanical, electrical and SCADA (instrumentation).

Table 1: Summary of downtime in FY16

	FY16				
Item	Description	Mech	Elec	SCADA	Frequency
1	Airlock	232	243		18
2	Apron	229			18
3	Boiler		90	28	6
4	Bundlebuster	109		35	14
5	Compressor		25		1
6	Conveyor	3 717	1 916	291	244
7	Cylinder	181			13
8	Disk - C Pad		70		3
9	Elec	580	70		11
10	Fan	644	100	22	23
11	Fire			20	3
12	Knives	140	5	15	16
13	Micropulse		15		1
14	Press	117	170	25	16
15	Scada	125	47	269	11
16	Shaker	32		12	4
17	Splitter	32			2
18	Thresher	35	7		6
19	Turntable	70	30		2
20	Winnower	133	264	50	22
	Total Stoppages (minutes)	6 376	3 052	767	10 195
	Total Stoppages (Hours)	106	51	13	

Table 2 Summary of failures in FY17

	FY17				
Item	Description	Mech	Elec	SCADA	Frequency
1	Airlock	37	77		8
2	Apron	453	27		17
3	Boiler	350	60		8
4	Bundlebuster	86			7
5	Compressor		10		1
6	Conveyor	3 791	2 612		146
7	Cylinder	141	15		9
8	Disk - C Pad	25			1
9	Elec	37	143		7
10	Fan	258	117		22
11	Fire				
12	Knives	104	8		13
13	Micropulse		35		2
14	Press	85	95		7
15	Scada	107	142	37	16
16	Shaker	21	7		2
17	Splitter	97	19		10
18	Thresher	12	147		4
19	Turntable				
20	Winnower	107	94		12
	Total Stoppages (minutes)	5 711	3 608	37	9 356
	Total Stoppages (Hours)	95	60	1	

A glance at the tables reveals that mechanical downtime is predominant followed by electrical and lastly SCADA. It is however not surprising since mechanical components are always in motion and as such there is friction which results into wear. Electrical failures are mainly due to motor failures also attributed to motion that result in wear. Very little time is attributed to lose cables or load factor which results in over heating of cables and so on. However, the number of motors is less compared to moving mechanical components hence a low downtime allocation for electrical. In SCADA, instrument motion is very minimal hence the least downtime. Other than instruments, the electrical component is of magnitude 0 – 24 volts hence downtime is mainly due to voltage and current transients hence the least downtime allocation. There is also PLC connectivity using Ethernet which is affected by signal interference due to electrical disturbance and Ethernet cable related faults. However, this is negligible

The table below shows the time account for the two years:

Table 3 Time account

FY16			FY17
Start	12/5/2015		17/5/2016
Stop	9/03/2016		28/2/2017
Weeks	43		41
Weekends	42		40
Holidays	16		15
Total Days	302		287
Operating Days	202		192
Operating Hours	4848		4608
Open Minutes	290880		276480
Total stoppage minutes	10195		9356
OTE	96%		97%
Downtime	4%		3%

The total days represent the number of days in the season. Operating days represent the number of planned production days which excludes scheduled maintenance stops and public holidays. These have been converted to hours and minutes (open minutes).

The total stoppage time represents the sum of all mechanical, electrical and Scada downtime.

$$OTE = \frac{(Op.time - Total\ Stoppages\ )\ x\ 100}{Operating\ time} \quad (1)$$

$$Downtime = \frac{(Total\ Stoppages\ )\ x\ 100}{Operating\ time} \quad (2)$$

Table 4: FY16 failure metrics

Equipment						MTBF	MTTR	MTTF		Per Unit at 90% Confidence level calculated		Calculated Using Excel X2 Crtical	
Description	Number of Failures	Installed Units	Failed Units	Operating time (Hrs)	Accumulated time (Hrs)	Straight MTBF (hrs)	MTTR	MTTF	Total Time	Lower MTBF	Upper MTBF	Lower MTBF	Upper MTBF
Airlock	18	57	9	4,848	43,632	269	0.44	269	7.92	174	366	196	417
Apron	18	15	7	4,848	33,936	269	0.21	269	3.82	174	366	196	417
Boiler	6	2	1	4,848	4,848	808	0.33	808	1.97	222	1,476	460	1,855
Bundle Buster	14	4	5	4,848	24,240	346	0.17	346	2.40	222	524	241	573
Compressor	1	4	1	4,848	4,848	4,848	0.42	4,848	0.42	1,022	94,136	1,246	94,515
Conveyor	244	239	69	4,848	334,512	20	0.40	19	98.73	18	22	18	22
Cylinder	13	6	4	4,848	19,392	373	0.23	373	3.02	258	664	256	630
Disk - C Pad	3	1	1	4,848	4,848	1,616	0.39	1,616	1.17	625	5,930	726	5,929
Elec	11	1	1	4,848	4,848	441	0.98	440	10.83	258	894	292	786
Fan	23	125	17	4,848	82,416	211	0.56	210	12.77	144	280	159	308
Fire	3	1	1	4,848	4,848	1,616	0.11	1,616	0.33	625	5,930	726	5,929
Knives	16	4	4	4,848	19,392	303	0.17	303	2.67	222	524	216	483
Micropulse	1	6	1	4,848	4,848	4,848	0.25	4,848	0.25	1,022	94,136	1,246	94,515
Press	16	12	1	4,848	4,848	303	0.33	303	5.20	222	524	216	483
SCADA	11	1	1	4,848	4,848	441	0.67	440	7.35	258	894	292	786
Shaker	4	66	3	4,848	14,544	1,212	0.18	1,212	0.73	530	3,548	606	3,548
Splitter	2	4	1	4,848	4,848	2,424	0.27	2,424	0.53	770	13,637	911	13,642
Thresher	6	17	5	4,848	24,240	808	0.12	808	0.70	409	1,855	460	1,855
Turn Table	2	3	1	4,848	4,848	2,424	0.83	2,423	1.67	770	13,637	911	13,642
Winnower	22	38	14	4,848	67,872	220	0.34	220	7.45	174	366	165	326

Table 5: FY17 failure metrics

Equipment						MTBF	MTTR	MTTF		Per Unit at 90% Confidence level calculated		Calculated Using Excel X2 Crtical	
Description	Number of Failures	Installed Units	Failed Units	Operating time (Hrs)	Accumulated time (Hrs)	Straight MTBF (hrs)	MTTR	MTTF	Total Time	Lower MTBF	Upper MTBF	Lower MTBF	Upper MTBF
Airlock	8	57	6	4,608	27,648	576	0.24	576	1.90	319	1,157	355	1,158
Apron	17	15	10	4,608	46,080	271	0.47	271	8.00	211	498	195	425
Boiler	8	2	2	4,608	9,216	576	0.85	575	6.83	319	1,157	355	1,158
Bundle Buster	7	4	5	4,608	23,040	658	0.20	658	1.43	350	1,403	391	1,403
Compressor	1	4	1	4,608	4,608	4,608	0.17	4,608	0.17	971	89,476	1,185	89,836
Conveyor	146	239	52	4,608	239,616	32	0.73	31	106.72	28	36	28	36
Cylinder	9	6	4	4,608	18,432	512	0.29	512	2.60	293	981	324	981
Disk - C Pad	1	1	1	4,608	4,608	4,608	0.42	4,608	0.42	971	89,476	1,185	89,836
Elec	7	1	1	4,608	4,608	658	0.43	658	3.00	350	1,403	391	1,403
Fan	22	125	14	4,608	64,512	209	0.28	209	6.25	201	348	157	309
Fire	-	1	1	4,608	4,608	4,608	4,608.00	-	-	1,538	2,304,000	2,001	2,343,762
Knives	15	4	5	4,608	23,040	307	0.12	307	1.87	211	498	216	498
Micropulse	2	6	1	4,608	4,608	2,304	0.29	2,304	0.58	732	12,962	866	12,967
Press	7	12	1	4,608	4,608	658	0.43	658	3.00	350	1,403	391	1,403
SCADA	16	1	1	4,608	4,608	288	0.30	288	4.77	211	496	205	459
Shaker	2	66	2	4,608	9,216	2,304	0.23	2,304	0.47	732	12,962	866	12,967
Splitter	10	4	3	4,608	13,824	461	0.19	461	1.93	293	849	299	849
Thresher	4	17	3	4,608	13,824	1,152	0.66	1,151	2.65	503	3,372	576	3,373
Turn Table	-	3	1	4,608	4,608	4,608	4,608.00	-	-	1,559	2,304,000	2,001	2,343,762
Winnower	12	38	10	4,608	46,080	384	0.28	384	3.35	245	631	259	665

Note that this is engineering time account only. However, there are stoppages that are recorded and are due to extraneous matter (force majoure), operational, power failure, load shedding, water supply interruption and weather. These stoppages are not part of this research.

$$MTTR = \frac{Total\ Test\ Time}{Total\ number\ of\ repairs} \qquad (3)$$

$$MTBF = \frac{Total\ Operating\ Time}{Total\ number\ of\ failures} \qquad (4)$$

$$MTTF = \frac{Total\ hours\ of\ operation}{Total\ number\ of\ units} \qquad (5)$$

$$Lower\ MTBF\ (C\%) = \frac{2T}{X^2@((\frac{\alpha}{2}), 2(F+1))} \qquad (6)$$

$$Upper\ MTBF\ (C\%) = \frac{2T}{x^2@((1-\frac{\alpha}{2}),2F)} \qquad (7)$$

Where

C is Confidence Level

α is Type 1 risk and = *1 – C*

T is test time

F is number of failures

X^2 is Chis-Square distribution

The X^2 values are taken from X^2 tables or using excel (both have been shown). The straight or actual *MTBF* are within the Lower and Upper critical values. Note that the lower the *MTBF* the higher the failure rate.

Hazard Rate

The hazard rate is defined as *h(t)=f(t)/R(t)*

Where *h(t)* is the hazard rate, *f(t)* is the probability density function and *R(t)* is the Reliability function .

The probability function is represented by

$$f(t) = \lambda e^{-\lambda t} \qquad (8)$$

$$R(t) = e^{-\lambda t} \qquad (9)$$

$$h(t) = \lambda e^{-\lambda t}/e^{-\lambda t} \qquad (10)$$

$$h(t) = \lambda \qquad (11)$$

Hazard Rate for Weibul Distribution

The hazard rate is given as

$$h(t) = f(t)/R(t) \qquad (12)$$

In a Weibul distribution

$$f(t) = \frac{\beta}{\eta^\beta} t^{\beta-1} e^{-(\frac{t}{\eta})^\beta} \qquad (13)$$

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (14)$$

$$h(t) = \left(\frac{\beta}{\eta^{\beta}} t^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}}\right) / \left(e^{-\left(\frac{t}{\eta}\right)^{\beta}}\right) \quad (15)$$

$$h(t) = \frac{\beta}{\eta^{\beta}} t^{\beta-1} \quad (16)$$

When $\beta < 1$, $h(t)$ decreases indicating early life when design changes have been affected and the equipment is stabilizing. When $\beta = 1$, $h(t)$ is constant indicating maturity stage when failures are random. When $\beta > 1$, $h(t)$ increases indicating end of life where failures are persistent. This will be discussed later on the data discussion points.

Table 6: FY16 Failure by section

FY16							
Item	Description	Mech	Elec	SCADA	Frequency	Number of Units	*h(t)*
1	Airlock	232	243		18	62	0,0068
2	Apron	229			18	18	0,0233
3	Boiler		90	28	6	3	0,0465
4	Bundlebuster	109		35	14	4	0,0814
5	Compressor		25		1	4	0,0058
6	Conveyor	3 717	1 916	291	244	422	0,0134
7	Cylinder	181			13	5	0,0605
8	Disk - C Pad		70		3	1	0,0698
9	Elec	580	70		11	780	0,0003
10	Fan	644	100	22	23	127	0,0042
11	Fire			20	3		-
12	Knives	140	5	15	16	4	0,0930
13	Micropulse		15		1	5	0,0047
14	Press	117	170	25	16	6	0,0620
15	Scada	125	47	269	11	1	0,2558
16	Shaker	32		12	4	78	0,0012
17	Splitter	32			2	4	0,0116
18	Thresher	35	7		6	19	0,0073
19	Turntable	70	30		2	5	0,0093
20	Winnower	133	264	50	22	16	0,0320

Table 7 Failure by section

FY17							
Item	Description	Mech	Elec	SCADA	Frequency	Number of Units	*h(t)*
1	Airlock	37	77		8	62	0,0003
2	Apron	453	27		17	18	0,0021
3	Boiler	350	60		8	3	0,0060
4	Bundlebuster	86			7	4	0,0040
5	Compressor		10		1	4	0,0006
6	Conveyor	3 791	2 612		146	422	0,0008
7	Cylinder	141	15		9	5	0,0041
8	Disk - C Pad	25			1	1	0,0023
9	Elec	37	143		7	780	0,0000
10	Fan	258	117		22	127	0,0004
11	Fire						-
12	Knives	104	8		13	4	0,0074
13	Micropulse		35		2	5	0,0009
14	Press	85	95		7	6	0,0026
15	Scada	107	142	37	16	1	0,0363
16	Shaker	21	7		2	78	0,0001
17	Splitter	97	19		10	4	0,0057
18	Thresher	12	147		4	19	0,0005
19	Turntable					5	-
20	Winnower	107	94		12	16	0,0017

It has been seen that conveyors, aprons, fans, knives, bundle busters and winnowers are the main equipment responsible for downtime and top of the list in both seasons are conveyors. However, looking at the hazard rate, it can be seen that SCADA in FY16 was actually more vulnerable. Similarly other vulnerable equipment in terms of hazard rate were the boilers, bundle busters, cylinders, shakers, and winnowers.

In FY17, the hazard rate for all equipment went down and not showing alarm. However, SCADA trended high. Conveyors despite accounting for more downtime had a reasonable hazard rate. The tendency though would be to focus on areas giving more downtime as opposed to vulnerability in terms of hazard rate.

Reliability growth

Reliability growth theory was proposed by (Duane, 1964). In the stipulation, any new equipment goes through a period of design changes with multiple failure modes before reaching maturity. Thus, development programs and observed failures are investigated and life data models applied to reach maturity stage. Thus, empirically *MBTF* should be increasing monotonically.

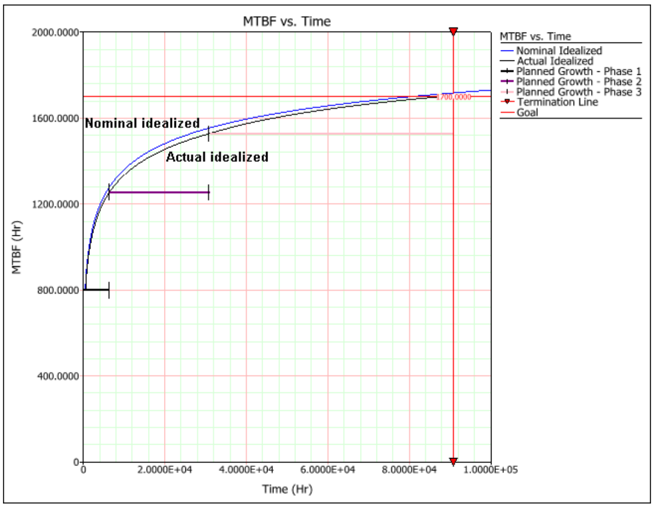

Fig 7: MTBF vs Time chart

When *MBTF* is constant, it means the system is stable. However, *MBTF* increases to a new higher level if system is changed or redesigned

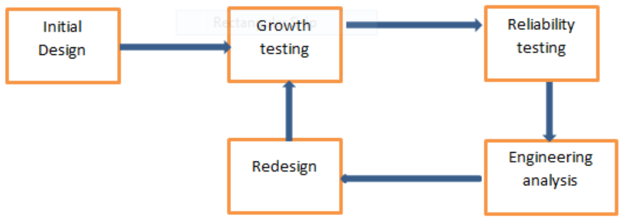

Fig 8: Reliability Growth

$$\theta c = \theta o(\frac{T}{To})^{-\alpha} \qquad (17)$$

where

θo=Cumulative MBTF at start of testing

θc=Cumulative MBTF at anytime T

To=Time at start of testing

α=MBTF growth rate

Taking logarithms:

$$ln\,(\theta c) = ln\,(\theta o) + \alpha(lnT - ln\,To) \qquad (18)$$

$$ln\,(\theta c) = (\,ln\,(\theta o) - \,\alpha\,ln\,To) + \,\alpha(lnT) \qquad (19)$$

This equation of a straight line $y = mx+c$ with slope α

Table 8 Meaning of reliability growth slope

ά	bility Effort
0.6	riority is to eliminate failure modes
0.4	tion should be paid to reliability efforts
	ne attention should be paid to reliability improvement
2	is no growth

$$\theta c = \theta o(\frac{T}{To})^{\alpha} \qquad (20)$$

by definition *θc=T/n*

where n = number of failures

$n = T/\theta c$

$dn/dt = Instantaneous\ failure\ rate$

$dt/dn = Instantaneous\ MBTF\ or\ \theta i$

Substitute θi above and differentiating with respect to time T

$$n = T/\theta c \tag{21}$$

$$n = \frac{T}{\theta o(\frac{T}{To})^{\alpha}} \tag{22}$$

Therefore
$$dn/dT = (1 - \alpha)T^{-\alpha}(\frac{To}{\theta c})\frac{\alpha^2}{} \tag{23}$$

$$\frac{dn}{dT} = \frac{(1-\alpha)1}{\theta o}(\frac{To}{T})\ \ \alpha \tag{24}$$

$$\frac{dn}{dt} = (1-\alpha)/\theta c \tag{25}$$

$$\frac{dt}{dn} = \theta c/(1-\alpha) \tag{26}$$

The Duane reliability growth model was defined. Using this model, an assumption was made to take the entire factory as a repairable system. This is very reasonable since factories are always maintained to ensure continuous and quality productivity. Computing the reliability growth rate for the two seasons, the following charts are obtained.

Table 9 Reliability growth rate FY16

MONTHLY ENGINEERING DOWNTIME 2015 PROCESSING SEASON					
T&T Month	**Cumulative hours**	**Number of failures**	Cumulative MBTF	Log (t)	Log (MBTF)
1	456	38	12,00	2,66	1,08
2	1032	67	15,40	3,01	1,19
3	1512	32	47,25	3,18	1,67
4	2112	32	66,00	3,32	1,82
5	2568	64	40,13	3,41	1,60
6	3168	47	67,40	3,50	1,83
7	3648	23	158,61	3,56	2,20
8	4152	45	92,27	3,62	1,97
9	4632	43	107,72	3,67	2,03
10	4944	38	130,11	3,69	2,11

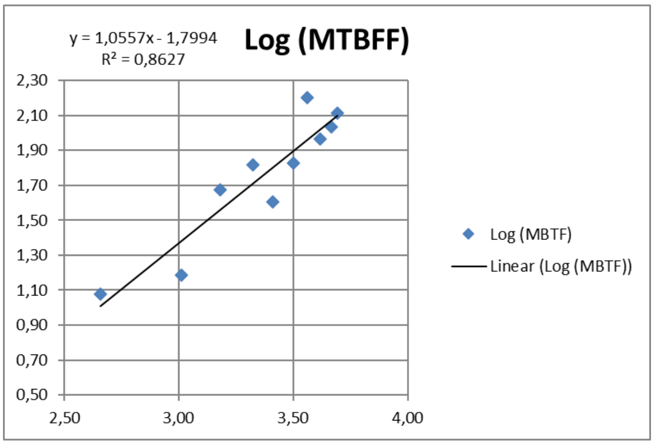

Fig 9: Reliability growth plot FY16

Table 10: Reliability growth rate FY17

MONTHLY ENGINEERING DOWNTIME 2016 PROCESSING SEASON					
T&T Month	Cumulative hours	Number of failures	Cumulative MBTF	Log (t)	Log (MBTF)
1	456	16	28,50	2,66	1,45
2	10008	35	285,94	4,00	2,46
3	1488	30	49,60	3,17	1,70
4	2088	36	58,00	3,32	1,76
5	2568	26	98,77	3,41	1,99
6	3144	46	68,35	3,50	1,83
7	3624	27	134,22	3,56	2,13
8	4200	30	140,00	3,62	2,15
9	4704	44	106,91	3,67	2,03

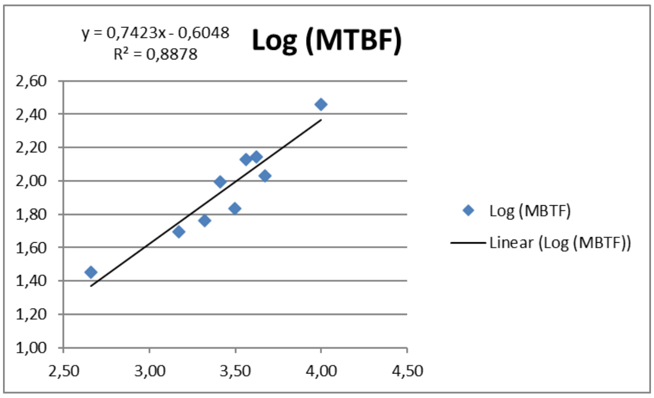

Fig 10: Reliability growth plot FY17

In FY16 the reliability growth rate was at 1.0557 and in FY17 it was at 0.7423. In both years, for a repairable system, this is far out of world class standards. The minimum requirement is 0.6 on which focus is to eliminate failures. The figures obtained show that in as much as the factory is maintained, the numbers of failures are way too high. However, the significant drop has been noted indicating efforts carried out to improve system design through re-engineering and application of maintenance methods.

The cumulative distribution function for a two parameter Weibull distribution is given by

$$f(t) = 1 - e^{-(\frac{t}{\eta})^{\beta} t}$$

where β is the shape parameter and η is the scale parameter.

The reliability function is given by $R(t) = 1 - f(t)$

$$R(t) = e^{-(\frac{t}{\eta})^{\beta}} \quad (27)$$

$$f(t) = \frac{df(t)}{dt} = d(\frac{\left(\frac{t}{\eta}\right)^{\beta}}{dt}) \quad (28)$$

$$f(t) = -\left(\frac{1}{\eta}\right)^{\beta} t^{\beta-1}. e^{-(\frac{t}{\eta})^{\beta}} \quad (29)$$

$$f(t) = (\frac{\beta}{\eta^{\beta}}) t^{\beta-1} e^{-(\frac{t}{\eta})^{\beta}} \quad (30)$$

The hazard rate will be given by $h(t) = f(t)/R(t)$

$$h(t) = \frac{(\frac{\beta}{\eta}) t^{\beta-1}}{e^{-(\frac{t}{\eta})^{\beta}}} e^{-(\frac{t}{\eta})^{\beta}} \quad (31)$$

$$h(t) = (\frac{\beta}{\eta^{\beta}}) t^{\beta-1} \quad (32)$$

At $\beta < 1$, $h(t)$ decreases. At $\beta = 1$, $h(t)$ is constant and at $\beta > 1$ $h(t)$ increases.

At $\beta = 1$, *h(t)=(1/η^1)t^(1-1)*

h(t)=1/η which is a constant rate

At β = 2, h(t)=(1/η^2)t^(2-1)

h(t)=(t/η^2) which is a straight line

at time t = η the reliability becomes:

$$R(\eta) = e^{-(t/\eta)^{\beta}} \quad (33)$$

$$R(\eta) = e^{-1} \quad (34)$$

$$R(\eta) = 0.368 \quad (35)$$

$$f(t) = 1 - 0.368 = 0.632 \quad (36)$$

This mean at $t = \eta$, 63.2% of parts are expected to fail in any repairable system.

When a third component δ known as failure free life is introduced in a Weibul distribution, the probability distribution function becomes

$$f(t) = \frac{\beta}{\eta^{\beta}}(t-\delta)^{(\beta-1)}e^{-(t-\delta)/\eta)^{\beta}} \quad (37)$$

$$R(t) = e^{-(t-\delta)/\eta^{\beta}} \quad (38)$$

The failure free life is the useful life that a component operates before failure occurs

Firstly, the reliability growth is not measured. Detailed analysis is not done hence difficult to make proper judgement. When machinery undergoes annual overhaul, most parts are changed. Some parts are in wear out phase while others have reasonable residual life to failure. The machines are repaired and become somehow new (reconditioned). Then it should be expected to behave in accordance with two-parameter Weibul distribution.

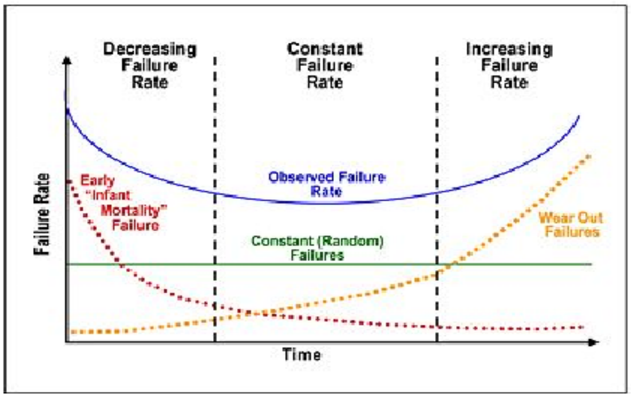

Fig 11: Bath tub curve

The idea of complete overhaul during annual shut down is costly. Firstly, parts are replaced without completely failing. Secondly, handling of some spares results into failure. For example, most bearing failures arise from handling and improper fitting procedures. This is similar to seals. Once a seal is taken out, it cannot be put back. Instead, it has to be replaced. Conveyor belts are usually bonded. When taking them out, they need to be cut and as such a patch must be prepared to bond it again. Else, lacings have to be used. Joining with lacings creates a weak point where failure will ultimately occur.

So to ensure that maintenance methods are effective, an optimum strategy has to be developed.

First and most important, an asset management policy must be defined with set goals and objectives. This shows management commitment to asset maintenance.

There are formal management methods used by organizations to run their business processes and by maintenance to determine and select maintenance strategies that can optimize maintenance. The ones considered in this research include reliability cantered maintenance (RCM), six sigma and lean maintenance. In addition, the methods representing the informal decision and planning processes used by various maintenance organizations are to manage their maintenance processes are considered under classical management methods.

There exists a considerable literature on reliability growth modelling. They assume the time of an innovation (improvements or redesign) is known and that there is a coincidental improvement in performance

Industries must develop asset management policies which have holistic approach to factory maintenance. Maintenance should not be regarded as a cost but rather an opportunity to enhance and achieve objectives. The policies should adequately cover maintenance aspects in terms of equipment maintenance. The life cycle management policy should comprehensively cover procurement, operation, maintenance, renewal, and disposal. Innovations to enhance performance should be addressed and limits defined. Undefined limits lead to missed opportunity when renewal or disposal period is achieved leading to reduced reliability.

Skills development should also form part of the policy. Apart from technical skills for personnel, management skills in reliability measurements should be included. From the failure modes, it has been seen that technical skills can help optimize performance of factories. Likewise understanding of reliability growth should also help management to develop means to optimize factory performance

The maintenance methods being deployed are standard and undoubtedly being utilized. Whilst deploying these methods, it is noted that there is a stumbling block on the way which is cost of maintenance materials. The problem however does not lie on the cost but how these methods are being applied. These methods are being marked to give the impression that once adopted, they will bring desired performance. As such they are implemented only by means of copying what other industries have done. However, the necessary tools to aide decision making are not known hence not being utilized. This renders the maintenance methods ineffective. By copying and implementing these, there is a missed opportunity to improve factory reliability because key aspects of the methods are not being utilized. For example, off-season maintenance practice has been to strip, inspect and repair where necessary all equipment. In-season maintenance likewise follows the same and additionally preventive maintenance practices focuses on replacing parts that have not completely failed. Scheduling of maintenance has been tradition in that limits are based on cleaning specific parts of equipment which has been set as a routine. This provides an opportunity to execute costly preventive maintenance activities. Maintenance engineers and managers have not been able to distinguish between repairable and non-repairable equipment which has resulted in wrong and poor decisions.

It is suggested here that scientific and statistical reliability modelling be utilized to schedule preventive maintenance. Life data analysis for repairable and non-repairable items should be done to aide decision making. Though the use of reliability software is deemed expensive, it however presents a useful tool to aide maintenance execution. Maintenance engineers should be equipped with analytical tools in this aspect if the benefits are to be realized.

This process is dynamic and should be considered the heart of the maintenance function. With a strong and purposeful asset management policy, the maintenance methods aided with reliability and life data analysis tools will optimize the maintenance function and enhance the factory performance.

A measure of importance will help also improve factory uptime because this would aide areas to be prioritized and where redundancy should be considered.

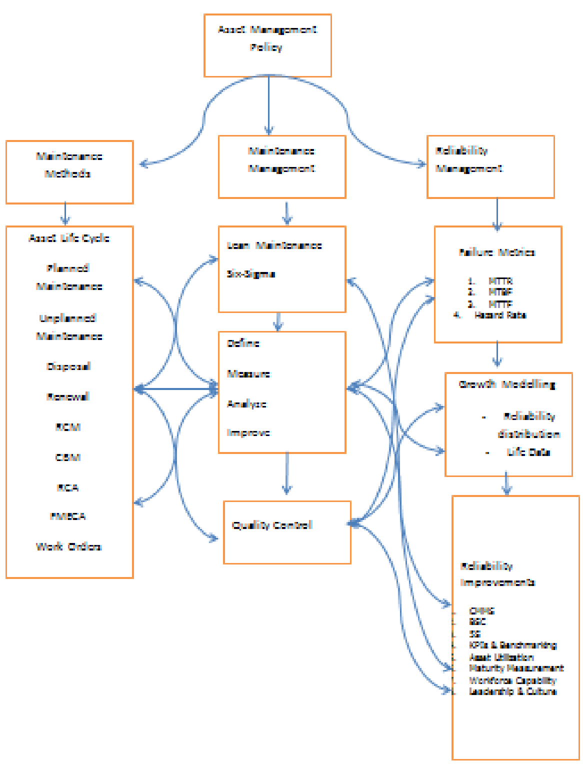

Fig 12: Reliability improvement process

4. Conclusions and Future Work

An asset management policy with emphasis on maintenance management should be helpful to ensure that maintenance methods are directed towards overall factory performance. This has been the finding in this research. However, it has been pointed out that the overall maintenance function should be cost effective. This means there should be a balance between maintenance and costs.

Also to avoid likelihood of failure, there should be a balance in the equipment type as too many similar types of drives provide room for frequent failures.

Cost models have not been explored in this research. This presents a gap to be explored for meaningful maintenance optimization in Malawi. Maintenance costs in Malawi are a challenge due to importation and volatility of the currency.

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Paper 9: Exploring Geothermal Resources: A Case Study of Mawira in Nkhotakota

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Abstract

This study presents findings from a reconnaissance investigation aimed at identifying potential geothermal reservoir location at Mawira in Nkhotakota, Malawi. The study area, situated within the Malawi Province of the Mozambique Orogenic Belt, is characterized by Precambrian to lower Palaeozoic basement rocks and unconsolidated deposits. Aeromagnetic data, collected as part of the World Bank's Malawi Governance and Growth Support Project, was processed and analyzed using various techniques including reduced-to-pole filtering, tilt derivative, and analytical signal amplitude. Results indicate the presence of two notable low magnetic anomalies in the south and north of the study area, suggesting potential geothermal reservoirs. These reservoirs are connected to surface hot springs via a network of faults, particularly those trending NW-SE and NE-SW direction. The hot springs, with temperatures ranging from 75°C to 85°C, are classified as alkali chloride type with an estimated reservoir temperature of approximately 120°C±10°C. Additional resistivity surveys revealed the presence of hot water reservoirs at various depths, further supporting the potential for geothermal resources in the area. The analysis revealed a highly faulted nature of the study area, indicative of significant tectonic activity conducive to the upward flow of hydrothermal fluids from the geothermal reservoir to the surface.

Keywords: Aeromagnetics, Resistivity, Faults, Reservoir, Hot Springs

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1. Introduction

Geothermal energy, much like nuclear, solar, and wind power, stands as a sustainable and environmentally friendly source of renewable energy. It resides within geological formations such as rock-soil masses, rocks, and subterranean fluids, offering high energy density and a consistent energy supply (Tester et al., 2006). This versatile energy form serves multiple sectors including heating, electricity generation, and medical applications. Geothermal exploration involves pinpointing areas with anomalous geothermal fields and studying the properties of geothermal reservoirs (Wang et al., 2022; Ke et al., 2022). Geophysical exploration can map out geothermal anomalies, reservoirs, and field boundaries; locate concealed magmatic rocks and their alteration zones; detect basement morphology and hidden faults; and identify stratigraphic structures, reservoir burial depths, and potential zones of geothermal fluid enrichment in the surveyed area (Ge et al., 2017; Wu, 1996). Malawi's energy demand is on the rise, but its current capacity falls short of meeting the needs of its people. To address this, the country is exploring alternative energy sources such as geothermal power. Nkhotakota, situated in the central region of Malawi, lies within the rift plain of the southern arm of the western branch of the Great East African Rift Valley. The area boasts eleven natural thermal springs, with the primary cluster located just south of Nkhotakota, making these springs likely the most renowned in the country. The thermal springs discharge into the lower parts and margins of the Mawira stream valley, with some of them utilized for the water supply of the township. These thermal springs are typically viewed as indicative of the initial stages of volcanic activity linked with the East African Rift System. However the location of the geothermal reservoir in the study area is not known. This study seeks to define and locate the boundaries of the geothermal reservoir at Mawira.

2. Outline geology of the study area

According to Harrison and Chapusa (1975), the area lies within the Malawi Province of the Mozambique Oregenic Belt. The entire western part of the area is referred to the Malawi Basement Complex of Precambrian to lower Palaeozoic age. Much of the eastern section is underlain by unconsolidated and superficial deposits of the Lakeshore Plain.

Biotite and hornblende-bearing gneisses, variably modified by migmatization, are the most usual and widely developed of the Basement Complex lithologies. Limited developments of pyroxene-hornblende gneisses occur in the west. Quartzo-feldspathic gneisses have been mapped within the biotite and hornblende-bearing gneisses, particularly in the southern and central sections of the area, and numerous smaller developments have been noted throughout. Calc-silicate rocks are widely distributed but comprise only a small proportion of the Basement Complex of the area.

In the south-west perthitic gneisses underlie the Ntchisi Mountains and are surrounded by pelitic schists; certain zones in the latter are either graphite bearing or highly ferruginous. Meta-igneous and igneous rocks of ultrabasic, basic and intermediate composition from pods, bands, diffuse zones and larger, describe intrusions in the country gneisses. Two major intrusive episodes are postulated on the basis of field relationships and mineralogical and textural criteria.

A major body of late to post-tectonic granite has been mapped at Sani and minor granite and pegmatitic intrusions and quartz reefs occur throughout the area. Alkaline dykes, which are possibly of upper Jurassic or lower Cretaceous age, are sparsely developed.

Throughout the Lakeshore Plain, Basement Complex rocks are largely obscured by alluvial and colluvial deposits and by limited developments of rather older unconsolidated and semi-consolidated sediments (Cretaceous or Tertiary age) near Kamuona. Thin, stony soils are developed throughout most of the Rift Valley escarpment zone to the west of the Lakeshore Plain, but the pelitic schists weather to brown, clayey soils.

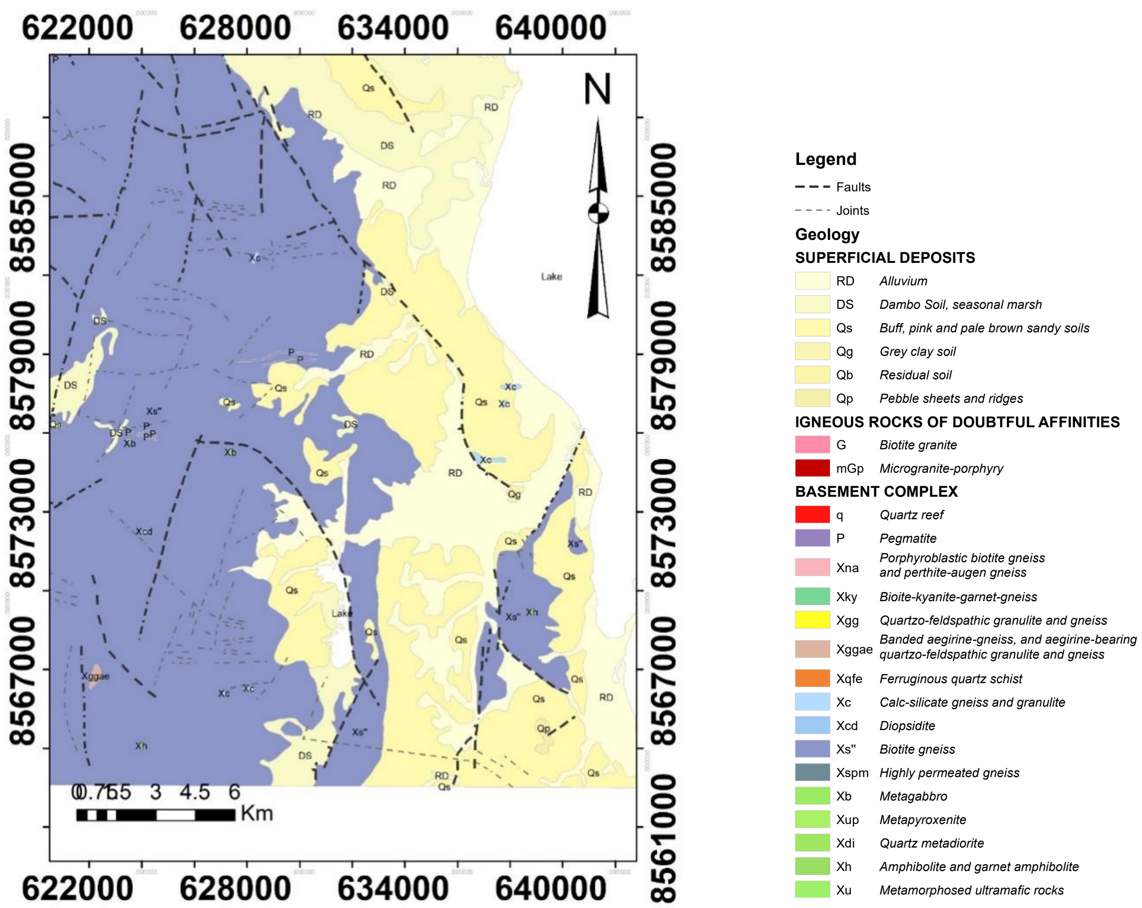

Figure 1: Geological map of the study area

Three phases of large scale deformation and folding are recognized in the Basement Complex. Regional metamorphism under amphibolite facies conditions is associated with the development of the regional foliation and gneissic banding, and the later episodes of deformation are considered to have taken place under conditions of decreasing metamorphic grade. Overall northerly trends prevail throughout much of the area, with the exception of the south-central sections where east-northeast trends are developed. The area was later subjected to intense faulting, again with an overall northerly trend, during the development of the Rift Valley. Although in the absence of stratigraphic control, the age(s) of the faulting cannot be stated with certainty, the presence, particularly along the Lakeshore Plain, of the scarps and fault-controlled lake cliffs, indicates that the latest fracturing is of a recent date (Harrison and Chapusa, 1975).

3. Materials and Methods

This research utilized aeromagnetic anomaly data sourced from the Geological Survey of Malawi (GSM), which was collected by Sanders Geophysics on behalf of GSM during 2012-2013. The data acquisition formed part of the World Bank's Malawi Governance and Growth Support Project (MGGSP), aimed at aiding the exploration of Malawi's mineral resources. The aeromagnetic survey employed a 3*-Scintrex CS3 Cesium Vapour Magnetometer, operating at a flight altitude of 80 meters. Flight lines were oriented perpendicular to regional structural trends in a NE-SW direction, spaced 200 meters apart, with tie lines covering distances of 2000 meters.Transient magnetic variation effects were corrected for in the collected data as well as the International Geomagnetic Reference Field (IGRF 2005 model) was eliminated. This IGRF corrected aeromagnetic anomaly data is the basis for all subsequent interpretations of the data.

The study area's total magnetic intensity (TMI) map was generated through a minimum curvature gridding method, with intervals set at 50 meters. To address the asymmetry linked with low-latitude anomalies, the reduced-to-pole (RTP) filter was employed on the TMI grid, producing the RTP anomaly map.Tilt Derivative (TD) and Analytical Signal Amplitude (ASA) was applied to the RTP TMI grid to enhance and delineate the signature of the subsurface structures and lithologic boundaries.

To achieve continuous subsurface coverage along the investigation line, resistivity data was collected using the PASI GEA RM1 1.0 resistivity meter (P.A.S.I. Srl, 2018). A setup (refer to Figure 2) comprising the resistivity meter and four electrodes (comprising current and potential electrodes) was arranged in a linear configuration (see Figure 3) using the specified array. Four electrodes labeled C1 (A), C2 (B), P1 (M), and P2 (N) were inserted into the ground at varying intervals. A known electrical current was applied to electrodes A and B, penetrating the ground. As the current traversed the ground, it encountered resistance from subsurface materials. Meanwhile, the potential difference between electrodes M and N was measured while maintaining a consistent separation distance between electrodes A and B. This potential difference is directly related to the resistance of subsurface materials between electrodes A and B. The AGI EarthImager 2D software was utilized for preprocessing and analyzing the data from the two profiles.

Figure 2: Resistivity survey setup in the field

4. Results and Discussion

The survey aimed to define the boundaries of the geothermal reservoir and the geological structures governing the flow of geothermal fluids. Magnetic methods prove highly effective in studying such structures and determining the depth to the heat source in geothermal environments. This study utilizes magnetic methods, both ground-based and airborne, to map out the potential geothermal reservoir in the study area.

Figure 4 illustrates the distribution of the total magnetic intensity across the study area. Total magnetic anomalies within the study area exhibit notably high anomalous values, with the highest recorded value reaching about 715 nT. Conversely, the blue areas on the map indicate anomalous values decreasing in magnitude, with the lowest recorded value being approximately -868 nT.

In the quest to pinpoint the geothermal reservoir's location, attention is directed towards areas with low anomalies. The magnetic anomaly map unveils two noticeable and expansive low magnetic anomalies situated to the south and north of the study area. These distinct low anomalies suggest the potential existence of a geothermal reservoir. The subdued magnetic signatures are likely attributed to the presence of heated fluids and are interpreted as outcomes of alteration effects on magnetic minerals induced by the demagnetization process inherent in rocks hosting steam and hot water.The positive anomaly can be interpreted as stemming from the intrusion process of materials with high magnetic susceptibility. The geothermal manifestations observed at the Mawira geothermal field are situated directly to the south of anomaly B. These manifestations are linked to a fault system trending in the NW-SE direction. This suggests that hot fluids likely migrated laterally towards the south of the identified potential reservoir B, eventually surfacing as a collection of hot springs.The hot springs are primarily linked to the identified reservoir via a network of faults that serve as conduits. Through these fault pathways, geothermal manifestations have been identified at various points across the study area, manifesting as hot springs (refer to Figure 3). These surface expressions of the hot springs are attributed to ongoing tectonic activities and the prevalence of diverse fault systems in the region. Particularly, the NW-SE and NE-SW faults are deemed significant conduits for geothermal resources. In the Mawira Nkhotakota area, there are over five hot springs clustered within a remarkably short distance. The surface temperatures of these hot springs typically range between 75°C and 85°C. The close proximity of these hot springs strongly suggests that they originate from the same reservoir source and, consequently, should exhibit similar chemical compositions. The thermal waters are classified as alkali chloride (Cl-Na-Ca) type. Analysis of manganese and iron content in the thermal water indicates that it has primarily mingled with meteoric water, with a minimal presence of saline components. According to conventional geothermometry, the reservoir temperature for the hot springs belt is estimated to be approximately 120°C±10°C. This implies an interaction between the reservoir water and shallow groundwater and surface water, leading to a decrease in temperature by the time it emerges from the hot springs.

Figure 3: Some of the hot springs in the study area

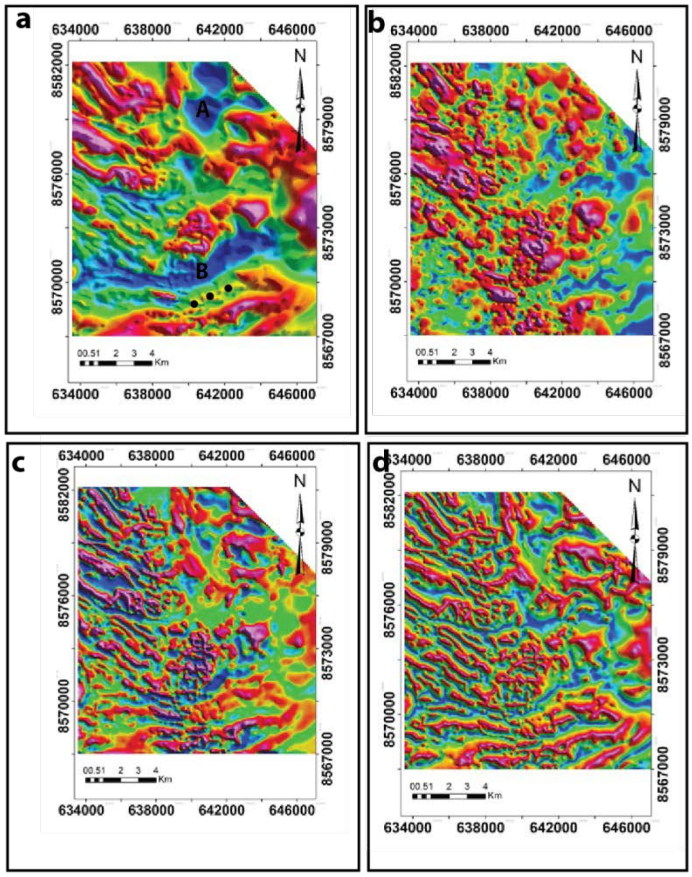

Figure 4: Magnetic data of the study area, (a) Total magnetic Intensity Map, the blue areas labeled A and B are potential reservoirs, the black dots are the hot springs Mawira I,2 and 3 respectively. (b) Analystic Signal image (d) Vertical derivative and (d)Tilt derivative image indicating dominant structures such as faults and fractures that act as fluid pathways for hot water.

The influence of faults and fractures on crustal fluids has been a significant focus in earth sciences. The static and dynamic effects of various stresses on rocks often lead to changes in the rock mass, such as the formation of fractures, faults, and, more broadly, alterations in permeability, which subsequently regulate fluid flow within the Earth's crust. Fractures and faults represent planes of tensile or shear failure, ranging from microscopic to regional scales, particularly in brittle rocks. These structural features are predominantly developed within competent rocks within the Earth's crust. Fractures typically form when the applied stress surpasses the elastic limit of the rock.These deformations play a crucial role in the distribution and regulation of crustal fluids. The migration of crustal fluids, particularly hydrothermal fluids, from the reservoir rock to the surface hinges on the presence of active faults and fractures in the subsurface.

Broadly, a geothermal system comprises several components: the heat source, the reservoir, the recharge area, and the connecting pathways, such as faults and fractures. These pathways facilitate the percolation of fluids into the reservoir (the host rock) and often lead to their emergence at the surface as fumaroles and hot springs.

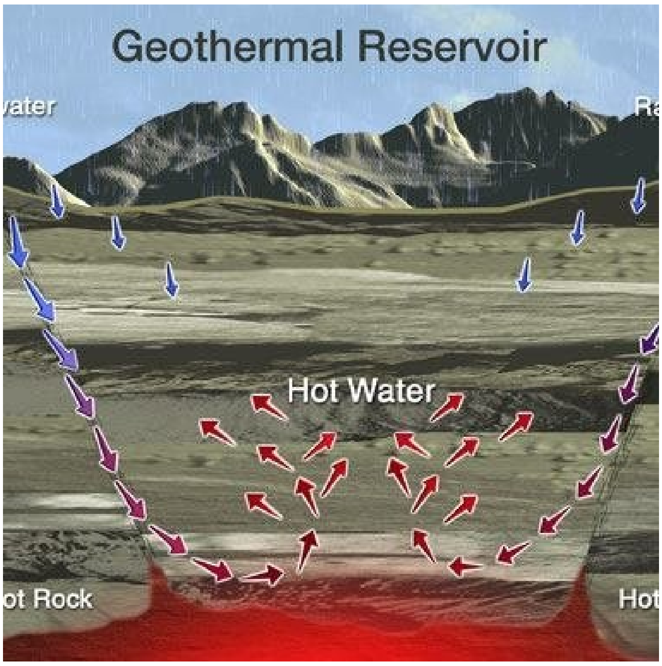

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Figure 5: Genetic model for geothermal manifestation

In the context of geothermal systems, it is commonly postulated that the heat originates from magmatic intrusion, typically reaching relatively shallow depths of approximately 5 to 10 kilometers. The reservoir comprises permeable rock formations, facilitating the circulation of fluids that absorb heat from the aforementioned heat source. This reservoir is capped by impermeable rock layers and is intricately linked to a surface recharge zone. Fractures within the geological structure allow for the infiltration of meteoric water, which may either entirely or partially displace the existing fluids within the reservoir. Consequently, these displaced fluids may manifest as springs or emerge during drilling activities.

In the study area, geothermal phenomena are closely linked with the Malawi rift valley. The emergence of hot springs is primarily facilitated by the connectivity between these springs and the recognized reservoir via a network of faults, which serve as conduits for thermal activity. Specifically, within the Nkhotakota region, hot springs manifest at different locations, owing to the prevalence of these fault systems. The surface expression of these hot springs is attributed to ongoing tectonic processes and the intricate faulting patterns present in the area. Among these fault systems, the NW-SE and NE-SW orientations are particularly emphasized as significant conduits for the transmission of geothermal resources within the region.

Resistivity Survey

The 2D electrical resistivity model along profile AB, illustrated in Figure 6, reveals complex subsurface structures indicative of potential geothermal activity.

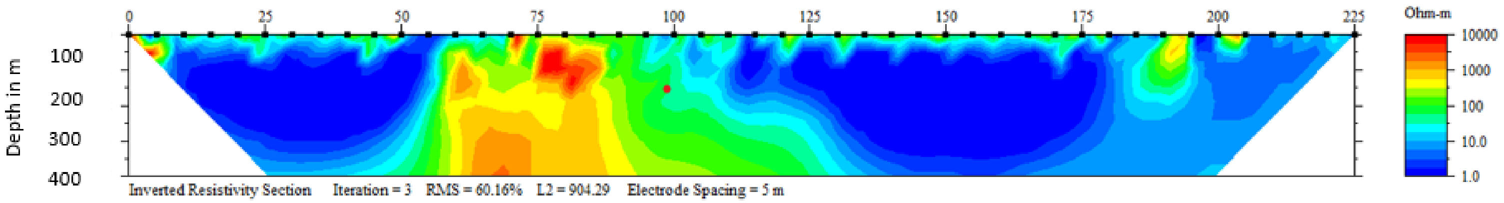

Figure 6: 2D resistivity profile indicating low resistivity potential areas

Two distinct zones of interest were identified based on their resistivity characteristics:

1. A low-resistivity zone was detected between 10 to 60 meters along the profile, extending from depths of 100 to over 400 meters. This zone is interpreted as a potential hot water reservoir due to its low resistivity values, which are consistent with the presence of geothermally heated, highly conductive fluids.
2. Another low-resistivity anomaly was observed between 100 to 225 meters along the profile, with a vertical extent from approximately 100 to 400 meters depth. The resistivity contrast and geometry of this feature suggest a second potential hot water reservoir, possibly originating from or influenced by a fault located around 100 meters along the profile. The elongated shape and orientation of this feature suggest a strong structural control, likely associated with a NE-SW trending fault system.

The resistivity model provides compelling evidence for the presence of two distinct geothermal reservoir systems within the study area. The spatial relationship between these low-resistivity zones and the inferred fault structures supports the hypothesis of fault-controlled geothermal fluid circulation.

The underlying high-resistivity gneissic formations likely serve as a heat source and/or cap rock for the geothermal system. The interaction between these basement rocks and the overlying lower resistivity zones suggests a complex interplay of geological structures and hydrothermal processes.

The observed resistivity patterns align well with the regional tectonic setting of the Malawi Rift system, where extensional forces have created favorable conditions for the development of geothermal resources. The north-south trending fault inferred from the resistivity data is consistent with the dominant structural grain of the rift, further supporting the tectonic control on geothermal fluid circulation.

5. Conclusions and Future Work

The magnetic and 2D electrical resistivity survey has provided valuable insights into the subsurface structure and potential geothermal reservoirs in the Mawira area. The identification of two distinct low- magnetic and low resistivity zones, interpreted as hot water reservoirs, underscores the area's geothermal potential. However, further investigations are recommended to refine our understanding of these potential reservoirs:

1. Additional resistivity profiles perpendicular to the current survey line to delineate the 3D extent of the reservoirs.
2. Magnetotelluric (MT) surveys to probe deeper structures and validate the resistivity model.
3. Detailed structural mapping to confirm the presence and orientation of the inferred fault systems.
4. Geochemical sampling and analysis of any surface thermal features to constrain reservoir temperatures and fluid compositions.
5. Shallow temperature gradient wells to directly measure heat flow and validate geophysical interpretations.

These additional studies will be crucial for assessing the economic viability of the geothermal resource and guiding future exploration and development efforts in the Mawira geothermal prospect.

The primary aim of this reconnaissance study was to pinpoint potential geothermal reservoir locations, identify secondary structures, and elucidate the fluid flow patterns from the reservoir to surface manifestations. Suspected geothermal reservoir sites were identified based on areas exhibiting low magnetic intensity values. The absence of magnetic sources in the magnetic data pinpointed the location of fluid-filled zones within the basin.

Detailed analysis of aeromagnetic data uncovered a highly faulted nature of the study area, indicative of significant tectonic activity. These fault structures play a pivotal role in facilitating the upward movement of hydrothermal fluids from the hot geothermal reservoir to the surface, where they manifest as hot springs.

Given these findings, further investigation is imperative to verify the presence of the geothermal reservoir. We advocate for comprehensive studies and additional geophysical assessments, such as resistivity surveys, particularly in potential areas B and A. These investigations aim to confirm the presence of the reservoir and determine its potential depth, providing crucial insights for subsequent exploration efforts.

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Paper 10: Deformation Control Monitoring of Deep Basement Excavation – Novel Methods and Applications

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Abstract
In this paper, a deep excavation field case study was presented. Servo technology was used directly during the actual excavation process to provide lateral support enhancement. The excavation-induced deformation without and with servo technology was monitored. Servo technology controlled at least 75% of the excavated pit lateral displacement. Servo technology actual field application effectiveness on deep excavated pit deformation control was validated. This paper provides a significant and practical reference on the existing, planned and future similar projects in Malawi.

Keywords: Basement Construction Site, Earth Retaining Structure, Soft Soil Excavation, Hydraulic Servo System, Deformation Control Monitoring

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1. Introduction

Underground excavations (for different structures such as high-rise buildings and underground carparks) to specific depths have increased recently with the increase in the urbanization worldwide [1]. However, the underground excavation results with the deformation challenge on the excavated pit and nearby structures [1], which is attributed to the insufficient capacity of the conventional lateral support methods [2,3]. Therefore, a comprehensive study is needed to enhance support members' lateral load capacity at the actual excavation sites.

Several studies have shown the effectiveness of steel support in restraining the displacements during the deep excavation [2-6]. Specifically, Wu et al. [2] used steel support on different excavations with depth of more than 10.0 m, and found the maximum displacements within 50 - 175 mm range. They had to use extra steel sections which led to the additional cost and bracing labor to satisfy the projects displacement limits [2]. Marco et al. [4] study used the preloaded steel to support a 13.0 m excavation in soft soil, and restrained displacement up to 34% in comparison with other supports like concrete struts. However, in a loaded case scenario, the stiffness of a preloaded steel support cannot be adjusted [5]. It loses axial loading capacity in unpredicted scenario where the exerted lateral loads surpasses the steel support stiffness [2]. Eventually, the deformations caused by excavation exceed the acceptable limits [6], and endanger the structures adjacent to the excavated pit [3,5].

Lately, some researchers have incorporated servo technology to the steel support, which is a feedback system that changes electric motion into a controlled motion using an electromagnetic device [7-12]. Its working principle during excavation compensates in real time for the loss in axial load support capacity by controlling displacement and axial load simultaneously [8]. However, the available number of servo technology application studies in excavation projects are limited [11], and the present ones depend on numerical modelling [9]. With a recent increase in the urbanization process in Malawi, there is much demand for structures that require deep excavation works such as high-rise buildings and underground carparks. Hence, the research with respect to the excavation-induced deformation control using servo technology at the actual construction site is still required. Thus, this study is significant to Malawi as a country as it shall contribute to the realization of the many existing and planned construction projects that require deep foundation excavations.

Therefore, in this study, a 14.20 m Triumph Unit (TU) foundation pit excavation project served as a reference for the servo technology application at the actual site of construction. Field works were performed by monitoring the induced deformation directly during the excavation process in regard to the addition of the servo method.

2. TU Basement Excavation Field Project

2.1 Description

The case for analysis in this paper is the excavation project of TU in Hangzhou, China. This project is preferred because it provides a practical use of the servo technology.

The excavated pit had a depth of 14.20 m with an area of 2134.60 m^2, and was enclaved within existing structures as shown in Fig. 1.

Sample survey and drilling methods were used to obtain the soil samples for in-situ and laboratory tests [13]. The project soil parameters within 29.50 m depth are shown in Fig.2, and the test results demonstrated that the site soils were mainly of soft clays.

With the strict need to protect the adjacent structures, the project excavation standards were set. One of the standards for displacements was set at 0.209% H (H represents excavated depth; standing for 29.857 mm). The set requirements corresponded to the different technical codes for deep excavation projects in urban areas [14-16]. Moreover, the inclinometer instruments were casted around the pit and the adjacent structures for monitoring purpose.

2.2 Excavated pit support structure

A 29.50 m deep TRD interpolated H700 section steel pile with a grade of Q235 and HN700x300 material parameter was used as a retaining wall of the excavated pit. The pile wall had the shear, compression, and bending resistance of 215.0 MPa, and 1.05 of plastic coefficient. Figure 2 displays the section support cross-section view of the excavated pit.

Three steel support levels (800 mm diameter and 16 mm thickness) were installed. The steel support was spaced 5.0 m apart diagonally at each installation corner. They were spaced 1.600 m, 4.500 m, and 3.500 m vertically respectively. Axial force of 1520 kN was used to preload the steel supports. Pre-loaded steel had 500 MN/m stiffness, 1.000 adjustment coefficient, a resistance of 9000 kN, adjustable ends, and was incorporated with the servo system for pre-stress application. Table 1 details the project execution steps.

3. Monitoring Results and Analysis

Three scenarios were used for excavation-induced displacement examination with unchanged excavation profile and three different scenarios of servo method application.

In the first scenario, the 1520 kN preloaded steel support was employed at level of 1.600 m, level of 6.100 m together with the depth level of 9.600 m. Determined displacement was 26.900 mm, 45.02 mm, and 60.75 mm at respective levels of 1.600 m, 6.100 m, and 9.600 m as shown in Fig. 3(a). The findings met the limit of 29.857 mm displacement at 1.600 m level only. Displacements increased with the depth as confirmed by the results at 6.100 m and 9.600 m depths.

Then a 640 kN servo load was added at 6.10 m and 9.60 m depths where a 1520 kN preloaded steel support was erected during second scenario. This brought the loading capacity at levels of 6.100 m and 9.600 m to 2160 kN. Then 10.02 mm, 21.98 mm, and 38.12 mm displacements were experienced in all three levels respectively (Fig. 3(b)). The displacements exceeded the acceptable requirement at 9.6 m erection depth only.

During a third scenario, servo axial load of 860 kN was applied at 9.600 m level alone. Then the support at 1.600 m level was kept unchanged at 1520 kN, the lateral support at 6.100 m level was maintained at 2160 kN, and the lateral support at 9.600 m stage became 2380 kN. The determined displacements were 7.12 mm, 11.44 mm, and 15.99 mm at respective level of 1.600 m, level of 6.100 m, and level of 9.600 m (Fig. 3(c)). Measured displacements satisfied the required limits in all three levels.

Maximum displacement was 15.99 mm as required during the third scenario. Comparing the displacement results of the third scenario to that of the first scenario, the displacement measurements in the third scenario declined on average by 75.9% with servo technology inclusion. Addition of greater servo load capacities in the third scenario played a tremendous displacement control role. This finding corroborated well with the previous results based on numerical simulations [8-12]. The servo load installed at deeper elevation depth optimizes support members axial load capacities and restrains the displacement of soil mass desirably [12,17].

4. Conclusions and Future Work

This study discussed the application of servo technology at the actual excavation site. TU project acted as a practical reference for servo technology application. With the servo technology application, the support structure stiffness increased and the soil mass displacements declined above 75% in comparison to using steel bracing as support structure alone. The excavation induced displacements were kept actively within the allowable limits. The project and adjacent structures' safety from the excavation-induced displacement effect was ensured. The actual servo technology application validated numerical simulation previous works. The site servo technology application works provided a basis for the use of servo technology on the existing, planned and future similar projects in Malawi.

While the works from this study have provided vital insights into the servo technology application, it is significant to acknowledge that this study did not demonstrate the pre-or post-loading effects of servo technology on the excavation-induced deformations. Future works could examine these phenomena in order to optimise the field application of servo technology.

Data Availability

This article includes the data used to support the findings.

Conflict of Interest

No conflicting interest is declared by the authors.

Figures and Tables

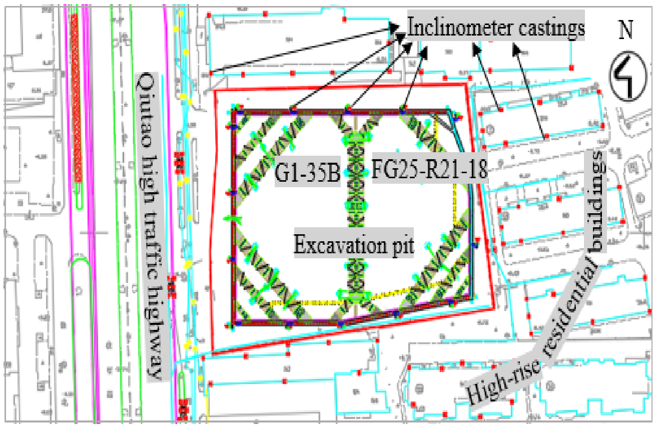

Fig. 29 Plan view of Triumph Unit project

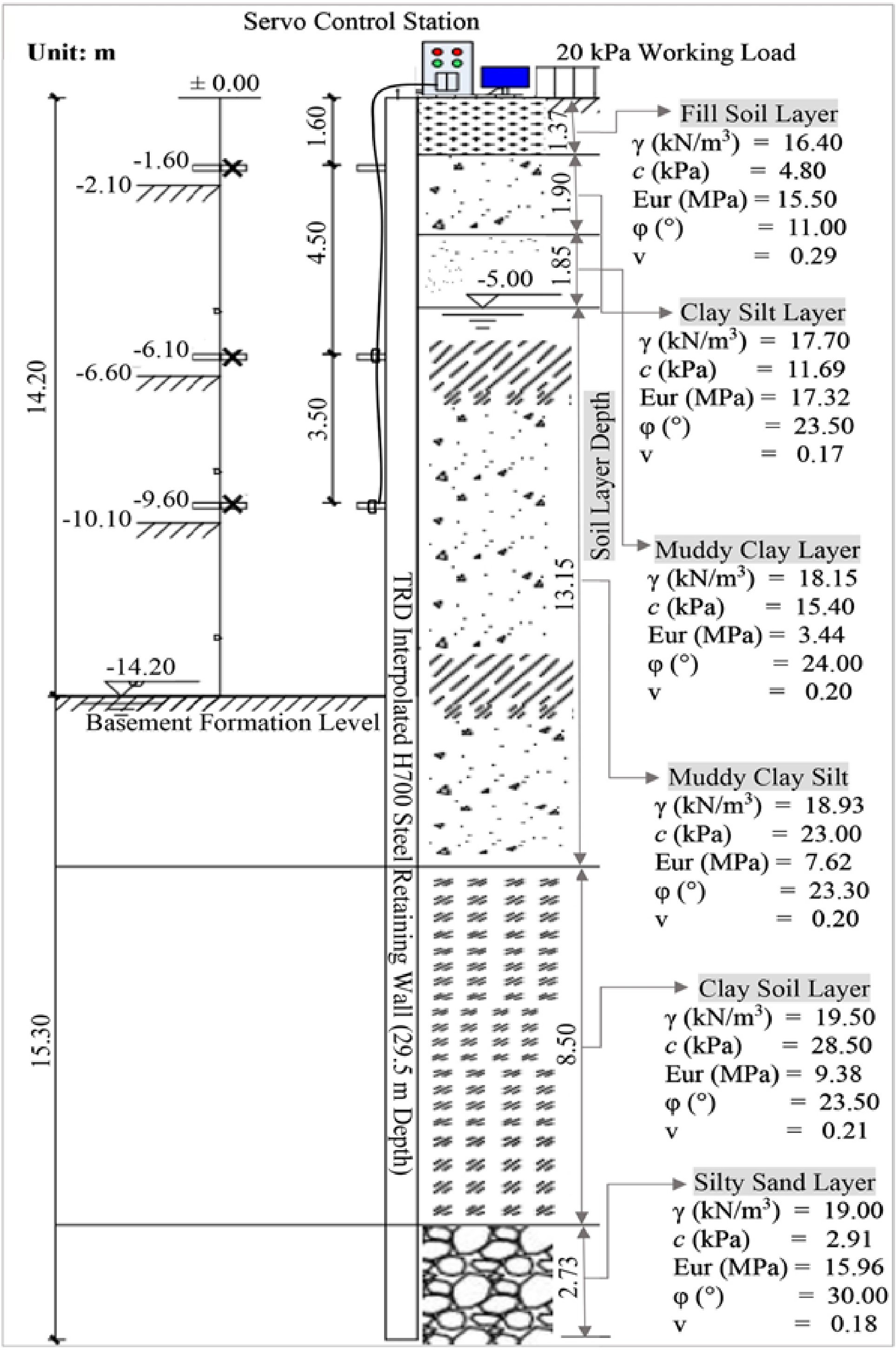

Fig. 30 Excavated pit cross-section view and soil parameters

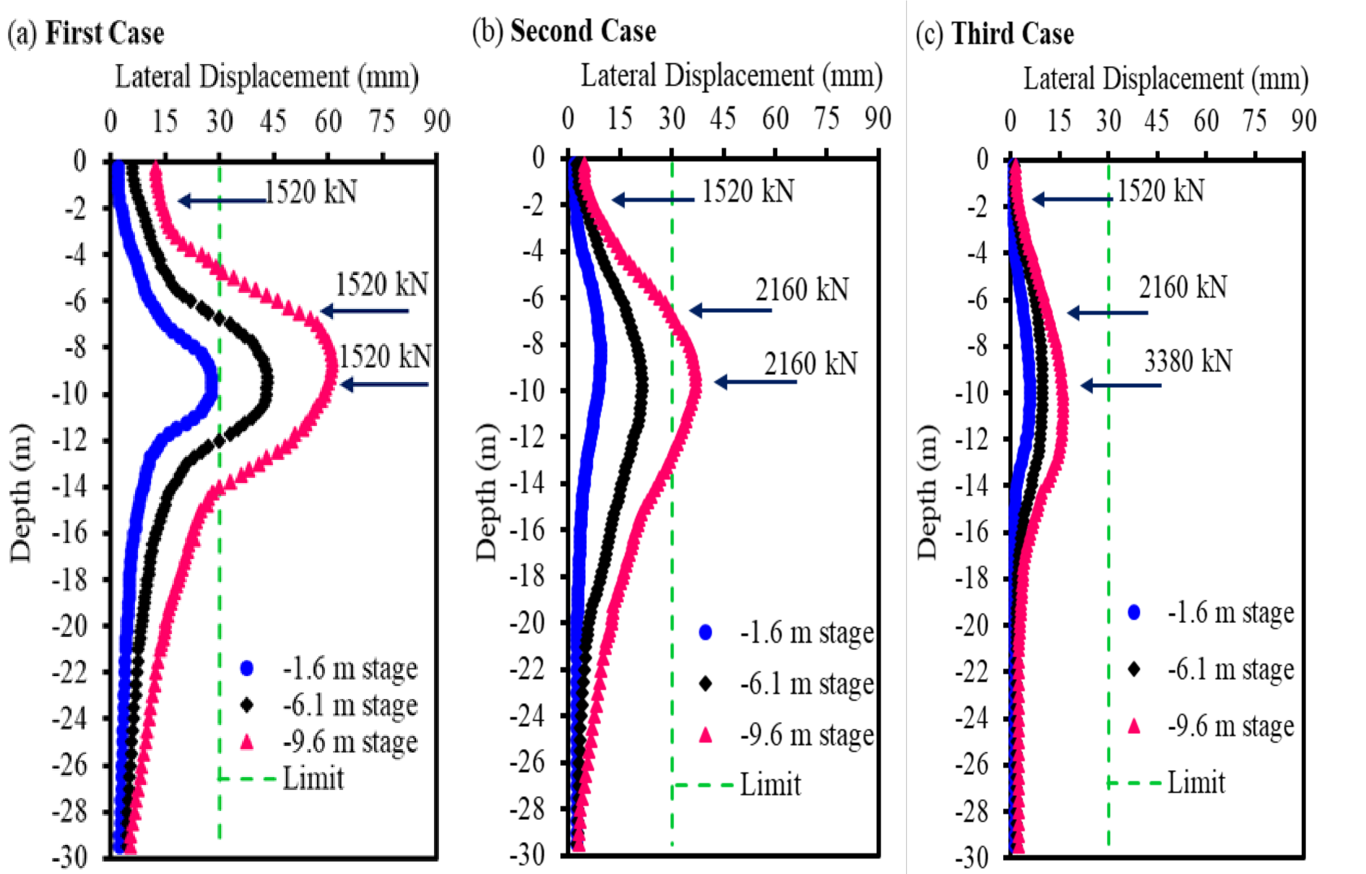

Fig. 31 Profile of wall displacement with respect to servo method application

Table 1 Project execution stages

Stage	Work	Depth (m)
1	Erect retaining wall	
2	Excavation	2.10
3	Install first support	1.60
4	Add servo support	1.60
5	Excavation	6.60
6	Install second support	6.10
7	Add servo support	6.10
8	Excavation	10.10
9	Install third support	9.60
10	Add servo support	9.60
11	Excavate to formation level	14.20

Acknowledgement

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Paper 11: Estimation of Small Hydropower potential using a HBV Hydrological Model Tool

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Keywords: Hydrological Modelling, HBV, Hydropower, Streamflow

Abstract
This paper reviews the application of a conceptual hydrological model in improving the estimation of stream flow for small hydropower and other water resources projects in data-scare regions. Small hydropower is among the renewable sources that are used widely. Small hydropower is characterized by the utilization of varying daily streamflow and power production. The study reviews the application of a conceptual model in different catchments globally and regionally through a thorough systematic literature review of research projects, papers, and case studies. The conceptual model used is the HBV (Hydrologiska Byrans Vattenbalansavdelning), developed at the Swedish Meteorological and Hydrological Institute (SMHI) in 1970 and has been used widely globally south. The model simulates, fills in missing data, and forecasts stream flow in gauged and scaling of hydrological data in ungauged catchments for water resources planning purposes. The systematic review also indicates the model's performance, particularly focusing on altering, adjusting, and changing model parameters due to limited techniques in hydrological data collection and management. Studies have indicated that the model's performance was satisfactory with a Nash-Sutcliffe efficiency coefficient (NSE) for model performance with an accepted value of > 0.74. The system review has indicated the model has been widely used in the global north and can ably simulate streamflows in data-scarce regions. The systemic review has also indicated that Flow Duration Curves (FDC) have been used to scale data from gauged to ungauged catchments and estimate hydropower in river basins. The limitation of the model is the limited application of the model in the global north. This review indicates that the HBV model can predict stream flows and can be applied to the planning of hydropower and other water resources projects.

1. Introduction

Hydropower is the main source of electricity globally, provides (Kwakye and Bárdossy, 2020). Globally hydropower contributes 16.6% to 23% of the total energy production (Sahin *et al.*, 2017). Hydropower is sustainable and has relatively few emissions (Khurana and Kumar, 2011). The exploitation of hydropower in the Sub-Saharan region remains a challenge (Killingtveit, 2019). Hydropower is classified as large, small, mini and Pico (Mdee *et al.*, 2018). Hydropower plants are broadly classified based on the size of the production, head, operation, and type of flow (Majumder *et al.*, 2013). The classification is important as it reflects the level of investment, expertise required, permits required, and generally the complexity of the power plant. (Singh and Singal, 2017).

Table 1: Hydropower development classification

Size	By capacity (MW)	By head (m)	By operation
Pico	0.005	0.2 < H >4	Run of river
Micro	0.1	1 < H <10	Reservoir
Mini	1	2 < H < 40	Pumped storage
Small	1-100	10 < H < 350	In-stream using technology existing facilities
Medium	100 -500	50 < H < 1300	
Large	>500	50 < H < 250	

Source: (Mdee *et al.*, 2018)

Small hydropower is widely used to provide electricity at a relatively lower cost (Ndhlovu and Woyessa, 2022). Small hydropower plants are classified as "run-of-river" which depend on daily stream flows to produce power (Ayik *et al.*, 2023). Small hydropower offers alternative and low-cost means of providing power (Mdee *et al.*, 2018). A study by Kaunda, Kimambo and Nielsen (2012) indicated that Malawi has a potential of 7.6 MW of small hydropower mostly in the northern region. A total of 5.8 MW is installed in the country and most of the plants are not functional for different reasons (Ehimen *et al.*, 2023).

The assessment of Small Hydro Plants (SHP) potential requires a high degree of estimation of stream flows and available gross head based on hydrological historical data and topographic data in a river basin (Kumambala, 2010). Historical hydrological data has limitations in terms of completeness, missing data and poor data collection techniques (Ndhlovu and Woyessa, 2022). The reliability of hydrological data is a concern in the decisive process concerning the design and operation of water resources projects (Bernier, 1987).

Application of the HBV model

Computer hydrological simulation models are a promising technique to improve the accuracy of the estimation of hydropower potential combined with remote sensing techniques (Ndhlovu and Woyessa, 2022). The computer-based models provide a platform for quick and easier assessment of potential hydropower sites so that developers understand the availability and adequacy of water resources and reliable decision-making (Kusre *et al.*, 2010). The use and promotion of hydrological models in water resources provide accurate and cost-effective techniques in planning and operations (Weigend *et al.*, 2023). The HBV model is a lumped hydrological model which has been used widely (Kwakye and Bárdossy, 2020). The required data for developing the HBV model is generally easily accessible and easy (Rusli, Yudianto and Liu, 2015).

The HBV model was initially developed and founded by the Swedish Meteorological and Hydrological Institute (SMHI) and was first applied in the early 1970s (Bergström, 2006). The HBV model has been used widely in the global north and is a standard model in the Nordic area and more than other 50 countries (Bergström, 2006). The model has evolved over the years and is used for various purposes. The model has among others evolved such as the HBV TEC version (Mendez and Calvo-Valverde, 2016), the NTNU Education version (Hamududu and Killingtveit, 2016) version of the HBV IWS version (Kwakye and Bárdossy, 2020) and HBV light among others. The model requires calibration and validation to confirm its performance and suitability of the model (Seibert and Bergström, 2021). HBV requires relatively few parameters compared to other types of models (Kwakye and Bárdossy, 2020). It is one of the models that provides robustness in simulating stream flows based on observed stream flows in a given catchment which generally requires fewer data and has few parameters (Seibert and Bergström, 2021). Most Low-income countries have scarce data due to limited funding in techniques for acquiring data for meteorology and stream flows (Kwakye and Bárdossy, 2020).

The choice of a hydrological model depends on so many factors. Some pertinent factors include the availability of the model to predict scenarios and the purpose and time availability to construct the model (Marshall, Nott and Sharma, 2005). The HBV model is widely used in the global south because it is a relatively simple model requiring few data and few parameters (Bergström, 2006).

HBV Model Structure

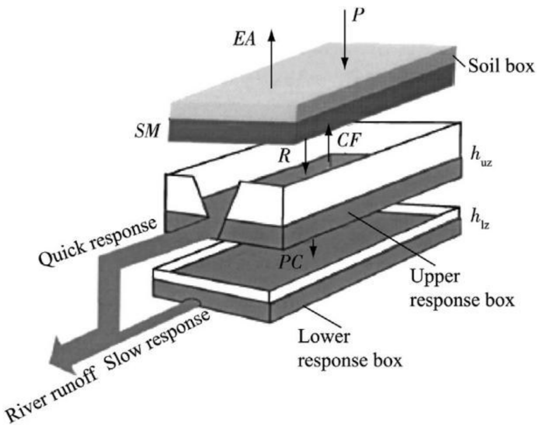

Fig. 1: The HB Structure adapted (Mendez and Calvo-Valverde, 2016)

The HBV model consists of three zones as shown in Fig. 1. The inputs are precipitation (P) and Evaporation (EA). Water flows from the Soil Moisture zone (SM) through infiltration to the Quick Upper response zone and percolates into the Slow Lower response zone. The combined runoff from quick and slow response is the stream flow.
The primary parameters of the HBV model are catchment area, field capacity (FC), evapotranspiration limitation (LP), capillary action (CFLUX), percolation of water (PERC), coefficient of subsurface (K_f), and the coefficient of groundwater (K_4), the power of recharge coefficient (β), power of coefficient for subsurface (α) (Rusli, Yudianto and Liu, 2015).
The model inputs are climate (precipitation and temperature) and spatial (Digital Elevation Model) data. There are four routines in the model: the precipitation routine, the soil moisture routine considers loss due to evaporation, infiltration and saturation of the soil, and the response function which consists of quick runoff and slow runoff (Mendez and Calvo-Valverde, 2016).

The soil moisture zone represents the soil surface and conditions. Parameters such as FC and LP represent the transformation of precipitation to water flow. The soil zone has a free parameter, which is the initial soil moisture (SM_o) used in the simulation (Rusli, Yudianto and Liu, 2015). The main variables in the simulation are in the equations.

$$EA = \frac{SM}{LP}EP \qquad (1)$$

$$R = P\frac{{SM_o}^{\beta}}{FC} \qquad (2)$$

$$CF = CFLUX\frac{FC-SM}{FC} \qquad (3)$$

$$SM = SM_o + P + EA + CF \qquad (4)$$

Where EA is the actual evaporation (mm), SM is the soil moisture storage (mm), EPA is the potential evaporation (mm), and P is the precipitation (mm).

The upper response zone has a similar transformation of water flow in which recharge (R) is the input from the soil moisture zone and the capillarity flux (*CF*). The initial water depth (h_{uzo}) percolates as percolation (*PC*) that moves to the lower response zone and the baseflow (Q_{uz}) which has the following equations (Rusli, Yudianto and Liu, 2015).

$$PC = PERC\frac{SM^{\beta}}{FC} \qquad (5)$$

$$Q_{uz} = K_f h_{uz}^{a+1} \qquad (6)$$

$$h_{uz} = h_{uz0} + R - CF - PC - Q_{uz} \qquad (7)$$

Where h_{uz} is the water depth in the upper zone (mm).
A similar scenario in the lower zone occurs. The percolation is the major input with h_{uz0} as the initial water level in the zone. Groundwater flow is the output. The total of Q_{uz0} and Q_{lz} is the considered total stream flow of the river basin. The equations are as follows: -

$$Q_u = K_4 h_z \qquad (8)$$

$$h_{lz} = h_{lz0} + PC - Q_{lz} \qquad (9)$$

$$Q_t = Q_{uz} + Q_{tz} \qquad (10)$$

Where h_{lz} is the water depth in the lower zone (mm).

Model performance.

Calibration of a hydrological model is performed to understand the relationship and correlation between the model parameters and the catchment response (Harlin, 1991; Zhang and Lindström, 1997; Rusli, Yudianto and Liu, 2015; Singh and Singal, 2017). This involves adjusting parameters manually to achieve the goodness of fit between the observed stream flow and the simulated flows (Hamududu and Killingtveit, 2016). The objective tests for calibration of a hydrological model are the Nash-Sutcliffe efficiency coefficient (*NSE*) widely used for goodness of fit, relative error (*RE*) and the root mean square error (*RSME*) and coefficient of determination (R^2) (Rusli, Yudianto and Liu, 2015; Zeybek, 2018). *NSE*, R^2, *RE* and *RSME* are dimensionless (Rusli, Yudianto and Liu, 2015). The NSE assesses the goodness of fit of a simulation of observed and simulated values through the variances of the variables. If the variance is large, then the model is deemed to be performing well (Bergström, 2006; Rusli, Yudianto and Liu, 2015; Zeybek, 2018).
The acceptable value of *NSE* and R^2 must be close to 1.0, while the values of *RE* and *RSME* should be as close as possible to zero (Rusli, Yudianto and Liu, 2015). The other test for the performance of a hydrological model is the coefficient of determination (R^2) which is used to determine the goodness of fit (Tibangayuka, Mulungu and Izdori, 2022).
Several studies have indicated that hydrological models were calibrated and validated with sub-catchments and a best-of-fit greater than $NSE > 0.74$ was achieved (Kwakwe & Bardossy 2020,

Hamududu & Killingveit, 2016). The equations below have been used to check the goodness of fit of a hydrological model: -

$$NSE = 1 - \left(\frac{\sum_{t=1}^{T}(Q_{oi}(t) - Q_{si}(t))^2}{\sum_{t=1}^{T}(Q_{oi}(t) - Q)^2}\right) \qquad (11)$$

$$RE = \frac{\sum_{i=1}^{n}(Q_{si} - Q_{oi})^2}{\sum_{i=1}^{n} Q_{oi}} \qquad (12)$$

$$RMSE = \sqrt{\frac{1}{n}}\sum_{i=1}^{n}(Q_{si} - Q_{oi})^2 \qquad (13)$$

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \qquad (14)$$

Where Q_{oi} (t) and Q_{si} (t) represent the observed and simulated streamflow at the time (t) respectively and Q is the mean streamflow.

Flow Duration Curves

Stream flow estimation in ungauged catchments remains a subject of research (Ndhlovu and Woyessa, 2022). A study by Ngongondo *et al.* (2013) recommended use of the Flow Duration Curve (FDC) in the analysis of the stream flow regime. The flow duration curve is a graphical presentation of the percentage of time of exceedance of a particular stream flow (Vogel and Fennessey, 1994).
Conventional techniques with reasonable high accuracy have been developed to predict streamflow data from gauged to ungauged catchments (Ndhlovu and Woyessa, 2022). Some of the common methods to transfer stream flows include the Drainage Area Ratio (DAR), the Standard Mean Method (SMM), the Mean and Standard Deviation Method (MSM), and the Regional Flow Duration Method (Castellarin *et al.*, 2004; Ndhlovu and Woyessa, 2022). In a study, of the Kabompo River basin by Ndhlovu and Woyessa (2022), the Regional Flow Duration Method was used and the results were acceptable.

Derivation of Flow Duration Curves

Flow duration curve is a handy technique to streamflow of a particular river at a given time of exceedance (Burgan and Aksoy, 2022). FDCs are useful for determining flooding and lean stream flows. In a gauged catchment, the FDC is derived by sorting the observed streamflow data from the largest to the smallest and plotting each against the corresponding exceedance percentages (Requena, Chebana and Ouarda, 2018). Regional FDCs are generated at ungauged catchments based on the gauged FDCs (Burgan and Aksoy, 2022). Regional curves are useful in hydrological practices such as the urban stormwater system design, environmental flow allocation, hydropower potential and water availability (Mutua and Klik, 2007; Mohamoud, 2008)
FDCs are built as explained in the following (Ridolfi, Kumar and Bárdossy, 2020):

- rank the streamflow values in descending order.
- plot the sorted values against their corresponding frequency of exceedance.

The duration d_i of the ith sorted observation is its exceedance probability P_i. If P_i is estimated using a Weibull plotting position (Weibull, 1939), the duration d_i for any q_i (with i=1; …; N) is

$$P_i = \frac{I}{N+1} \qquad (15)$$

Typical FDC curve (Mutua and Klick, 2007)

2. Results and Discussion

Previous studies have shown that the value of hydrological models provides a robust and accurate measure of stream flows for the planning of hydropower and water resources projects in data-scarce areas. The scaling of such simulations needs to be carefully studied. The application of an integrated methodological approach on the use of regional FDCs, linear regression, and GIS tools to estimate flows and potential head of hydropower for the ungauged sites is a novelty in the Kabompo River Basin(Ndhlovu and Woyessa, 2022). It has shown promising results in developing countries (Hamududu and Killingtveit, 2016).

A study by Tibangayuka, Mulungu and Izdori (2022), in Tanzania assessed the HBV model in the data-scarce tropical catchment, and the model was calibrated and validated in multiple catchments with limited hydrological and climatic data with varied topography. The goodness of fit was found at *NSE* = 0.73 and R^2 = 0.74 respectively (Tibangayuka, Mulungu and Izdori, 2022) The minimum values for *NSE* and R^2 values are 0.65 and 0.7 respectively (Bergström, 2006; Seibert and Bergström, 2021; Tibangayuka, Mulungu and Izdori, 2022). The results indicate that the HBV model can adequately be used to predict stream flows in data-scarce tropical catchments.

Another study A study by Moshe and Tegegne (2022) in Ethiopia applied the hydrological model to assess potential small hydropower. The *NSE* = 0.76 was determined which was found to be satisfactory.

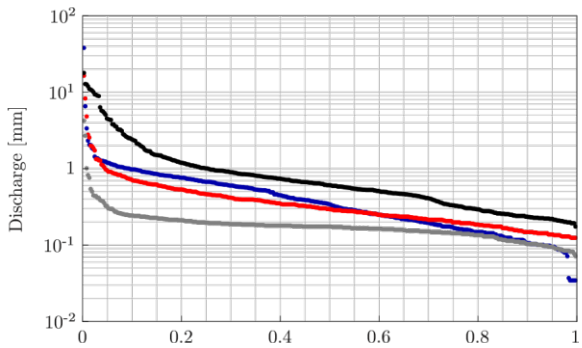

Fig. 2: Runoff-rainfall model

A similar study by Nonki *et al.* (2021) performed a runoff-rainfall model using HBV – Light in the Upper Benue River Basin in Cameroon, the performance varied from good to the marginal band of uncertainty. The model was useful for estimating streamflow for hydropower estimation.

In another study by Hamududu and Killingtveit (2016), assessed hydropower under climatic changes in the Zambezi River basin. The HBV model was integrated with other computer software such as nMAG to assess the hydropower in a changing climate. The HBV model was used to predict streamflow changes in the catchment. The average R^2 = 0.78, the fit was to be reasonable and good for use (Hamududu and Killingtveit, 2016).

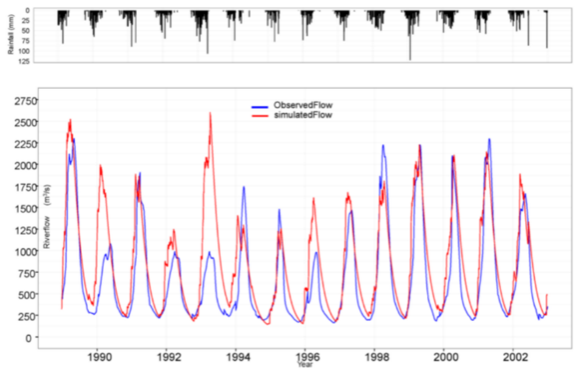

Fig. 3: Victoria falls (Hamududu and Killingveit, 2016)

In the Kafue river basin, the average $R^2 = 0.75$ was found by Hamududu and Killingtveit (2016). This was lower than the Zambezi, in both cases, the model performed well to predict streamflow to estimate hydropower potential.

A study by (Mavaringana *et al.*, 2023) the modelling of flood events in climate-changing scenarios in the Pungwe River (two catchments) used the HBV model and the calibration was adequate. The NSE > 0.86 and $R^2 = 0.89$

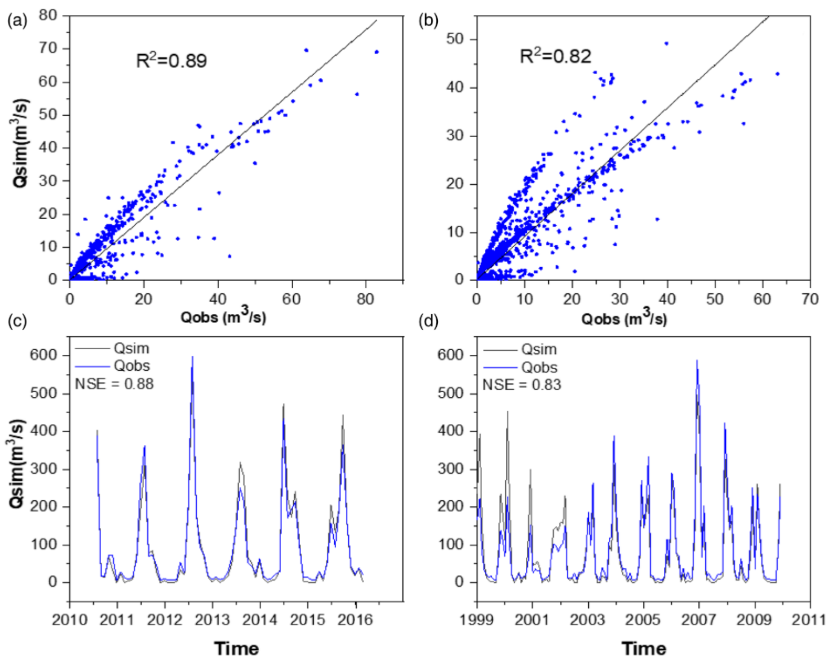

Fig. 4: Calibration of the HBV model (Mariangana et., 2023)

Estimation of Hydropower Potential

The estimation of hydropower potential is computed from a derived flow duration curve of the gauged stream flow regime (Kwakye and Bárdossy, 2020; Hamududu and Killingtveit, 2016); Ayik *et al.*, 2023). Often the 95% time of exceedance is the minimum stream flow design criteria for 'run of river' power plants. The $Q_{95\%}$ is the primary power for a particular catchment flow regime. The computation of hydropower is as follows.

$$P = \eta \rho Q g h \tag{15}$$

Where P = power (Watts), n = efficiency of the turbine, p = density of water (1000kg/m3), Q = streamflow (m3/s), h = gross head (m). The gross head is determined by the DEM for the catchment (Abebe, 2014).

A study by Ndhlovu and Woyessa (2022) assessed hydropower sites for the Kapombo River basin in ungauged catchments at 95% time of exceedance. The study successfully evaluated small hydropower potential in the river basin.

Table 2: Hydropower computation for Kapombo

Hydropower Potential Site (Ungauged)	Area (km^2)	Potential Height(m)	Estimated Design Flow (m^3/s)	Estimated Potential Gen Capacity (KW)
Mujila Falls Lower site	501.04	40	16.32	5123
Mujila Falls Upper site	1275.98	30	17.09	4024
Kasanjiku falls site	1625.11	40	17.44	5475
Chauka Matambu fall site	555.03	40	16.37	5139
Satelenge Falls	3598.22	15	19.41	2285
Kangongo Falls	0.3	4	15.81	496

Source : (Ndhlovu and Woyessa, 2022)

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SESSION 3A: Construction and Transport

Paper 12: Mechanical Performance of Egg Shell-based Supplementary Cementitious Material

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Abstract

The waste disposal is a major concern in the drive for environmental protection as enshrined in Malawi 2063 agenda. Malawi has suffered from the impact of global climate change which is exacerbated by the incessant emissions of greenhouse gases emanating from cement production. The blended cement with waste-based supplementary cementitious materials (SCMs) is the solution to the environmental challenges. Egg shells are wastes and potential (SCM) whose application in cement production can tremendously address inherent global landfill challenges while minimizing carbon footprint from clinker production. This paper presents an investigation on the mechanical performance of the egg shell powder (ESP) blended cement at the dosages of 5%, 15% and 30% and the corresponding clinker factors of 0.9, 0.8 and 0.65. Standard consistency and setting time were determined by series of physical tests. The compression tests at water to cement (w/c) ratios of 0.45, 0.5 and 0.6 were performed, and the results were compared with the performance of the conventional masonry cement on the Malawian market. The results revealed that standard consistency varied linearly with ESP dosages while setting time reduced with ESP dosages. The values of setting time met the minimum requirement for cement according to BS EN 197-1:2011. The optimum (w/c) was found to be 0.5 with the highest compressive strength of 26.1 at 5% ESP dosage. The strength of ESP-blended cement exhibited superior strength compared to batches of masonry cement on Malawian market, showing potential use of the ESP blended cement in the Malawian construction industry.

Keywords: Compressive strength, setting time, standard consistency, dosages, SCM
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1. Introduction

The construction industry strives to achieve a carbon free global concrete production. Limited utilisation of natural resources, energy and decreasing of greenhouse gases emission have become critical components of construction management as volume of cement and concrete production is projected to continuously increase in the next two decades. Concrete is exclusively used in the construction industry and it plays a very vital role in realising resilient infrastructure.

There has been a growing concern over impacts of climate change which are exacerbated by global greenhouse gas emission which is at 9% from cement industry. The economic development in developing economies has caused an increase in the demand for concrete [1, 2]. Therefore, there is a need to explore alternative ways of cement production that are cost effective and environmentally friendly [3].

Literature indicates that the use of supplementary cementitious materials (SCMs) to reduce the clinker content in cement is the most successful intervention to reduce greenhouse gas emissions in the global cement industry. Several researchers[4-8] have proposed the use of binary blended cement with (SCMs) from the industrial waste products such as fly ash, silica fume, and GGBS, however their availability to meet the growth in cement demand depends on the level of industrialisation [9].

The pozzolanic reaction of natural SCM depends on their chemical composition, chemical reactivity index, and mineralogical composition mainly on the amounts of reactive silica [10]. Adding 5–20% of different SCMs positively affect mechanical properties, durability, and microstructures of the cement composite materials.

Malawi's manufacturing industry is currently growing and susceptible to economic shocks, hence the conventional SCMs are available in limited quantities which makes it difficult to replace clinker content at a large scale. Nevertheless, animal-based waste such as egg shells have mineralogical composition similar to industrial-based SCMs. Eggshells are agricultural waste materials generated from chick hatcheries, bakeries, fast-food restaurant. Using eggshell powder is a means of reusing animal waste that may pose environmental management challenges especially the need of large landfills [11]. Malawi envisions to increase agricultural production in its quest to realise self-reliant economy [12]. The efficacy of converting eggshell for beneficial cement production is an idea worth embracing for Malawi's sustainable economic development.

This study aims at exploring potential use of eggshells produced in Malawi for cement production. The egg shell powder is prepared and characterised to establish mineralogical composition. A series of compression tests of a blended cement with eggshell powder dosages is performed to determine optimum compressive strength. The results are compared with the strength of Portland pozzolan cement available on Malawian to ascertain potential use of eggshells in the cement industry.

2. Materials and Methods

Materials

The materials used herein were clinker, gypsum and eggshells. Both clinker and gypsum were supplied by Lafarge cement manufacturers. Eggshell from hatcheries and restaurants within Blantyre City. The cement mortar was prepared using river sand with particle size distribution in conformity with EN-196-1.

Material Preparations

Limestone, gypsum, and clinker were ground separately to produce fine powder. The eggshell powder was prepared by cleaning and removal of membranes followed by oven drying at 60°C and grinding. All materials in powdery form were sieved using 75um aperture sieve.

The ternary binder system was subsequently prepared with constant gypsum content of 5% and eggshell dosages of 5%, 15% and 30%. The clinker contents were 90%, 80% and 65% for each batch, respectively. The river sand for cement was graded to achieve particle distribution that conformed the grading of standard sand according to EN 196-1. The ground materials are shown in Figure 1.

Figure 1: Clinker, Gypsum and Eggshell powder

The analysis of mineralogical composition of the materials was performed using X-ray Florescence (XRF) analyser. The summary of results is shown in Table 1.

Table 1: Mineralogical composition of materials

Mineral	Mineral Composition %		
	Clinker	Eggshell powder	Gypsum
Na_2O	0.03	0.114	0.003
MgO	4.00	0.756	4.80
Al_2O_3	7.35	3.443	1.90
SiO_2	34.07	18.99	1.50
P_2O_5	0.36	0.460	0.00
SO_3	1.19	0.886	52.5
Cl	0.03	0.00	0.005
K_2O	0.65	0.113	0.01
CaO	52.17	70.43	32.01
TiO_2	0.3	0.00	0.02
MnO	0.004	0.00	0.004
Fe_2O_3	2.58	0.75	0.07
LOI	0.00	4.1	7.7

Experimental Programme

The cement mortar for testing physical and mechanical properties such as standard consistency, setting time and compressive strength was prepared at water-binder (w/b) ratios of 0.45, 0.5 and 0.6. The specimens were cured in the full water bath (see Figure 2) and the total of 36 specimens of dimensions of 50 mm x 50 mm x 50 mm were prepared for testing. Three batches of masonry cement available on the Malawian market designated as MC1, MC2, MC3 were randomly collected from the retail suppliers and tested to serve as reference for strength comparison.

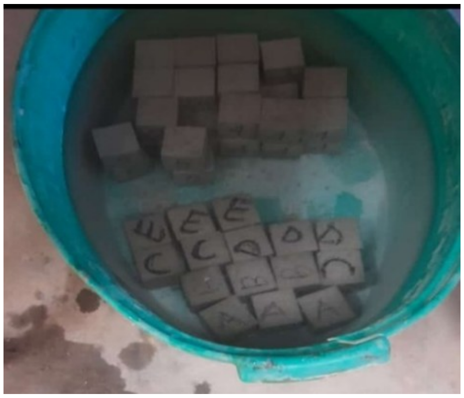

Figure 2: Specimens' curing process

The summary of experimental programme is shown in Table 2.

Table 2: Experimental design

Mix design %			Water-Binder ratio
Clinker	Gypsum	Eggshell Powder	
90	5	5	0.45
80	5	15	0.45
65	5	20	0.45
90	5	5	0.50
80	5	10	0.50
65	5	15	0.50
90	5	5	0.60
80	5	10	0.60
65	5	15	0.60

Specimen preparation for compression, standard consistency and setting time tests

The specimens for compression test were prepared according to EN 196-1.The testing was performed after 7 and 28 days of curing. On the other hand, standard consistency and setting time were conducted in accordance with EN 196-3.

3. Results and Discussion

Variation of standard consistency

The results of standard consistency of the blended cement mortar are summarised in Figure 3.

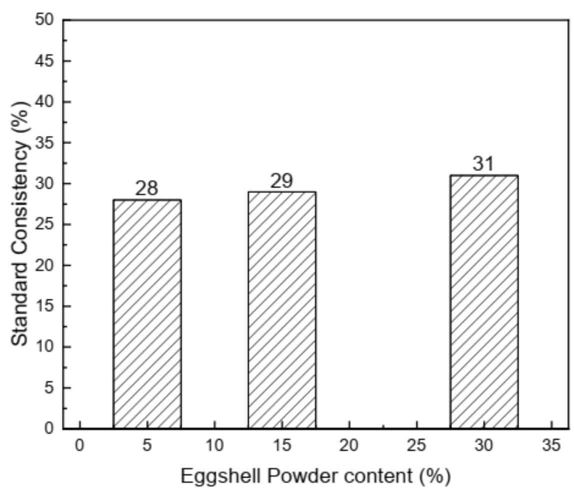

Figure 3: Standard consistency of ESP cement paste

It was observed that standard consistency of the cement paste varied linearly with increasing eggshell powder. An increase of 11% was registered at 30% ESP content. This could be attributed to an increase in the amorphous phase of ESP. Amorphous phases provide a large surface area for water absorption as a result of the disordered arrangement of molecules that allows penetration and dissolution of the water[13].

Variation of setting time

The effect of ESP on setting time of cement paste is shown in Figure 4. It was worth noting that both initial and final setting times reduced with the corresponding increase in the ESP dosage. Initial setting time varied inversely between 145min and 125min for 5% ESP and 30% ESP, respectively. On the other hand, final setting time varied between 200min and 170min for 5% ESP and 30% ESP, respectively. It is worth acknowledging that BS EN 197-1:2011 [14] recommends a minimum of 75min of initial setting time for conventional cement, thus all ESP-based cement herein studied met minimum requirement.

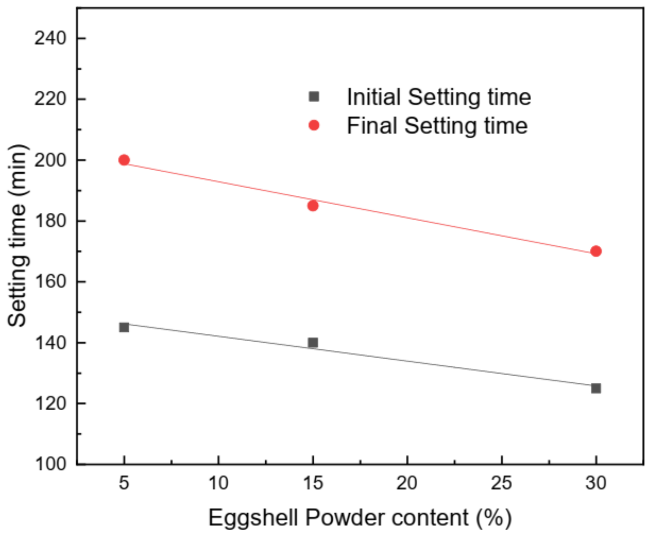

Figure 4: Variation of setting time with ESP content

Effect of water -binder ratio on compressive strength

The effect of water to binder ratio on the compressive strength is shown in Figures 5 and 6 for 7 and 28-day curing, respectively.

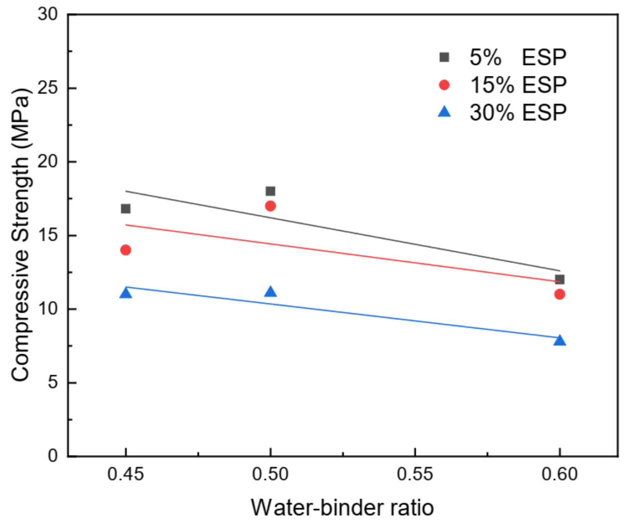

Figure 5: Variation of compressive strength with ESP content after 7 day-curing

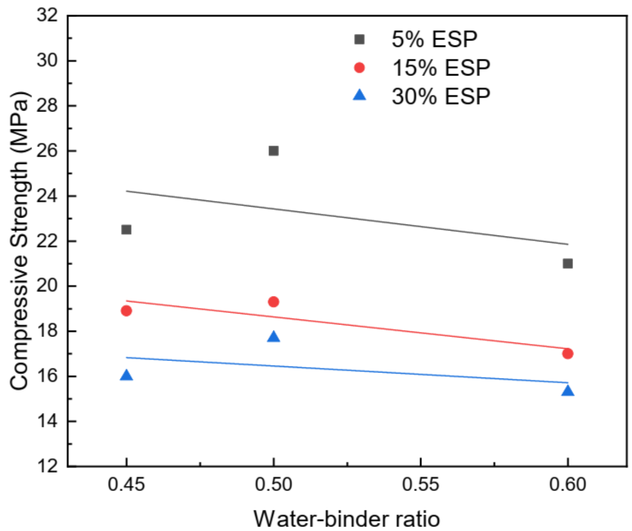

Figure 6: Variation of compressive strength with ESP content after 28 day-curing

Loss of strength was observed with an increase in ESP content. With 0.6 w/b ratio, the cement mortar, at 7-day curing, with 5% ESP registered 29% strength loss, 15% ESP indicated 21% loss in strength and that with 30% ESP registered 29% strength loss compared with mortar specimens prepared with 0.45 w/b ratio. The same trend was exhibited after 28 days of curing. The mortar specimens with 5% ESP showed strength loss of 7%, 15% ESP indicated 10% loss in strength and 30% ESP indicated strength loss of 4 % in comparison with specimens prepared with 0.45 w/b ratio. The segregation of aggregates in the cement mortar due to water in excess of the amount required for hydration could be a possible cause of low-strength development at high w/b ratio [13]. The pores created at the early stage due high w/b ratio were refined by the hydration products after considerable curing period, hence a marginal loss of strength after 28 days of curing.

Effect of Eggshell powder on compressive strength

The effect of ESP on compressive strength is shown in Table 3. It was observed that strength varied inversely with ESP dosages. The rapid early strength development was shown after 7 days of curing and a marginal strength development was registered after 28 days. The optimum w/b ratio was 0.5 and the maximum strength of 26MPa was registered with 5% ESP. The increased amount of calcium oxide (CaO) in ESP was responsible for an improved early-age strength development. The reduction in strength was due to the dissolution of clinker content emanating from the ESP replacements[15, 16]. This trend is typical of SCMs- based cement [6].

Table 3: Compressive strength with ESP dosages

ESP Content %	Compressive strength MPa					
	Water-cement ratio (7 days)			Water-cement ratio (28 days)		
	0.45	0.5	0.6	0.45	0.5	0.6
5	16.8	18.0	11.8	22.5	26.0	21.0
15	14.0	17.0	11.0	18.9	19.3	17.0
30	11.0	11.1	7.8	16.0	17.7	15.3

Table 4 compares the strength between three batches of masonry cements obtained from retail outlets and ESP-blended cement. The results showed that ESP-blended cements had better strength performance than batches on the market, indicating potential application of ESP-based cement in the Malawian construction industry.

Table 4: Comparison of ESP-blended cement with masonry cement batches on the market

Water-cement ratio	Compressive strength MPa					
	Masonry cement batches			ESP content %		
	MC1	MC2	MC3	5	15	30
0.45	19.2	*15.03*	10.6	22.5	18.9	16.0
0.5	18.9	*14.83*	10.4	26.0	19.3	17.7
0.6	11.6	*9.94*	7.0	21.0	17.0	15.3

4. Conclusions and Future Work

Based on the acquired experimental results, the following conclusions can be drawn:

- The ESP-blended cement demonstrated superior performance in strength compared to batches of masonry cement on the Malawian market. Therefore, environmental sustainability as enshrined in Malawi 2063 agenda can be achieved by replacing clinker with eggshell powder to promote sustainable development with clean and secure environment.
- The maximum dosage of ESP in the blended cement should be 15% at 0.5 water to binder ratio to ensure cost effectiveness of the cement batch.

It is recommended to establish hydration rate and durability properties of ESP based cement. The main durability parameters should include resistance to sulphate attack, porosity, resistance to elevated temperature, shrinkage and resistance to chloride penetration

5. Acknowledgement

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Paper 13: Adoption and challenges of Fourth Industrial Revolution Technologies in Malawian

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Abstract: The Fourth Industrial Revolution (4IR), also known as Industry 4.0 represents a major shift towards integrating digitization, automation, and information technology. This transformation is bringing about changes in standards and industrial practices. While technologies like the Internet of Things (IoT) robotics, drones and artificial intelligence (AI) are revolutionizing other sectors, the construction industry in Malawi has been slower to embrace them, hindering optimal performance and productivity. Despite the significant Global studies on the applications of 4IR in the construction sector worldwide, there hasn't been a thorough scientometric analysis of current status of technology adoption in Malawi. This study used a Quantitative method to assess the degree of adoption of technology trends in the Malawi construction field. A total of 80 questionnaires were distributed to building construction professionals, in the industry using purposive sampling methods and the collected data was thoroughly analyzed using descriptive analysis. The findings highlighted the technologies used throughout stages of construction from design to operation and maintenance. These technologies include 3D printing, drones, Building Information Modeling (BIM), and sensors. Furthermore, the research findings revealed lack of knowledge about Industry 4.0; high cost of implementation; and fear of change are the most significant issues hindering the adoption of 4IR in Malawi. The study concluded by providing recommendations to overcome these prevailing challenges and emphasize the potential of 4IR technologies in enhancing sustainable development in the Malawian construction industry.

Keywords: Construction, Fourth Industrial Revolution, Industry 4.0, 4IR, Adoption, Malawi

1. Introduction

The construction industry has historically been beset by perennial issues, including but not limited to budget overruns, schedule delays, poor quality delivery, health and safety problems, unnecessary material waste, project failures, and unsustainable construction methods (Fischer 2009; Mustapha et al. 2013; Sultan and Kajewski 2013). However, Malawi's building sector is not an exception to these challenges. According to Kamara et al. (2010), the majority of these recurring issues have become the norm, making the construction industry one of the sectors ideal for a radical shift. Concerns raised by Kamara et al. (2010) include unpredictability in the quality of infrastructure, cost, turnaround time; and dissatisfied clients when compared to other industries.

Unfortunately, poor project delivery and insufficient quality persist in Malawi's construction sector, despite the government's best efforts to improve the industry's capacity, resilience, quality, and sustainability through the National Construction Industry Development Act of 2016 and the Building Standards Act of 2018 (Mfune, 2021).

The construction industry is vital for promoting economic growth in developing nations like Malawi. The sector is crucial in driving the economic progress of the country, providing many job opportunities to a large section of Malawi's population, which has led to a fall in the unemployment rate. According to the African Development Bank Group's 2023 report, the industrial sector contributed 6.5% of Malawi's Gross Domestic Product (GDP). Improving the efficiency, productivity, performance, and sustainability of the Malawian Construction Industry will greatly influence the country's economy and infrastructure development.

A thorough analysis of the available literature has shown that the Fourth Industrial Revolution (4IR) provides a way to address current challenges by offering multiple opportunities to revolutionize industries through the incorporation of cutting-edge technologies such as Building Information Modelling (BIM), Artificial Intelligence (AI), Additive Manufacturing/ 3D printing, and Drones (Aliu and Oke, 2023; Keogh and Smallwood, 2021; Malomane et al., 2022). 4IR is currently a widely discussed subject because of its significant transformative potential across various industries, which has the primary focus of creating an intelligent and integrated ecosystem that spans several activities and sectors. This will address the issue of fragmentation that is commonly observed in Malawi's construction sector (Nasrun et al. 2014). Implementing new digital technology in the worldwide construction industry can result in an annual cost savings of around $1.7 billion (Sutton, 2018).

Despite the potential for enhancing performance and efficiency in the construction industry, there is a notable dearth of research on 4IR technologies in the construction sector in Malawi. The lack of comprehensive study on 4IR technologies in the Malawian context emphasizes the need for further investigation, considering the paucity of empirical studies on the adoption and challenges related to the implementation of digital technologies. Therefore, this research aimed to address the lack of information by examining the implementation and challenges associated with digital technology. The study will investigate the research objectives by adopting a quantitative technique, more precisely by making use of a questionnaire to collect data from experts working in the construction industry. E-procurement, Artificial Intelligence (AI), 3D printing, Automation and robotics, Drones, blockchain, Augmented reality (AR), Virtual reality (VR), Sensors, Big Data, and Building Information Modelling (BIM) are the eleven technologies that will be explicitly investigated in this research.

This research endeavor's primary objective is to investigate the degree to which 4IR technologies are being used at various phases of the building process, including procurement, design, construction, as well as operation and maintenance stages. The secondary objective is to investigate the challenges that are preventing the construction sector in Malawi from effectively using digital technologies during construction projects. Jaafar et al. (2023) found that, compared to other kinds of businesses, building firms are very hesitant to adopt technologies from the Fourth Industrial Revolution. Therefore, the study follows that looking at building-specific construction firms would show clear barriers to technology adoption in this industry.

In addition to the research objectives outlined above, the study integrated a word cloud, visually representing key concepts of Industry 4.0 trends in Malawi construction as depicted in Figure 1. The terminology relating to Industry 4.0 includes BIM, Big Data, 3D Printing, and drones as shown below.

Figure 1. Word cloud of key concepts

2. Materials and Methods

A multifaceted methodology was used in the study. The first step was to conduct a systematic review of the relevant literature to define the problem, formulate a strategy, locate relevant sources, filter, and assess their quality. Sources for this literature on the implementation and limitations of 4IR technology in the building sector were obtained from respected publications indexed in Google Scholar, Scopus, and the Web of Science. According to Qi et al. (2021), the most recent research on a certain topic might be better understood by compiling existing academic works from various perspectives.

Secondly, the study adopted the use of quantitative research methods. The population of the study included professionals working in the construction industry in Blantyre, this included construction project managers, architects, quantity surveyors, and engineers. The population consists of building firms in Blantyre that are registered with the National Construction Industry Council (NCIC), as reported by the NCIC register of 2023. The sample size of this study, which is 110, was determined using Cochran's Formula with a 95% confidence level. The corresponding Z value of 1.96, obtained from normal distribution tables, was used in the calculation. Given that, p = 0.5 and a minimum precision of 5% is required.

Purposive Sampling was used to reach the targeted participants who were familiar with the technologies of the Industry 4.0, whilst Palinkas et al. (2014) underlined comparable findings. This methodological decision guarantees that the study includes participants who can provide useful perspectives on digital technology in the construction sector of Blantyre. By excluding responses from participants who lacked full awareness of technology, the obtained data is ensured to be pertinent and make a significant contribution to the research aims.

A questionnaire was used to gather data from participants using a 5-point Likert scale, which was deemed suitable for this research (Claydon, 2015; Okoro, 2015; Hamid et al., 2014). The survey questions were derived from a literature review that looked at the construction industry's implementation and challenges with 4IR technology implementation (Okoro,2014; Malomane et al.,2022; Keogh and Smallwood, 2021). The variety of answers might be limited by the use of closed-ended questions, which Farrel (2016) introduced. This study conducted a scientific face validity test on the questionnaire. Churchill and McLaughin (2001) suggested that utilization a scientific face validity ensures that the original items remained unchanged. Part A of the questionnaire was devoted to gathering demographic data from the samples. The second part of the survey sought information on how Malawian construction firms had used digital technologies. The third section discussed the challenges of incorporating technology from the 4IR.

On a 5-point Likert scale, participants were asked to indicate how much they agreed with statements about the acceptance and difficulties with adopting 4iR technologies, which were found in the literature study, on a scale of 1: "Strongly disagree" (SD) to 5: "Strongly agree" (SA). Smallwood and Emuze (2016) indicated that the Five-point Likert scale is a measurement tool that uses a scale of five response options to assess people's attitudes or opinions toward a certain statement or question and concludes that such studies provide meaningful results. Eighty (80) questionnaires were distributed to the participants and 60 were returned, depicting a return rate of 75%. Returned data below 40% cast doubt on the reliability of the research. But 60% is considered acceptable (Fairfield University, 2020). Therefore, it was determined that the data was sufficient for analysis.

The survey results were evaluated, omitting individuals unfamiliar with Industry 4.0. The data was entered into an Excel spreadsheet and imported into IBM SPSS Statistics version 26 for quantitative analysis. Prior to analysing the findings, missing values were found and removed (Okoro, 2015). With few outliers, the data did not follow a normal distribution. The dataset included outliers since they were part of the desired population and offered useful information (Frost, 2021). This research used descriptive data analysis. The variables' relative importance was assessed using mean score (MS) and standard deviation (SD) values in descriptive analysis.

3. Results

3.1. Background Information

The respondents' demographics include 19% Quantity Surveyors, 20% Construction Managers, 27% Civil Engineers, 12% Electrical Engineers, 10% Architects, 8% Structural Engineers, and 4% Mechanical Engineers. The sample population is diverse and homogenous which shows that the research participants have a well-rounded and appropriate professional knowledge. Additionally, 58% of participants have 0–5 years of professional experience, 22% have 5 to 10 years of job experience, 12% have 11 to 15 years, and 8% have more than 15 years. All survey participants were aware of digital technologies in construction. However, 30% indicated they hadn't employed digital technology for building projects.

3.2. Adoption of Digital Technologies in Construction Projects

This section presents the results related to the adoption of 4IRtechnologies in the construction industry of Malawi, aligning with the primary objective of the study. The reliability of this part, as assessed by Cronbach's alpha, is 0.88, above the minimal criterion of 0.7, which indicates its dependability.

3.2.1. Descriptive statistics

Table 1 displays the ranking of the Mean Item Score (MIS) and the Standard Deviation (SD) for the respondents' views on the extent of technology adoption in the construction industry of Malawi. The participants assessed the characteristics using a Five-point Likert scale: 1 = Very low (VL); 2 = Low (L); 3 = Average (A); 4 = (H); 5 = Very high (VH). The table displays the respondents' assessment of the degree of implementation of 4IR Technologies in the building sector of Malawi.

The findings show that Sensors are ranked first with MIS=1.846 and SD= 0.500 followed by E-Procurement (MIS=1.636, SD=0.472). The third-ranked technology is Drones (MIS=1.409, SD=0.307, R=3) followed by Building Information Modelling (BIM) (MIS=1.309, SD=0.302, R=4); Big Data (MIS=1.218, SD=0.304, R=5); Block Chain (MIS=1.145, SD=0.226, R=6) and Artificial Intelligence (MIS=1.091, SD=0.197, R=7). The least ranked are 3D Printing (MIS=0.945, SD=0.197, R=8); Virtual Reality (VR) (MIS=0.150, SD=0.110, R=9); Augmented Reality (AR) (MIS=0.125, SD=0.110, R=10) and Automation and Robotics (MIS=0.100, SD=0.104, R=11).

Table 1. Technologies Adopted in the Construction Sector

Digital Technology adoption	$\bar{x}$	SD	Ranking
Sensors	1.846,	0.500	1
E-Procurement	1.636	0.472	2
Drones	1.409	0.307	3
Building Information Modelling (BIM)	1.309	0.302	4
Big Data	1.218	0.304	5
Block Chain	1.145	0.226	6
Artificial Intelligence	1.091	0.197	7
3D Printing	0.945	0.197	8
Virtual Reality (VR)	0.150	0.110	9
Augmented Reality (AR)	0.125	0.110	10
Automation and Robotics	0.100	0.104	11

$\bar{x}$= Mean item score; SD = Standard deviation; R=Rank

3.3. Integration of Digital Technologies at Different Phases of Construction Projects

Table 2 displays the degree to which digital technologies are used at different phases of building projects. The participants were asked to identify the degree to which they use digital technology at different phases in project execution using a Five-point Likert Scale: 1 = Very low (VL); 2 = Low (L); 3 = Average (A); 4 = High (H); 5 = Very high (VH). The design phase was regarded as the highest priority, with a Mean Importance Score (MIS) of 2.112, a Standard Deviation (SD) of 1.034, and a Rank (R) of 1. This was followed by the building phase, which had a MIS of 2.057, an SD of 0.608, and a Rank of 2. The Procurement Phase, with a Mean Impact Score (MIS) of 1.398, a Standard Deviation (SD) of 0.456, and a Rank (R) of 3, is rated third. On the other hand, the Operation and Maintenance phase, with an MIS of 1.113, an SD of 0.352, and had the last Ranking.

Table 2. Extent of adoption in various phases of construction

Phases of Construction	x̄	SD	Ranking
Design phase	2.112	1.034	1
Construction phase	2.057	0.608	2
Operation and maintenance	1.398	0.456	3
Procurement phase	1.113	0.352	4

x̄= Mean item score; SD = Standard deviation; R=Rank

3.4. Challenges Affecting Technology Adoption in Malawian Construction

This section discusses the difficulties associated with implementing 4IR technologies in the construction industry in Malawi which is the secondary objective of the study. The dependability of this section, as measured by Cronbach's alpha, is 0.80, which is above the minimum threshold of 0.7, indicating its reliability.

3.4.1. Descriptive statistics

The Mean Item Score (MIS) ranking and Standard Deviation (SD) measure the respondents' view on the Challenges that are impeding the use of 4IR technologies in the construction sector in Malawi. The participants assessed the characteristics using a Five-point Likert scale:1 = Strongly disagree (SD); 2 = Disagree (D); 3 = Neutral (N); 4 = Agree (A); 5 = Strongly agree (SA).

Table 3 highlighted several key challenges affecting technology adoption in Malawi with a Lack of knowledge about Industry (MIS=3.90, SD=1.221, R=1) followed by High cost of implementation (MIS=3.71, SD=1.460, R=2); Fear of change (MIS=3.37, SD=1.562, R=3) and Lack of skilled personnel (MIS=3.25, SD=1.534, R=4), Lack of interest (MIS=3.25, SD=1.508) is the fifth ranked challenge whilst the sixth concern is They affect the standardization of the organization (MIS= 2.86, SD= 1.549, R=6). Unavailability of training capacities (MIS=2.69, SD=1.476, R=7); Lack of adequate policy and regulatory framework (MIS=2.63, SD=1.523, R=8) and Fear of job loss (MIS=2.61, SD= 1.313, R=9) are ranked seventh, eighth and nineth respectively. The least challenge is the Lack of access to wireless broadband (MIS=2.58, SD=1.936, R=10)

Table 3. Challenges Affecting Technology Implementation in the Construction Industry

Challenges	x̄	SD	RANK
Lack of knowledge about Industry 4.0	3.90	1.221	1
High cost of implementation	3.71	1.460	2
Fear of change	3.37	1.562	3
Lack of skilled personnel	3.25	1.534	4
Lack of interest	3.25	1.508	5
They affect the standardization of the organization	2.86	1.549	6
Unavailability of training capacities	2.69	1.476	7
Lack of adequate policy and regulatory framework	2.63	1.523	8
Fear of job loss	2.61	1.313	9
Lack of access to wireless broadband	2.58	1.936	10

x̄= Mean item score; SD = Standard deviation; R=Rank

4. Discussion

The primary objective of this research was to explore the degree to which 4IR technologies are being used across the different phases of building projects. The second objective was to analyze the obstacles that are preventing the effective application of digital technologies in the construction industry in Malawi.

4.1. Key Findings

4.1.1. Degree of Adoption

The results obtained indicate that the Mean score values were below 2.00, suggesting that the use of digital technology in the construction sector of Malawi is currently at a low level. This aligns with the findings of the Ernst & Young study (2021), which concluded that the adoption of modern technology in Malawi is still in its early stages. The findings suggest that sensors are the predominant technology used in the construction sector in Malawi. This is consistent with the study done by Adekunle et al (2020), which highlighted that low-income nations are progressively embracing these technologies because of their cost-effectiveness and capacity to provide essential data for infrastructure projects. E-Procurement is the second-ranked technology. The Malawian government is aggressively encouraging the use of E-procurement by developing the necessary framework and infrastructure to permit its broad implementation (Public Procurement and Disposal of Assets Authority, 2023).

The use of unmanned aerial vehicles (UAVs), also known as drones, is progressively rising within the construction sector in Malawi. This aligns with the conclusions of the study conducted by the African Development Bank Group (2019), which highlighted the growing prevalence of Drone technology. Furthermore, it highlighted that Malawi now has the biggest designated space for drone experimentation in Africa. The technologies used to a moderate degree include Building Information Modelling (BIM), Big Data, Block Chain, and Artificial Intelligence. Li and Kassem (2021) discovered that despite the existence of advanced technologies in the construction sector, their integration and broad use may face obstacles during real-world implementation and execution. The technologies exhibiting the least widespread use include 3D printing, virtual reality (VR), augmented reality (AR), and automation and robotics. These results are consistent with the study done by Son et al. (2010), which indicates that the utilisation of technologies such as Automation and Robotics is restricted because of their expensive installation costs and the need for proficient personnel to operate them.

4.1.2. Adoption across project phases

According to the results, the construction industry in Malawi mostly uses digital technology throughout the design and construction phases of the various stages of the building process. These results are consistent with the research carried out by Aghimien et al. (2018), which lends credence to the idea that digital technologies are largely employed at the first phases of development in building projects. According to the research, there is a modest level of adoption during the procurement stage, but there is a very low level of adoption throughout the operation and maintenance stage. The assertion that Trevik and Nilsson (2017) stated that there is a restricted application of digital technology in the operation and maintenance phase of construction projects, is supported by this perspective.

4.1.3. Challenges of Adoption

A lack of familiarity with Industry 4.0 was one of the main issues affecting Malawi's technological landscape. These findings corroborated those of Angeles and Nath (2007), who demonstrated that continuous communication is crucial for influencing end-user behaviour and facilitating the internal acceptance of new processes and policies. Public acceptability would increase, and the system's performance would be enhanced if extensive civic education on the benefits of Industry 4.0 were offered. To encourage the use of Industry 4.0 technologies, it is crucial to educate professionals on their benefits.

According to the results, the high cost of implementation is another major problem in Malawi's construction sector. A major obstacle to implementing 4IR trends in South Africa's construction industry, according to Aghimien et al. (2019), is the associated high cost. The initial investment required to implement new technology is a major deterrent, according to Stanley and Thurnell (2014). Because of the investment, maintenance, and operating expenses, most stakeholders have a hard time accepting innovations. Another important consideration when executing the adoption is the price of staff training. Due to the study region's status as a developing nation without the adoption-related infrastructure, stakeholders are already under a lot of financial strain.

The adoption of 4IR technologies was impeded by the public's resistance to embrace change. The participants were asked if their unwillingness to change hindered the implementation of Industry 4.0 construction techniques in Malawi's public sector. Based on the research results, this particular element had an impact on the widespread acceptance and implementation of technical advancements at a national level. The results confirmed the findings of a 2001 research conducted by Kalakota and Robinson, which revealed that resistance to change is prevalent throughout the implementation process. Managers should surmount this resistance by disseminating information and motivating personnel to adhere to the new regulations. The findings corroborated Mose's (2013) claim that individuals would exhibit hesitancy in embracing a novel system unless they have a definite assurance of its advantages. Early-stage involvement of stakeholders reduces opposition to innovation. According to Bryman and Bell (2013), it is necessary to modify solutions such as 4IR technologies in order to enhance their competitiveness.

Malawi's construction industry is experiencing a significant shortage of skilled labour, a challenge not unique to the country alone but a global issue affecting different countries (Biruk, 2023; Liu-Farrer, 2023; Karimi, 2016). Proficiency has a significant role in shaping the uptake and use of new and developing technologies. An obstacle of significant magnitude is the absence of technical expertise among professionals. Adekunle et al. (2020) emphasised the indispensability of proficiently using Building Information Modelling (BIM) for professionals in the building industry. The lack of a skilled workforce in Industry 4.0 hinders the growth of Industry 4.0, since the competency of the participants is crucial. Another factor identified by the study as hindering the implementation of 4IR in Malawi is a dearth of enthusiasm. In support of this, Mahachi (2020) presents findings, asserting that the construction industry lacks interest in adopting these technologies due to their impracticality.

Additionally, digital technologies exert an influence on the standardization of organizations, which is a recognized factor contributing to the construction industry's sluggish adoption of technology. The potential for 4IR technologies to disrupt the existing organizational culture and norms raises concerns among stakeholders, leading to their adoption advancements. When new ideas are implemented, it is often expected that they will clash with existing industry standards. An inherent challenge in adopting new technological trends is their potential incompatibility with existing systems (Stanley and Thurnell 2014).

An obstacle of significant magnitude that impeded the progress of technology was the scarcity of readily available training capacity and resources. These results support the claims made by Alves de Sousa (2012) that organizations are reluctant to implement new systems because of insufficient user training. This is because a corporation cannot bear the cost of hiring staff members who are less competent and incapable of effectively managing and comprehending new systems throughout their implementation. Due to the multitude of obstacles posed by new technologies, professionals must get sufficient training prior to their implementation.

Malawi's inadequate legislative and policy framework hinders the promotion and application of technology, posing a significant challenge. According to a study conducted by Kibe et al. (2023), the government should actively encourage the use of 4IR technologies. The study emphasises the insufficiency of current policies, infrastructure, and stakeholder engagement in this regard.

According to the study, job insecurity was a significant determinant of the use of digital technologies. This is of utmost significance in Malawi, where a substantial number of individuals are actively seeking employment but encountering significant challenges in securing it. Workers see the extensive use of novel technologies as the most significant danger to their job opportunities in the construction industry. Gaspar et al. (2018) discovered that one of the primary concerns about the deployment of technology in the industry was the potential for unemployment. The industry is very concerned about the significant loss of jobs, as highlighted by Birkel et al. (2019).

The lack of wireless broadband connectivity was shown to provide a reduced risk in the implementation of these technologies. Nevertheless, most technologies heavily depend on wireless communication to function, so the lack of access poses a substantial barrier, Birkel et al. (2019) conducted a study on this. The data shown here challenge the assertions made by Bayode et al. (2019), who contended that the functionality of these tools is significantly impeded by the absence of a wireless internet connection since these tools mainly depend on wireless technology.

5. Conclusions and Recommendations

The productivity issues prevalent in the construction industry need to be addressed, to mitigate the effects of cost overruns, delays, poor quality delivery, health and safety issues, material wastage, and unsustainable practices, the use of 4IR technologies is key. The study aimed to assess the current level of technology adoption and the challenges of implementation and has shown valuable insights. Findings indicated the nascent stage of technology adoption in the Malawian construction sector. While other 4IR technologies like sensors and E-procurement are showing significant adoption due to their low cost and government support, while technologies like 3D printing, VR, AR, and Automation, and Robotics are still lagging. The findings show that Malawi is still in its early stage of technology adoption, therefore there is still a need for more advancement to achieve widespread adoption and implementation of industry technologies.

The findings revealed significant challenges hindering the adoption of technologies namely; lack of knowledge about Industry 4.0, high cost of implementation, fear of change, lack of skilled personnel, and lack of interest. The results depict the need for a multi-pronged approach to promote the trends of Industry 4.0 in the Malawian construction sector. Educational initiatives should be put in place to increase awareness about the benefits of industry technologies, this can close the knowledge gap within the sector. Another approach is to invest in training programs to promote the skills development of professionals so that they will be able to acquire skills that are necessary to utilize these technologies. Government policies that incentivize technology adoption should be put in place and create a more enabling environment that will encourage the adoption of digital trends. Furthermore, government support is very crucial which can also bridge the digital divide and address infrastructure limitations. Stakeholder collaboration should be encouraged between policymakers, industry professionals, and educational institutions to drive change and the challenges identified in this study. By unlocking these aspects, stakeholders can effectively unlock the transformative potential and benefits of Industry 4.0 trends and contribute to a more resilient, productive, and sustainable construction sector of Malawi.

This study contributes to the existing body of knowledge by closing the knowledge gap on the current status of technology adoption in Malawi's construction sector. The findings can inform policymakers, industry experts, and researchers on the significant strategies to improve technology adoption and which technologies to prioritize as the findings show that other technologies are lagging compared to others. The findings will also inform relevant stakeholders on which significant challenges to address to improve the adoption of digitalization in Malawi construction.

This research is in alignment with Malawi's Vision 2063, by highlighting the importance of adopting Industry 4.0 technologies to enhance infrastructure development and economic growth. These advancements can lead to development of sustainable urban areas which is crucial for addressing the overarching goals of poverty eradication and environmental preservation (Keogh and Smallwood, 2021). Thus, the study's focus on understanding the adoption and challenges of digital trends directly supports the broader agenda of sustainable development outlined in the Malawi's Vision 2063.

It is important to focus on the limitations of the study. The study focused on building construction firms in the city of Blantyre, which limits the generalization of the findings to other contexts. Future research could explore a wider scope and compare research findings from various regions. Future studies can also focus on longitudinal research that will take place over some time to track technology adoption assessing the impact of policy reforms and training programs. Comparative studies across industries or countries can provide insights into the best practices of technologies in construction. Additionally, future research can focus on the sustainable implementation of technologies that could promote environmentally friendly practices in the Malawian construction sector.

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Paper 14: Sustainable Construction Practices in the Execution of Building Infrastructure Projects: the Extent of Implementation in Malawi

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ABSTRACT

The urgent need to adopt construction methods that emphasise the long-term health of the planet and its inhabitants has led to critical consideration of sustainable construction across various fields and contexts. This is anchored on the global agenda for Sustainable Development Goals. In Malawi, Malawi 2063 provides its vision for attaining sustainable development through three pillars: agricultural productivity and commercialisation, industrialisation, and urbanisation. Environmental sustainability is among the enablers, hence the need to promote sustainable construction practices. A holistic approach is required for the selection of appropriate construction practices that consider environmental, social, and economic impacts throughout the project life cycle. This study established current sustainable construction practices implemented in building infrastructure projects in Malawi. An extensive literature review identified twenty-two sustainable practices based on the triple bottom line of sustainability. A survey of 193 professionals was conducted to assess the level of implementation of sustainable practices. The study revealed that economic practices such as efficient allocation of resources, use of quick construction tools, and coordinated supply chain management in the construction process are the leading practices implemented in the execution of infrastructure projects. The study further revealed that while participants considered environmental sustainability practices in construction, their practices reflected economic and social sustainability dimensions. Therefore, to achieve a holistic approach to sustainable construction, there is a need to raise awareness about the environmental and social aspects of sustainable construction. This paper provides insights for project managers and policymakers to improve existing practices and promote sustainable construction practices.

Keywords: sustainability, construction practices, sustainable development, infrastructure.

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1.0 **Introduction**

Infrastructure development is crucial for the development of every nation, as it has the potential to support economic growth and improve the living conditions of individuals locally and internationally. Scholars worldwide have emphasised the significance of integrating sustainability into infrastructure development for long-term economic benefits. Sustainability refers to a position that combines present and future demands while addressing various problems arising from managing structures, organisations, and resources for short-term and long-term benefits (Kubba, 2010). This emphasises the significance of striking a balance between economic, social, and environmental factors in order to maintain a high standard of living for present and future generations while also preserving the natural resources and ecosystems that support us (Zulu et al., 2022; Zwickle et al., 2014). Therefore, sustainability in infrastructure should be an antecedent to project initiation as it directly affects the overall project performance.

The triple bottom line concept introduced in 1994 proposed that sustainability in construction would be achieved by attaining environmental, social and economic performance in the project delivery (Bamgbade et al., 2017). The broad understanding of the concept of sustainability gives rise to the concept of sustainable construction in response to the constantly emerging developments (Glavič & Lukman, 2007).

Sustainable construction practices are the methods, techniques, and processes used to execute infrastructure projects that are in tune with the environment, improve the well-being of all people and, advance economic equality, have the adaptability to meet shifting needs and preferences (Omopariola et al., 2022). Buildings and construction account for over 36% of the energy used globally and 39% of the carbon dioxide (CO_2) emissions (Heubaum & Biermann, 2015). With a growing population and increasing urbanisation, the demand for residential, commercial, and public infrastructure projects has steadily risen (Habitat, 2018).

Historically, the construction industry in Malawi has faced several challenges that have affected its growth and efficiency. Limited access to finance, inadequate water and power supply, and a shortage of skilled labour have been persistent issues faced by the construction industry in Malawi

(Dubosse et al., 2021). Nkado et al. (2021) opined that Malawi is experiencing rapid urbanisation and economic growth, increasing the demand for construction materials and infrastructure. However, most infrastructure projects in Malawi are carried out without adequate integration of sustainability in the construction process, which negatively affects project performance (Hershey et al., 2023). The recent Tropical Storm Gombe and Tropical Cyclone Freddy resulted in more damage to building infrastructure in Malawi. These devastating effects result from unsustainable construction practices, such as unregulated land use and construction practices that consume excessive amounts of raw materials, energy, and water, leading to resource depletion and higher environmental impact (Kamanga, 2020; Singh & Schoenmakers, 2023).

This has called for an urgent need to adopt sustainable construction methods emphasising the efficient use of resources and the long-term health of our planet and its inhabitants across various fields and contexts. In today's modern practice, sustainable construction practices are essential for infrastructure development, which promotes economic growth, improves the well-being of a nation's citizens, and plays a significant role in achieving sustainable development.

Despite the numerous studies on sustainability in Malawi, few studies have investigated sustainable construction practices in building infrastructure projects. As a result, this study aims to determine the sustainable construction practices implemented in building infrastructure projects in Malawi.

2.0 **Literature Review**

Sustainability practices in construction processes are essential for providing sustainable building infrastructure projects that promote national development. The building infrastructure development sector measures the well-being of a nation's citizens(Kwilirani et al., 2021). Most developing countries, like Malawi, mainly rely on conventional methods when it comes to construction, making the usage of modern techniques more challenging and stressful. Traditional approaches to project outcomes heavily depend on skills and resource availability (Charles et al., 2023). According to the Government of Malawi (2023), the infrastructure sector requires $161.21 million to construct and rehabilitate primary and secondary infrastructure after the devastating effect of Cyclone Freddy. The unavailability of these resources negatively affects the country's economy.

The construction industry contributed 3.6% of Malawi's GDP in 2017, and the government has set a goal to increase this contribution to 10% by 2025 (Government of Malawi, 2018). Previous research suggests that efficient and effective construction activities have the potential to contribute significantly to national economic growth.

According to Nkado et al. (2021) Malawi is experiencing rapid urbanisation and economic growth, increasing the demand for sustainable construction materials and infrastructure. Conventionally kiln-baked clay bricks are extensively utilised as a construction material in low and middle-income countries. In the case of Malawi, 90% of building structures are constructed using informal construction methods and traditional materials, with a notable transition from mud walls to burnt clay bricks observed in the last twenty years (Kloukinas et al., 2020). As a result, most contractors and clients extensively employed fired clay bricks in residential and commercial structures while exhibiting reluctance towards adopting sustainable alternatives such as prefabricated concrete blocks and other advanced building materials (Mahdjoub et al., 2021). Ngwira & Watanabe (2019) state that burnt clay bricks are extensively utilised throughout Malawi.

Exploiting natural resources for conventional construction materials, such as burnt clay bricks, thatch, and timber, has significantly strained tropical forests. In order to tackle these difficulties, advancements in building technologies such as nanotechnology for structural steel, precast concrete, green building, and the use of recycled building materials which are socially, economically and environmentally sustainable should be adopted (Mahdjoub et al., 2021; Nerfa et al., 2020).

2.1 Sustainable construction

According to Du Plessis (2005) Sustainable construction encompasses a comprehensive approach aimed at establishing and sustaining a harmonious relationship between the natural and the built environments. Additionally, it seeks to develop buildings that uphold human dignity and promote equitable economic growth. When a building or piece of infrastructure is constructed sustainably, it satisfies the needs of both the present and future generations in a comprehensive and well-balanced manner while also being economically viable, socially responsible, and environmentally sustainable(Fischer & Amekudzi, 2011).

These objectives must be met through a holistic approach to building design, construction, and operation that takes into account how economic, social, and environmental issues interact and aims to strike a sustainable balance between them. This entails developing projects that integrate sustainability criteria into every stage of the construction process, from planning and construction to operation and maintenance, while maintaining resilience in the face of climate change (Zulu et al., 2022). Most previous studies have focused on the economic and environmental dimensions of sustainable construction while ignoring the social dimension. In order to achieve sustainable construction in the industry, there is a need for a multidimensional approach to construction with the triple bottom line (TBL) approach, which aims to strike a sustainable balance between the three dimensions (Zulu et al., 2022).

2.2 Sustainable performance criteria for construction practices in building infrastructure

In order to assess the sustainability of construction practices and buildings, it is necessary to measure and verify their performance. In response to the growing recognition within the construction industry of the environmental, social and economic impact of buildings, significant efforts have been made in the past decade to develop evaluation criteria that can assess buildings during their entire lifecycle in terms of sustainability.

In 1990, the UK developed the Building Research Establishment Environmental Assessment Method (BREEAM), which is the most extensively utilised approach globally for evaluating and enhancing the environmental efficiency of buildings. BREEAM has demonstrated several sustainability assessment categories, including land and resource usage, energy consumption, water, building waste management, health and wellbeing, and materials selection(Nelms et al., 2005). BREEAM further provides indicators of the impact of building on occupant health, running costs, and environmental footprint. BREEAM influenced the development of numerous building assessment models worldwide. The US Green Building Council in the United States established the Leadership in Energy and Environmental Design (LEED) Green Building Rating System to evaluate new and major renovations of institutional, commercial, and high-rise residential projects (Kim et al., 2012).LEED assesses buildings during the design phase and after construction, covering the entire life cycle of the structure. Several other nations, such as France, Australia, Norway, Sweden, and the Netherlands, have been developing their own evaluation frameworks. The metrics of each of these building assessment methodologies largely emphasise the environmental performance, particularly during the operation of the structure. This includes factors such as energy consumption, water usage, greenhouse gas emissions, and storm-water runoff (Cole et al., 2020).

It was also discovered that most African countries do not have their own assessment models for building infrastructure projects. However, indicators obtained from already existing rating systems can be assessed by collecting data and interpreting these indicators in the context of Malawi. Table 1 below shows a list of sustainable performance criteria for construction practices in infrastructure projects obtained from the literature.

Table 10 Sustainable performance criteria for construction practices in building infrastructure

Environmental criteria	Social criteria	Economic criteria
E1: The use of waste reduction technologies in design and construction	S1: Indoor water and air quality performance of buildings	C1: Quick return on investment
E2: The use of recyclable building materials	S2: Occupant Health and safety quality performance	C2: Less maintenance cost
E3: The use of renewable materials in buildings	S3: Acoustic and visual quality performance of the building	C3: Less disposal cost
E4: The use of energy-efficient building materials	S4: Maximise the service life of the structure	C4: Quick construction time
E5: Use of local and regional materials	S5: Promote social inclusiveness	C5: Use of automatic systems in building
E6: Use of low carbon emission equipment in buildings	S6: Community disturbance	C6: Efficient allocation of resources

E7: The use of less water consumption in design and construction	S:7 Thermal comfort	C7: Construction lead-time
		C8: Maintain Asset value C9: Integration of building service in the construction process

2.3 Requirement for the implementation of sustainable construction practices

The successful implementation of sustainable construction practices and principles, as identified by their importance, requires the commitment of all stakeholders involved in the construction process, including government, professionals and the community, who are the end users.

According to Shurrab et al. (2019), implementing sustainable construction requires innovation and technological enhancement. Also, there is a need for commitments by stakeholders to sustainable principles and concepts to motivate and boost performance (Jamil & Fathi, 2016). As highlighted by Djokoto et al. (2014) other requirements include the presence of waste management strategies and practices, the holistic application of practices rather than project-based ones, and intra-organizational leadership in promoting sustainable construction practices. Sfakianaki (2018) proposed training and investment in resource-efficient building, developing strategic metrics to analyse sustainable construction practices and the presence of sustainable building codes and policies. Ismael & Shealy (2019) opined that project management knowledge and skills for sustainable design and construction should be improved. However, given the requirement for integrating sustainable construction practices, the implementation becomes difficult in developing countries like Malawi.

2.4 Benefits of Sustainable Construction

According to Zhang et al.(2017) the construction industry plays a crucial role in ensuring the sustainability and development of human life on earth by providing necessary living conditions. According to Dania et al.(2013) the construction industry typically accounts for approximately 10% of the Gross Domestic Product (GDP) in many nations. Additionally, it serves as a significant source of employment for numerous individuals across various job functions and plays a crucial role in fostering economic expansion.

Environmentally responsible construction practices minimise carbon emissions from buildings while minimising construction waste generation (Loizou et al., 2021). Similarly, incorporating energy-efficient design strategies can contribute to the reduction of long-term energy costs(Ganda & Ngwakwe, 2014). According to Bowen et al. (2020), Environmental sustainability practices increase building Resilience to climatic shocks, and utilising recycled materials or designing with energy efficiency assists in lowering material and energy expenses. Loizou et al. (2021) postulated that implementing waste management techniques, such as recycling or material reuse, can also cut disposal expenses and reduce the negative environmental impact.

According to Goh et al. (2023) implementing social sustainability practices, such as promoting social inclusiveness in the construction sector, can enhance project performance by improving worker productivity and generating positive community interactions. According to Robichaud et al. (2011), establishing a conducive and encouraging work environment, along with active engagement with local communities and stakeholders, plays a crucial role in ensuring the timely and cost-effective completion of projects while meeting the necessary quality standards. Moreover, this approach also generates favourable social outcomes for both workers and the surrounding community. This proposition suggests that social sustainability practices have a favourable impact on the overall success of construction projects.

According to Ogunmakinde et al.(2022) implementing economic sustainability practices in the construction sector, such as efficient resource allocation and waste reduction, can contribute to cost reduction and improved project performance. For example, the utilisation of recycled materials and the implementation of energy-efficient design result in the reduction of recovery time and cost for the structure, lower building maintenance expenses, enhancement of the local economy, and decreased lifecycle cost for achieving the desired performance of the structure (Benoy et al., 2023; Borkowski et al., 2011). Implementing construction practices that prioritise economic sustainability can also improve project management practices, ensuring timely project completion and adherence to the required quality standards. For example, using efficient construction methods such as just-in-time material delivery and component prefabrication can enhance the pace of the construction process and mitigate the likelihood of delays or excessive costs (Shah, 2016).

3.0 **Materials and Methods**

The procedures and approaches used to carry out a study are described in the research methodology (Kothari, 2017). Consequently, the research methodology enables researchers to determine the outcomes of a particular research subject. This study aimed to determine the sustainable construction practices that are implemented in the execution of building infrastructure projects in Malawi. An extensive literature review revealed that there was no comprehensive list of performance criteria for sustainable construction practices specific to building infrastructure. Several studies related to the subject area were explored to develop a meaningful list of performance criteria for sustainable construction. The developed list was coded into a questionnaire and a pilot survey conducted for experienced industry professionals to rate the level of implementation of the derived criteria based on a scale of 1-5, where 1= never used,2 = rarely used,3 = occasionally used,4 = frequently used and 5 = very frequently used to validate the final questionnaire. Also, respondents were encouraged to provide supplementary practices they consider sustainable but were not listed in the questionnaire provided.

The population of the study comprised 938 firms, including construction firms, consultants, specialist engineering firms and district councils drawn from the National Construction Industry Council,2023 register. The sample size was determined to be 273 using stratified random sampling. Rahi (2017) stratified random sampling techniques allow the researcher to choose a number of samples representing each stratum of the population. It is also the most efficient among all the probability sampling techniques as it has higher generalizability of the research findings (Ab Talib et al., 2013).

The final questionnaire was administered to 273 experienced construction professionals (Architects, project managers, civil engineers, quantity surveyors, electrical engineers, mechanical engineers, builders and procurement officers) within the Malawian construction industry.

A total of 193 questionnaires were returned with valid responses, which represented approximately 71% response rate. According to Baruch (1999) a response rate of approximately 35% is satisfactory for most academic studies. A response rate of approximately 71% is acceptable for the purpose of this study.

The data obtained was analysed using descriptive statistics such as mean, standard deviation and standard error mean. This allows for the presentation of findings in tables and figures for easy understanding (Deci & Ryan, 2004). A reliability test was also conducted using Cronbach's Alpha to determine the internal consistency of the scale used to rate the variables.

4.0 **Results and Discussion**

4.1. Demographic information of respondents

A total of 193 valid responses out of the 273 questionnaires deployed were received, representing approximately 71% of the population; the findings are summarised in Table 2 below. From Table 2.0, most (54.4%) of the respondents had a degree, while 14% and 3.6% had master's and PhD qualifications, respectively. Also, 23.8% and 4.1% had diploma and secondary qualifications, respectively. Most of the respondents were architects (23.8%), project managers (22.3%), civil engineers (19.7%), quantity surveyors (16.6%), mechanical/electrical Engineer (9.3%), builders (4.7%) and procurement officers (3,6%). Furthermore, 40.9% of the respondents work with construction companies, 28.5% with consulting firms,16.1% with real estate companies, and 14.5% with public institutions. Out of these organisations, 37.8% were small firms, 33.2% were medium firms, 15% were micro, and 14% were larger firms. The respondents also had varying levels of experience. Approximately, (74%) had worked in their current role for at least five years, while 21.8% had at least eleven years of experience. Also, 3.3% had at least 16 years of work experience, and only 1% had worked in their current position for at least 21 years. The sample data indicates that participants had significant knowledge and experience required to offer valuable information for the study.

Table 11 Respondents' demographics

Demographics of respondents	Responses per (n=193)	Characteristic	Frequency (%)
Educational Qualification			
Secondary/Senior High	8		4.1
Diploma	46		23.8
Degree	105		54.4
Master's Degree	27		14.0
PhD	7		3.6
Profession			
Architect	46		23.8
Project Manager	43		22.3
Civil Engineer	38		19.7
Quantity Surveyors	32		16.6
Mechanical/Electrical Engineer	18		9.3
Builder	9		4.7
Procurement officer	7		3.6
Work Experience			
1-5 years	74		38.3
6-10 years	68		35.2
11-15 years	42		21.8
16-20 years	7		3.6
21 years and above	2		1.0
Organisations of respondents			
Construction Company	79		40.9
Consultant	55		28.5
Real Estate Company	31		16.1
Public Organization	28		14.5
Size of Organisations			
Small firm 20-60 Employees	73		37.8
Medium firm 60-100	64		33.2
Micro firm ≤ 20 Employees	29		15.0
Employees Large firm >100	27		14.0

4.2. Reliability of analysis

Cronbach's alpha was calculated to determine the internal consistency and reliability of the scale used to rate the various variables. The alpha reliability coefficient normally ranges between 0 and 1. The closer the alpha coefficient to 1, the greater the internal consistency and reliability of the criteria used in the scale (Bonett & Wright, 2015). From Table 3, the alpha coefficient values for environmental, social, economic and all the criteria used are

0.900,0.876,0.862 and 0.922, respectively. It was discovered that all the alpha coefficients were greater than 0.7, indicating a higher level of reliability and an excellent internal consistency of the criteria used in the scale.

Table 12 Reliability test

Categories	N of Items	Cronbach's Alpha
Environmental	8	0.900
Social	8	0.876
Economic	6	0.862
Overall	22	0.922

4.3. Sustainable construction practices implemented in the execution of building infrastructure projects.

The sustainable construction practices obtained from the survey are presented in Table 4 below.

Table 13 Sustainable Construction Practices

N	Sustainable Construction practices	Mean	Std. Error Mean	Std. Deviation	Ranking by Category	Overall Ranking
	ENVIRONMENTAL	**2.65**				
E1	Use of local and regional materials	2.83	0.070	0.967	1	5TH
E2	Responsible land use, including protecting green places and reusing land.	2.81	0.071	0.988	2	16TH
E3	Use of less water consumption in design and construction	2.75	0.067	0.937	3	17TH
E4	Use of energy-efficient building materials	2.74	0.065	0.904	4	18TH
E5	Use of low carbon emission equipment in buildings	2.71	0.062	0.859	5	19TH
E6	Use of renewable materials in buildings	2.56	0.068	0.950	6	20TH
E7	Use of recyclable building materials	2.41	0.071	0.986	7	21ST
E8	Use of waste reduction technologies in design and construction	2.34	0.067	0.928	8	22ND
	SOCIAL	**3.04**				
S1	Occupant Health and safety quality performance	3.19	0.063	0.876	1	6TH
S2	Acoustic and visual quality performance of the building	3.15	0.067	0.924	2	8TH

S3	Use of thermal insulations in buildings	3.09	0.068	0.940	3	9TH
S4	Adaptability in design and construction	3.03	0.064	0.892	4	10TH
S5	Use of Indoor air quality materials in buildings	3.02	0.067	0.932	5	11TH
S6	Use of less noise equipment in construction	2.98	0.070	0.973	6	12TH
S7	Social inclusive designs	2.97	0.062	0.865	7	13TH
S8	Use of water-quality materials in buildings	2.91	0.064	0.891	8	14TH
	ECONOMIC	**3.28**				
C1	Efficient allocation of resources	3.42	0.067	0.933	1	1ST
C2	Use of Quick construction tools (e.g. 3D printer, BIM)	3.34	0.075	1.044	2	2ND
C3	Coordinated supply chain in the construction process	3.32	0.067	0.930	3	3RD
C4	Proper implementation of Asset Management Plan in buildings	3.23	0.065	0.901	4	4TH
C5	Integration of building service in the construction process	3.20	0.063	0.881	5	5TH
C6	Use of automotive systems in building	3.18	0.068	0.941	6	7TH

Std=Standard

Table 4 is a summarised descriptive statistical analysis of the measurement of central tendency (mean), measurement of variation (standard deviation), and standard error mean to provide a statistical model for evaluating the level of implementation of sustainable practices in the execution of building infrastructure projects. It is important to highlight that the standard deviation of all the variables under consideration was less than one, which indicates a higher level of agreement between respondents on the variables with a minimum degree of variation(Njau & Karugu, 2014). Furthermore, the standard error means of all the variables were also close to zero, which shows that the sample was the actual representation of the population. Ahadzie (2007) stated that a standard error means closer to zero indicates that the sample represented the actual population of the study.

From Table 4, a total of 22 practices, consisting of 8 environmental, 8 social and 6 economic practices, were ranked based on their mean score values. The mean ranking was used to indicate the most commonly implemented sustainable practices. It was deduced that under the environmental dimension, the top five ranked practices were the use of local and regional materials, responsible land use, use of less water consumption in design and construction, use of energy-efficient building materials, and use of low carbon emission equipment in buildings with a mean score of 2.83, 2.81, 2.75, 2.74 and 2.71 respectively. This confirms the findings of Kloukinas et al.(2020) that most of the building structures in Malawi are constructed using locally and regionally sourced materials, with a notable transition from mud walls to burnt clay bricks over the past twenty years. A study by Akadiri et al. (2012) opined that prioritising the use of local and regional materials in construction reduces transportation distances, thereby minimising the carbon footprint associated with construction projects. Also, the use of renewable materials in buildings, the use of recyclable building materials and the use of waste reduction technologies in design and construction were ranked 6th,7th, and 8th with a mean score of 2.56, 2.41 and 2.34, respectively. The findings under this dimension confirm the importance of environmental-related practices towards the attainment of sustainable building infrastructure (Loizou et al., 2021). According to Bowen et al. (2020), environmental sustainability practices increase building Resilience to climatic shocks.

Interfering from Table 4, under the social dimension, the most commonly implemented practice is ensuring occupant health and safety quality performance of building infrastructure, with the highest mean value of 3.19. Acoustic and visual quality performance of the buildings, use of thermal insulations in buildings, adaptability in design and construction and use of indoor air quality materials in buildings were ranked 2nd,3rd,4th and 5th with mean values of 3.15, 3.09, 3.03 and 3.02 respectively. Furthermore, the use of less noise equipment in construction, socially inclusive designs, and the use of water-quality materials in buildings were ranked 6th,7th, and 8th, with means values of 2.98, 2.97, and 2.91espectively. According to Goh et al. (2023) implementing social sustainability practices enhances project performance by improving worker productivity and generating positive community acceptance.

The last dimension in Table 4 is the economic. Under economic practices, the Efficient allocation of resources was ranked the highest, with a mean value of 3.42. This entirely reflects the situation in Malawi, where construction resources are limited(Dubosse et al., 2021). The second and third-ranked practices under the economic dimension were the Use of Quick construction tools (3D printer, BIM, etc.) and the Coordinated supply chain in the construction process, with mean values of 3.34 and 3.32, respectively. Proper implementation of Asset management plans in buildings, integration of building service in the construction process, and use of automotive systems in buildings were ranked 4th,5th and 6th with means 3.23, 3.20 and 3.18, respectively. These findings confirm the study of Shah (2016) that implementing construction practices that prioritise economic sustainability ensures the timely completion of projects and adherence to the required quality standards. According to Ogunmakinde et al.(2022) implementing economic sustainability approaches in the construction sector contributes to cost reduction and improved project performance.

Furthermore, the triple bottom dimensions of sustainable construction practices were also ranked using the means obtained from the variables under each dimension. From Table 4, the economic dimension was ranked first with a mean (3.28), followed by the social dimension with a mean (3.04) and lastly the environmental dimension with (2.65). The data shows that, while participants consider environmental sustainability practices to be important, their practices reflected economic and social sustainability dimensions. The result is evident in pointing out that the economic aspect of sustainable construction is implemented. In contrast, less social and environmental aspects are implemented in the execution of building infrastructure projects in Malawi. In favour of the findings, Zulu et al. (2022) discovered the implementation of economic and social sustainability practices in the Zambian construction industry. Also, the low implementation of environmental sustainability practices has seen the recent Tropical Storm Gombe and Tropical Cyclone Freddy result in more damage to building infrastructure in Malawi(Braka et al., 2024).

5.0 **Conclusions and Future Work**

The study provided an overview of the Malawian construction industry, sustainable construction and the sustainable performance criteria for construction practices in infrastructure projects. The study further highlighted the requirements and benefits of implementing sustainable construction practices. Consequently, the study investigated the sustainable construction practices implemented in building infrastructure projects in Malawi. The findings revealed that economic practices such as efficient allocation of resources, use of quick construction tools, and coordinated supply chain management in the construction process are the leading practices implemented in the execution of infrastructure projects in Malawi. Regarding the triple-bottom-line sustainability practices, economic and social sustainability practices were ranked higher than those related to the environment. The data shows that, while participants consider environmental sustainability practices as important, their practices reflected economic and social aspects of sustainability. The findings imply that the actual construction practices implemented focus more on economic and social aspects of sustainability. Overall, judging from the various means, the level of implementation of sustainable construction practices in Malawi is still low compared to other developing countries Therefore, to achieve a holistic approach to sustainable construction, there is a need to increase the level of knowledge and awareness about the environmental and social aspects of sustainable construction. Future studies can be conducted to assess the causes of construction practices being focused on economic sustainability in addressing the sustainability issues in the construction industry.

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Paper 15: Urban land use change and its externality effects on residential property values: A case of Lilongwe City

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Abstract
Change in land use in cities can have significant impact on residential property values and overall urban sustainability, as generally observed in developing countries. In the city of Lilongwe, for example, rapid pace of urbanisation has brought about arbitrary changes in land use to the extent that a piece of land or a building serves many different purposes. This study investigated how positive and negative externalities of urban land use change, referred to as "proximity effects" and "disamenity effects" respectively, affect residential property values. A conceptual framework for externality effects of urban land use change on residential property values developed based on literature study was used to generate a questionnaire that was administered randomly to 100 respondents within Lilongwe City. The study targeted residents, tenants and landlords from Areas 10, 11, 12, 14, 15, 43 and 47 in Lilongwe city, Lilongwe City Council officials, and real estate experts in Malawi. The data collected was analysed with Relative Importance Index (RII) technique, regression analysis, and simple descriptive analysis, particularly with frequencies and percentages. The study established that economic factors are the major influencers of urban land use change in residential properties as landlords seek to increase economic turnovers of their properties. Proximity benefits related to adjacent commercial properties are not fully offset by disamenity effects. Mixed land use may contribute to the sustainability and viability of urban development by promoting economic vitality, reducing transportation emissions, and fostering social interaction. Based on the findings, the study recommends that mixed-use developments should be designed with careful consideration of the needs and desires of the local community, and that developers should be incentivized to build more affordable housing units in mixed-use developments. Furthermore, appropriate regulations and enforcement of the same be prioritised.

Keywords: Proximity effects, disamenity effects, mixed-use, sustainable development, zoning regulations

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1. Introduction

1.1 Background

Urbanisation is a global phenomenon driven by factors such as population growth, economic development, and social changes. In the context of Lilongwe City, Malawi, rapid urbanisation has brought about significant transformations in land use patterns, particularly the conversion of residential land into commercial use. This trend is influenced by economic incentives, urban planning principles, and the demand for land resources in a growing city (Gwamna, Yusoff, & Ismail, 2015).

Despite the economic rationale behind urban land use changes, they pose significant challenges for residential property values and urban sustainability. The arbitrary conversion of residential land into commercial use can lead to shortages in housing stock, escalating property prices, and adverse impacts on residential neighborhoods. While traditional zoning regulations aim to separate commercial and residential areas to mitigate negative externalities, contemporary planning principles advocate for mixed land use to create more sustainable and vibrant urban communities (Matthews & Turnbull, 2007).

The literature on urban land use changes provides valuable insights into the drivers, dynamics, and impacts of these transformations. Seminal works by scholars such as Harvey (1996) and Clapp (1993) have explored the economic rationale behind land use changes and the transition from lower-order to higher-order land uses. More recent studies, such as those by Yang et al. (2016) and Berke et al. (2006), have examined the positive and negative externalities of mixed land use on residential property values and urban sustainability.

However, despite the growing body of literature on urban land use changes, there remains a research gap in understanding the specific externalities of these changes on residential property values in the context of Lilongwe City. Existing studies often focus on broader theoretical frameworks or case studies from other regions; thus, the unique socio-economic and environmental dynamics of Lilongwe City presents a case for thorough consideration.

Therefore, this study seeks to fill this gap by investigating the externality effects of urban land use changes on residential property values in Lilongwe City. Specifically, the study aims to identify dominant factors driving land use changes, assess the balance between proximity benefits and disamenity effects, examine the contribution of mixed land use to urban sustainability, and evaluate the impact of residential-to-commercial land conversion on housing shortages.

1.2 Conceptual Framework

The study's framework offers a systematic approach to conceptualize the cascading impact of human activities on residential land use. The diagram presented below illustrates the conceptual framework, outlining the connection between the dependent variable (residential property values) and various independent variables (factors influencing urban land use change) that influence property values.

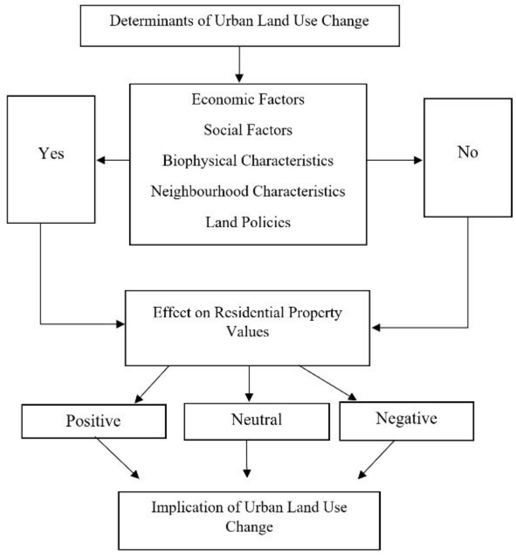

Fig. 1 Proposed Conceptual Framework for Externality Effects Urban Land Use Change on Residential Property Values

1.3 Theoretical Framework

The study employed Alonso's Bid Rent theory and Rosen's Hedonic Price Model as theoretical frameworks for analyzing the real estate market (Alonso, 1964; Richard, 2009). Econometrics, particularly in the field of real estate, involves the application of statistical methods to understand the impact of economic changes on real estate markets (Chris and Sotiris, 2010). This approach is crucial for developing econometric models that accurately represent real estate dynamics, requiring a solid theoretical foundation (Chris and Sotiris, 2010).

The Hedonic Price approach, utilized in modeling the real estate market, assesses the economic value of environmental goods by breaking down transaction or rental prices into various components influenced by property-specific and non-property-specific variables (Richard, 2009). This method is essential for evaluating attributes like landscape qualities and parks, emphasizing the statistical regression of collected data, including explanatory and explained variables, for effective application (Richard, 2009).

Conversely, the Bid Rent Theory, a geographical economic theory, explains how real estate price and demand change with distance from the Central Business District (CBD) (Alonso, 1964; Ross, Merger & Heeles, 2000). According to this theory, different land users compete for land closer to the CBD, with commercial establishments willing to pay higher prices for proximity to maximize productivity (Alonso, 1964; Ross, Merger & Heeles, 2000).

1.4 Justification

Through a mixed-methods approach combining questionnaire surveys and statistical analysis, this study will provide valuable insights for sustainable land use planning and development in Lilongwe City. By addressing the research gap and answering key research questions, this paper aims to contribute to the existing body of knowledge on urban land use changes and their implications for residential property values.

In the subsequent sections of this paper, a comprehensive review of the literature on urban land use changes is presented followed by a detailed explanation of the research methodology and design. The results of the data analysis are then presented and analysed, leading to a summary of the findings, conclusions, and recommendations for future research and policy implications.

2. Materials and Methods

This section presents a comprehensive overview of the methodology employed in the study, detailing the implementation process and ensuring replicability. The methods were rigorously validated and tested before implementation to ensure accuracy and reliability.

2.1 Study Area

The study focused on Lilongwe City, specifically targeting areas such as Area 10, Area 12, Area 11, Area 14, Area 15, Area 43, and Area 47 due to consistent data availability and significant land use changes.

2.2 Research Design

A mixed-methods approach, combining quantitative and qualitative methodologies, was adopted to investigate the externality effects of urban land use change on residential property values. Emphasis was placed on figurative presentations and quantitative analysis, with descriptive analysis addressing qualitative aspects.

2.3 Population and Sampling

Purposive sampling was utilized to select respondents based on their expertise on the research question. The sample size was determined using the Slovin's formula:

$n = N / (1+Ne^2)$ ……… (1)

Where:

- n = Sample size
- N = Total population of interest
- e = Error margin / Margin of error

Calculation of Sample Size:

$$n = \frac{134}{1+134(0.05)^2}$$

$$\mathbf{n \approx 100}$$

Whereas:

- **Confidence Level** = 95%
- **Margin of Error** = 5%

Based on the calculations above, the sample size was set at 100 respondents with confidence level and margin error at 95% and 5% respectively.

2.4 Methods of Data Collection

Data collection methods included self-administered questionnaires, spatial data analysis, face-to-face interviews, and document review. A pilot study was conducted to test the questionnaire's validity and refine it accordingly.

2.5 Data Analysis

Various analysis techniques were employed, including Relative Importance Index (RII) analysis and multiple regression analysis. These techniques enabled the investigation of the effects of urban land use change on residential property values.

The Relative Importance Index (RII) calculation follows the formula:

$$\text{RII} = \frac{\sum w}{A \times N}$$

Where:

- W = Weighing given to each statement by respondents (ranging from 1 to 5)
- A = Higher response integer (e.g., 5)
- N = Total number of respondents

Validity and Reliability

Pretesting and validation measures were implemented to ensure the reliability and validity of the research findings. Methodological triangulation, data collection from multiple sources, and statistical analysis enhanced the validity and reliability of the results.

Limitations

The study encountered limitations primarily related to non-cooperation of respondents. Measures were implemented to address non-cooperation errors, non-availability errors, and situation-induced errors during data collection.

In conclusion, this section provides a detailed account of the methodology, ensuring transparency, replicability, and robustness in the research process. It underscores the importance of rigorous validation, ethical considerations, and addressing limitations for producing credible research outcomes.

3. Results and Discussion

3.1 Demographic Background

The section outlines personal information about the participants to this study regarding gender, age group, length of experience in the real estate sector, personal involvement in the real estate sector, area of focus and level of education of respondents.

Table 1: Demographic Background

Variables	Frequency	Percentage
Gender of Respondents		
Male	62	77.5
Female	19	63.3
Total	81	81.0
Age of the Respondents		
0-5	9	11.1
6-10	34	42.0
11-15	21	25.9
16-20	12	14.8
21+	5	6.2
Total	81	100
Highest Professional Qualification		
Certificate	2	2.5

Diploma	26	32.1
Degree	33	40.7
MSc	17	21.0
PhD	3	3.7
Total	81	100
Experience in the Real Estate Sector		
0-5	9	11.1
6-10	34	42.0
11-15	21	25.9
16-20	12	14.8
21+	5	6.2
Total	81	100
Personal Involvement in the Real Estate Sector		
Property Owners	17	21.0
Property Developers	22	27.2
Property Managers	24	29.6
Residents/ Tenants	18	22.2
Total	81	100
Area of Focus		
Area 15 & Area 47	14	17.3
Area 10 & Area 43	23	28.4
Area 11 & Area 12	24	29.6
Area 14	20	24.7
Total	81	100

The demographic background of the respondents in the study reveals a predominantly male composition, constituting 77.5% of the total respondents, while females accounted for 22.5%. Regarding age distribution, the majority fell within the age brackets of 35-54 years, comprising 68.4% of the respondents, with the highest proportion in the 45-54 age group at 39.5%. In terms of educational qualifications, 72.8% of the respondents held degrees or diplomas, with degrees representing 40.7% and diplomas 32.1%. Experience in the real estate sector varied, with 53.1% of respondents having 6-20 years of experience, while 17.3% had less than 5 years of experience. Personal involvement in the real estate sector was diverse, with property managers representing the largest group at 29.6%, followed by property developers at 27.2%, property owners at 21.0%, and residents/tenants at 22.2%. Regarding the areas of focus within Lilongwe City, the distribution was relatively even, with Area 11 & Area 12 being the most prominent at 29.6%, followed closely by Area 10 & Area 43 at 28.4%, while Area 15 & Area 47 had the lowest representation at 17.3%.

3.2 Factors Influencing Urban Land Use Change in Residential Areas

Land use transformations are the outcome of a multitude of influences, operating across various spatial and temporal dimensions, and engaging in intricate, interdependent relationships (Briassoulis, 2019). Numerous theories, rooted in both the Natural and Social Sciences, and more recently, in interdisciplinary research, have emerged to elucidate the dynamics of land use change. This section provides an exposition of the determinants that exert influence on the process of land use change.

Table 2: Factors Influencing Urban Land Use Change in Residential Areas

Variables	Mean	Std Deviation	RII	Rank
Factor 1: Neighbourhood Characteristics				
There is good security	4.370	0.949	0.874	1
Electricity rates are cheap	3.716	1.136	0.743	5
Water rates are cheap	1.988	0.949	0.398	7

Steady power supply	1.790	0.842	0.358	8
Steady water supply	2.728	1.247	0.546	6
Good estate plans and quality designs	3.827	1.184	0.765	3
Good infrastructure developments	4.148	0.995	0.830	2
Good Ethnic Mix	3.802	0.823	0.760	4
Factor 2: Land Policy & Governance				
Subsidies to develop properties	1.790	0.560	0.358	6
Low property taxes	3.580	1.029	0.716	4
Financial constraints by the City Council	4.556	0.685	0.911	1
Lack of enforcement of development control laws	4.123	0.655	0.825	2
Inadequate public education about the activities	3.790	1.062	0.758	3
Delay to grant applicants triggers impatient developers to proceed development without permission	3.160	1.191	0.632	5
Factor 3: Economic factors				
Scarcity of commercial properties	4.099	0.640	0.820	4
High demand for commercial properties	4.198	0.777	0.840	2
High expected revenues	4.259	0.624	0.852	1
Affordable interest rates	4.111	0.969	0.822	3
Mortgage availability	3.790	1.141	0.758	5
Agglomeration of business activities	3.679	1.052	0.736	6
Factor 4: Social factors				
Access to resources	4.148	0.569	0.830	2
High income distribution	2.247	0.950	0.449	5
High level of income	1.951	0.915	0.390	6
Urban rural interaction	2.914	0.984	0.583	4
Cultural values	1.914	0.592	0.383	7
Preference - Lifestyle	3.111	1.361	0.622	3
Norms - Meeting up with trend	4.346	0.591	0.869	1
Factor 5: Biophysical Constraints & Potentials				
Low noise levels	4.642	0.528	0.928	2
Low pollution levels	4.420	0.664	0.884	4
Topography	1.444	0.521	0.289	7
Availability of parking space	4.753	0.459	0.951	1
Good sewerage & stormwater drainage	2.321	0.858	0.464	5
Nearness to schools	4.630	0.618	0.926	3
Nearness to shopping centres	1.852	0.944	0.370	6

The analysis of factors influencing urban land use change in residential areas revealed significant trends based on mean responses. In neighborhood characteristics, respondents strongly agreed that good security (mean = 4.370) and good infrastructure developments (mean = 4.148) influence urban land use change, while they disagreed on factors like steady power supply (mean = 1.790) and cheap water rates (mean = 1.988). Regarding land policy and governance, financial constraints by the City Council (mean = 4.556) and lack of enforcement of development control laws (mean = 4.123) were strongly agreed upon as influential, while subsidies to develop properties (mean = 1.790) were strongly disagreed upon. In economic factors, high expected revenues (mean = 4.259) and high demand for commercial properties (mean = 4.198) were strongly agreed upon, while subsidies to develop properties (mean = 1.790) were strongly disagreed upon. Social factors saw strong agreement on norms meeting up with trends (mean = 4.346) and access to resources (mean = 4.148) as influential, while high-income distribution (mean = 2.247) and high level of income (mean = 1.951) were strongly disagreed upon. Finally, for biophysical constraints and potentials, availability of parking spaces (mean = 4.753) and low noise levels (mean = 4.642) were strongly agreed upon as influential, while factors like topography (mean = 1.444) and nearness to shopping centers (mean = 1.852) were strongly disagreed upon. The Relative Importance Index (RII) analysis further emphasized the significance of these factors, with variables like availability of parking space and good security ranking highest in their respective categories.

Correlation Matrix Results – Factors Influencing Urban Land Use Change

To ensure the validity and robustness of the logistic regression results reported in this study, various tests were conducted, including the identification of potential multicollinearity issues. Given the study's nature and objectives, a correlation analysis was deemed appropriate for assessing the presence of multicollinearity. Specifically, the Spearman's matrix correlation test was employed to identify any potential multicollinearity problems. This test was also instrumental in gauging the extent to which the independent variables (predictors) correlated with the dependent variable (land use changes in urban areas). The ensuing section elaborates on the outcomes derived from applying this analytical technique.

VAR 1	Neighbourhood characteristics as a factor influencing urban land use change
VAR 2	Land policy and governance as a factor influencing urban land use change
VAR 3	Economic factors as a factor influencing urban land use change
VAR 4	Social factors as a factor influencing urban land use change
VAR 5	Biophysical constraints & potential as a factor influencing urban land use change

Spearman's rho Correlations

		VAR 1	VAR 2	VAR 3	VAR 4	VAR 5
VAR 1	Correlation Coefficient	1.000	-.943**	-0.486	0.714	0.036
	Sig. (2-tailed)		0.005	0.329	0.071	0.939
	N	8	6	6	7	7
VAR 2	Correlation Coefficient	-.943**	1.000	0.600	-0.714	-0.429
	Sig. (2-tailed)	0.005		0.208	0.111	0.397
	N	6	6	6	6	6
VAR 3	Correlation Coefficient	-0.486	0.600	1.000	-0.314	-0.314
	Sig. (2-tailed)	0.329	0.208		0.544	0.544
	N	6	6	6	6	6
VAR 4	Correlation Coefficient	0.714	-0.714	-0.314	1.000	0.286
	Sig. (2-tailed)	0.071	0.111	0.544		0.535
	N	7	6	6	7	7
VAR 5	Correlation Coefficient	0.036	-0.429	-0.314	0.286	1.000
	Sig. (2-tailed)	0.939	0.397	0.544	0.535	
	N	7	6	6	7	7

**. Correlation is significant at the 0.01 level (2-tailed).
Source: SPSS Output

3.3 Proximity Benefits and Disamenity Effects

Two opposing theories aim to clarify the impact of non-residential land use in neighborhoods on residential property values. Within the realm of urban economic theory, two explanations emerge regarding the relationship between commercial activities and residential property values. On one hand, the accessibility to commercial services is believed to exert a positive influence on residential property values by enhancing convenience and reducing travel expenses. These overall favorable effects are often referred to as "proximity effects." Conversely, the presence of external drawbacks, including noise, litter, and congestion, can have adverse impacts on residential environments and property values. These detrimental effects are commonly termed "disamenity effects." This section seeks to assess whether the benefits associated with proximity to nearby commercial activities are counteracted by the negative disamenity effects.

Table 3: Proximity Benefits and Disamenity Effects

Proximity Benefits	**Mean**	**Std Deviation**	**RII**	**Rank**
Spurs revitalization	4.235	0.504	0.847	3
Encourages high quality design	3.765	1.189	0.753	6
Increases affordable commercial properties	2.321	1.236	0.464	8
Promotes pedestrian and bicycle travel	4.481	0.611	0.896	2
Encourages economic investment	4.173	0.492	0.835	4
Promotes efficient use of land & Infrastructure	4.136	0.583	0.827	5
Increases revenue	4.531	0.499	0.906	1
Creates job opportunities	3.556	0.956	0.711	7
Disamenity Effects				
Distortion of real estate market	4.222	0.588	0.844	4
Creation of traffic	4.630	0.483	0.926	1
Noise pollution	3.852	1.079	0.770	5
Litter	3.321	1.359	0.664	6
Rental increase	4.578	0.623	0.916	3
Reduces housing stock	4.580	0.664	0.916	2

The analysis of proximity benefits and disamenity effects on residential property values elucidates significant trends. In terms of proximity benefits, respondents strongly agreed that factors such as spurring revitalization (mean = 4.235), promoting pedestrian and bicycle travel (mean = 4.481), and increasing revenue (mean = 4.531) positively impact residential property values. Conversely, respondents were unsure about factors like encouraging high-quality design (mean = 3.765) and creating job opportunities (mean = 3.556). Regarding disamenity effects, respondents strongly agreed that factors such as creating traffic (mean = 4.630), reducing housing stock (mean = 4.580), and increasing rentals (mean = 4.578) negatively impact residential property values. However, respondents were uncertain about the impact of litter (mean = 3.321) and noise pollution (mean = 3.852) on property values. The Relative Importance Index (RII) further highlighted the significance of these factors, with the creation of traffic ranking highest among disamenity effects and revenue increase ranking highest among proximity benefits.

3.4 Urban Land Use Change and Formal Housing Shortage

The formal housing market is structured as an assortment of diverse submarkets, categorized by factors such as house type, tenure, and geographical location. Furthermore, formal housing, as a commodity, is inherently tied to its specific geographical location, meaning it can only be sold within that particular area and cannot be traded across various markets.

Table 4: Urban Land Use Change and Formal Housing Shortage

Statements (Description)	**Mean**	**Std Deviation**	**RII**	**Rank**
There has been a high increase in rentals	4.420	0.645	0.884	4
There has been a high increase in land values	4.654	0.548	0.931	2
There has been an increase in slum formation	4.395	0.715	0.879	5
Developers prefer construction of commercial properties to residential properties	4.728	0.497	0.946	1
It is difficult to find a residential property to dwell	4.494	0.631	0.899	3
There is increase in demand for land	4.136	0.813	0.827	7
Low supply of residential properties	4.358	0.479	0.872	6
There has been an increase in squatter settlements	4.099	0.713	0.820	8

The analysis of urban land use change and formal housing shortage highlights several key findings. Respondents strongly agreed that various factors contribute to the city's formal housing shortage due to urban land use change. These factors include developers preferring construction of commercial properties to residential properties (mean = 4.728), high increases in land values (mean = 4.654), and difficulty in finding residential properties to dwell (mean = 4.494). Additionally, respondents expressed concerns about high increases in rentals (mean = 4.420) and an increase in slum formation (mean = 4.395) as contributing to the formal housing shortage. The Relative Importance Index (RII) further emphasized the significance of these factors, with the preference for commercial properties by developers ranking highest.

3.5 Mixed Land Use and Sustainable Development

According to UNDP Sustainable Development Goal II (2012), it makes a provision of cities being inclusive, safe, resilient and sustainable. It ensures access for all to adequate, safe, affordable housing and upgrade of slums. This section examines whether mixed land use contributes to sustainability and viability of urban neighbourhoods.

Table 5: Mixed Land Use and Sustainable Development

Measure 1: Decrease urban Sprawl	**Mean**	**Std Deviation**	**RII**	**Rank**
Promote infill development	4.148	0.755	0.830	4
Promote mixed-use, walkable and compact development	4.481	0.611	0.896	2
Urban and town centres restoration	4.247	0.510	0.849	3
Promotion of transit-oriented development	4.556	0.567	0.911	1
Limiting leapfrog/non-contiguous development	4.086	0.706	0.817	5
Measure 2: Protect open space and working landscapes				
Using open space to define urban communities	1.469	0.546	0.294	4
Conservation of lands of high recreational and scenic value	1.988	0.793	0.398	3
Minimize disruption to watershed function, including natural flood ways and water quality	2.247	0.619	0.449	1
Conservation natural habitat lands	2.086	0.834	0.417	2

Measure 3: Protect environmentally sensitive lands				
Avoid natural hazards	2.099	0.840	0.420	3
Preserving the connectivity of habitats	2.222	1.018	0.444	2
Providing support for resource and energy efficient industries	1.654	0.632	0.331	4
Promotion of alternative transportation options	3.358	1.126	0.672	1
Measure 4: Promote energy and resource efficiency				
Intensifying waste reduction programs such as recycling	2.025	0.929	0.405	2
Promoting the construction of buildings that are resource and energy efficient	3.877	0.655	0.775	1
Measure 5: Create strong local and regional economies				
Encouraging a strong balance between jobs and housing	4.296	0.728	0.859	1
Adequate housing provision for all income groups	1.716	0.652	0.343	3
Ensuring that land use planning process is predictable and fair	1.679	0.493	0.336	4
Encouraging the expansion of telecommunications services and infrastructure	4.111	0.737	0.822	2
Measure 6: Promote equitable development				
Improving accessibility and mobility through the promotion of alternative transportation choices	4.309	0.462	0.862	1
Ensuring that there is fair treatment in the preparation/design, adoption, implementation and enforcement of environmental regulations, policies and laws	4.222	0.994	0.844	3
Ensuring that there is equitable economic opportunity for all segments of the community	3.691	1.118	0.738	4
Providing protection for culturally significant sites	2.086	0.863	0.417	5
Promotion of the development of mixed-income housing	4.235	0.528	0.847	2

The analysis of mixed land use and its impact on sustainable development indicates varied perceptions among respondents. Regarding the decrease in urban sprawl, respondents strongly agreed that mixed land use contributes positively, with mean scores approaching 4.0 for factors such as promoting transit-oriented development and infill development. However, there was disagreement about the effectiveness of mixed land use in protecting open space, working landscapes, and environmentally sensitive lands, with mean scores below 3.0 for most variables. While respondents were uncertain about the promotion of energy and resource efficiency, they strongly agreed that mixed land use creates strong and local regional economies and promotes equitable development, particularly through improving accessibility and mobility and encouraging a strong balance between jobs and housing, as indicated by mean scores exceeding 4.0.

Correlation Matrix Results – Mixed Land Use & Sustainable Development

Measure 1	Decrease urban sprawl as a measure of sustainable development
Measure 2	Protects open space & working landscapes as a measure of sustainable development
Measure 3	Protect environmentally sensitive lands as a measure of sustainable development
Measure 4	Promote energy and resource efficiency as a measure of sustainable development

Measure 5	Create strong local and regional economies as a measure of sustainable development
Measure 6	Promote equitable development as a measure of sustainable development

Spearman's rho Correlations

		Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6
Measure 1	Correlation Coefficient	1.000	0.400	0.800	1.000	-0.200	-0.800
	Sig. (2-tailed)		0.600	0.200		0.800	0.104
	N	5	4	4	2	4	5
Measure 2	Correlation Coefficient	0.400	1.000	-0.200	1.000	-0.800	-0.800
	Sig. (2-tailed)	0.600		0.800		0.200	0.200
	N	4	4	4	2	4	4
Measure 3	Correlation Coefficient	0.800	-0.200	1.000	1.000	0.400	-0.400
	Sig. (2-tailed)	0.200	0.800			0.600	0.600
	N	4	4	4	2	4	4
Measure 4	Correlation Coefficient	1.000**	1.000**	1.000**	1.000	-1.000	-1.000
	Sig. (2-tailed)						
	N	2	2	2	2	2	2
Measure 5	Correlation Coefficient	-0.200	-0.800	0.400	-1.000**	1.000	0.400
	Sig. (2-tailed)	0.800	0.200	0.600			0.600
	N	4	4	4	2	4	4
Measure 6	Correlation Coefficient	-0.800	-0.800	-0.400	-1.000**	0.400	1.000
	Sig. (2-tailed)	0.104	0.200	0.600		0.600	
	N	5	4	4	2	4	5

**. Correlation is significant at the 0.01 level (2-tailed).
Source: SPSS Output

4. Conclusions and Future Work

From the findings of the research, the following conclusions can be made with regard to urban land use change and its externality effects on residential property values:

- Economic factors, followed by land policy and governance, significantly influence urban land use change in residential areas.
- Urban land use change has both proximity benefits (e.g., revitalization, increased revenues) and disamenity effects (e.g., traffic congestion, noise pollution) on residential property values, with the impact varying based on surrounding commercial activity levels.
- Mixed land use positively contributes to sustainability but not conclusively to energy efficiency or environmental protection.
- Conversion of properties from residential to commercial exacerbates the city's formal housing shortage, evidenced by various factors such as high increases in rentals, difficulty in finding residential properties, and increased slum formation.

From the research findings, it is clear and evident enough that urban land use change from residential to commercial has had more disamenity effects than proximity benefits. Based on the results, the following recommendations are suggested;

- Property owners and users must adhere to planning approvals and permissions for redevelopment.
- Government oversight bodies must conduct regular monitoring and inspections.

- Strengthen enforcement mechanisms for land use laws.
- Educate landowners and users on due process and societal impacts.
- Real estate professionals should offer clear guidance on property conversions.
- Estate Surveyors and Valuers should enhance public awareness and service delivery.

Overall, managing the externalities of urban land use changes requires a comprehensive approach that takes into account the unique characteristics of each community. By implementing these recommendations, urban planners can help ensure that the benefits of urbanization are maximized while the negative externalities are minimized.

4.1 Directions for Further Research

There is need for further research. This will help identify and assess other externality effects of urban land use change on residential values. There are several areas where further research could help to improve our understanding of the externality effects of urban land use change on residential property values. These areas include:

i. What are the most effective strategies for mitigating the negative externalities of urban land use changes on residential property values, and how do these strategies vary across different types of communities (e.g. urban, suburban, rural)?

ii. How does the impact of transportation infrastructure on residential property values vary across different modes of transportation (e.g. highways, public transit, bike lanes), and what are the most effective strategies for mitigating negative externalities associated with each mode of transportation?

iii. What is the rate at which land is being converted from residential to commercial use?

iv. What is the long-term impact of urban land use changes on residential property values, and how can we predict and plan for these impacts over time?

v. How can new technologies and innovations be leveraged to mitigate the negative externalities of urban land use changes on residential property values, and what are the most promising new technologies and innovations in the study area?

Overall, these research questions can help us deepen our understanding of the complex relationship between urban land use changes and residential property values, and identify new strategies and technologies for mitigating negative externalities and maximizing the benefits of urbanization.

4.2 Closing Statement

In summary, this study has established that the observed changes in land use within Lilongwe City are closely intertwined with the rapid pace of social and economic development in the region. This development, in turn, exerts a positive influence on the residential property values in the affected areas. However, it is paramount to emphasize that such developmental processes must be meticulously managed and guided by all stakeholders to avert potential urban growth-related chaos.

In broader terms, the findings of this research contribute significantly to the existing body of knowledge in the fields of urban economics, real estate economics, and land use dynamics. The outcomes of this study hold particular relevance for developing nations experiencing rapid urban expansion, akin to Lilongwe, which is characterized by a concurrent surge in demand and value escalation of residential properties.

The insights garnered from this research offer valuable guidance and lessons for urban planners, policymakers, and real estate professionals operating in similar contexts, facilitating more informed and sustainable decision-making processes in the realm of urban development and land use management.

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Paper 16: Mechanical and Physical Performance of Malawian-based Rice Husk Ash- blended Cement

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Malawi aspires to realise green economy by year 2063 through the promotion of sustainable infrastructure development and proper waste management strategies. Cement production is an integral part of Malawi's vision and the use of eco-friendly cementitious materials as an alternative to energy-intensive Ordinary Portland Cement (OPC) is the potential strategy to achieve green economy. In this study, Rice husk ash (RHA), a by-product of rice milling process was investigated for potential use as supplementary cementitious material (SCM) in cement with a view to reducing the carbon footprint associated with cement production**.** Series of mechanical and physical properties tests of RHA-blended cement at varying dosages of 5%, 15%, and 30%, and water to binder (w/c) ratios of 0.5, 0.55 and 0.6, and at a constant gypsum content of 5% were performed. The parameters of interest were setting time, optimum compressive strength, resistance to sulphate attack, water absorption, and drying shrinkage. The results revealed the optimum compressive strength of 34.2 MPa at 15% RHA and 0.45 w/c ratio which was higher than strength of some masonry cement batches on the Malawian market. The initial setting time was greater than 75min and met recommended requirements by BS EN 197-1:2011.The blended cement (15% RHA) exhibited superior performance in water absorption (<10%), sulphate attack resistance (strength loss <11%) and drying shrinkage (<10%). The study provided valuable insights into the potential use of RHA-blended cement in the Malawian construction industry for durable and resilient infrastructure development.

Keywords: supplementary cementitious materials, sulphate attack, water-cement ratio, shrinkage, water absorption

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1. Introduction

In recent years, there has been a significant transformation of the construction industry, with a growing emphasis on the sustainability and the adoption of eco-friendly building materials [1]. With the growing concern about climate change whose effects are exacerbated by carbon emissions in concrete production, researchers have turned attention to finding alternative, and environmentally friendly construction materials in a quest to achieve carbon-free construction industry[2, 3]. The drive to improve infrastructure in the developing countries like Malawi directly increases demand for cement, and ultimately makes the need for alternative sustainable and carbon-free materials very critical.

Several researchers[4-8] have proposed the use of supplementary cementitious materials (SCMs) to replace energy-intensive Portland cement (PC). The common SCMs that have proven to perform well are the industrial waste products such as fly ash, silica fume, and GGBS, however their availability to meet the growth in cement demand depends on the level of industrialisation [9]. Malawi's manufacturing industry is young and sluggishly growing due to the weak economic base, hence the use of waste industrial products for SCMs is unsustainable for a vibrant cement industry in Malawi.

Crop residues such as rice husk ash (RHA) exhibit high potential for use as SCMs. Rice husk is an agro-based waste from rice milling whose ash is produced from the on-field burning. Research has shown that RHA contains high amount of reactive SiO_2 which reacts with $Ca(OH)_2$ in concrete to form calcium silicate hydrate (CSH) [10]. Thus, enhances the strength of concrete. The addition of RHA to concrete reduces porosity at later ages rather than early ages, enhances resistance against chloride attack, sulphate attack, and the alkali–silica reaction [11].

Malawi currently produces 150000 ton of rice per year and the volume is likely to grow owing to the national agenda to put agriculture as the main driver to realising self-reliant economy as stipulated in the Malawi vision 2063 [12, 13]. High production RHA poses environmental management challenges which Malawi may face. It is therefore imperative to investigate potential use of the Malawian -based RHA to achieve environmental sustainability as an enabler in the Malawi vision 2063.

This study aims at establishing potential use of Malawian-based RHA as SCM in the blended cement through a series of test for mechanical and physical properties. Of special interest are optimum compressive strength and associated degradation under sulphate attack, water absorption, and drying shrinkage. The results are compared with specifications for the cement and the performance brands of cement on the Malawian market.

2. Materials and Methods

5. Materials

The materials used herein were clinker, gypsum and RHA. Both clinker and gypsum were supplied by Lafarge cement manufacturers. Rice husks were obtained from the rice milling spots supplied by local farmers. The cement mortar was prepared using river sand with particle size distribution in conformity with EN-196-1.

6. Material Preparations

A two-step process for preparing RHA was adopted, namely uncontrolled open air burning followed by furnace incineration. The burning process is simple and cost effectiveness; however, the resulting ash contains significant amounts of cristobalite and tridymite, which are non-reactive silica minerals. In this study, the non-reactive compounds were converted to reactive amorphous silica by incineration at 700ºC for 1 hr.

The constituent materials, clinker, gypsum and RHA were separately ground in a ball mill and sieved using 45um aperture sieve to obtain a homogenous material.

Figure 1: Samples of clinker, gypsum and RHA

The analysis of the mineralogical composition of the materials was performed using X-ray Florescence (XRF) analyser. The summary of results is shown in Table 1.

Table 1: Mineralogical composition of materials

Mineral	Mineral Composition %		
	Clinker	Gypsum	RHA
Na_2O	*0.03*	0.003	0.13
MgO	*4.00*	4.80	1.66
Al_2O_3	*7.35*	1.90	2.00
SiO_2	*34.07*	1.50	84.27
P_2O_5	*0.36*	0.00	5.68
SO_3	*1.19*	52.5	0.29
Cl	*0.03*	0.01	0.00
K_2O	*0.65*	0.01	1.68
CaO	*52.17*	32.01	1.10
TiO_2	*0.3*	0.02	0.08
MnO	0.01	0.01	0.00
Fe_2O_3	*2.58*	0.07	1.50

7. Experimental Programme

The cement mortar for testing physical and mechanical properties such as standard consistency, setting time and compressive strength was prepared at water to cement (w/c) ratios of 0.5, 0.55 and 0.6. The RHA dosages for each w/c ratio were 5%,15% and 30%. The specimens were cured in full water bath (see Figure 2) and the total of 54 specimens of dimensions of 50 mm x 50 mm x 50 mm were prepared for testing. Three batches of masonry cement available on the Malawian market designated as MC1, MC2, MC3 were randomly collected from the retail suppliers and tested to serve as reference for strength comparison.

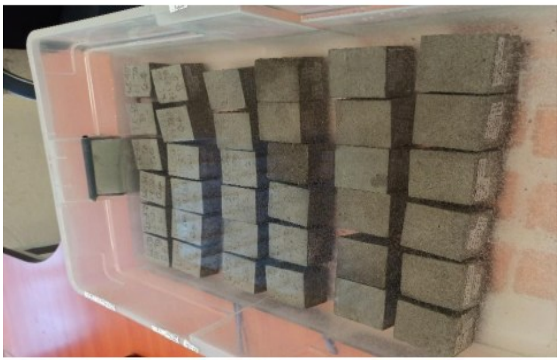

Figure 2: Specimens' curing process

The summary of experimental programme is shown in Table 2.The optimum water to cement ratio was used to prepare specimens for water uptake, sulphate attack, shrinkage and resistance to elevated temperature.

Table 2: Experimental design

SN	Mix design %			Water-Binder ratio
	Clinker	Gypsum	RHA	
1	*90*	5	5	0.5
2	*80*	5	15	0.5
3	*65*	5	30	0.5
4	*90*	5	5	0.55
5	*80*	5	15	0.55
6	*65*	5	30	0.55
7	*90*	5	5	0.6
8	*80*	5	15	0.6
9	*65*	5	30	0.6

8. Specimen preparation for compression, standard consistency and setting time tests

The specimens for compression test were prepared according to EN 196-1.The testing was performed after 7 and 28 days of curing. The standard consistency and setting time were conducted in accordance with EN 196-3.

9. Specimen preparation for water absorption test

The batches of specimens that were cured for 28 days were initially oven dried and subsequently exposed to full water bath until saturation. The dry weight and saturated weight were recorded. The degree of water absorption (%) was determined using Equation 1.

$$W = \frac{M_2 - M_1}{M_1} \qquad (1)$$

where M_1 is dry weight of specimen and M_2 is saturated weight of specimen. The rate of absorption was measured in accordance with ASTM C1585-13

10. Specimen preparation for dry shrinkage test

The specimens were prepared according to the procedure in section 2.3. The test was performed according to ASTMC157 using specimens of dimensions 50 mm x 50 mmx 250mm. The time related volumetric changes of the specimens were measured using length comparator at the room temperature. Dry shrinkage at a given curing time of the specimen was determined using Equation 2.

$$L = \frac{L_t - L_1}{GL_1} \times 100 \qquad (2)$$

where L_t is the length of specimen at time t minus reference length in millimetres, and L_1 is initial length of the specimen minus reference length and G is nominal reference length.

11. Specimen preparation for sulphate attack

The sodium sulphate solution with concentration of 0.05g/l was prepared using 50g of sodium sulphate and 1 litre of distilled water. The specimens prepared for compression test (see section 2.3) were cured for 28 days and subsequently immersed in the sodium sulphate solution. The specimens were conditioned and tested for compressive strength after 1day, 7days, 14days, 28days and 42days.The compressive strength was determined according to EN 196-1.

3. Results and Discussion

Variation of Standard Consistency with RHA

The effect of RHA on standard consistency of the cement mortar is shown in Figure 3. The results showed that standard consistency of the mortar increased with the corresponding increase in RHA content. The values varied between 34% and 50% for 5 % and 30% RHA, respectively, representing 47% increase. This could be due to the amorphous phases of silica that provide a large surface area for water absorption owing to their disordered arrangement of molecules that allows penetration of the water [14, 15].

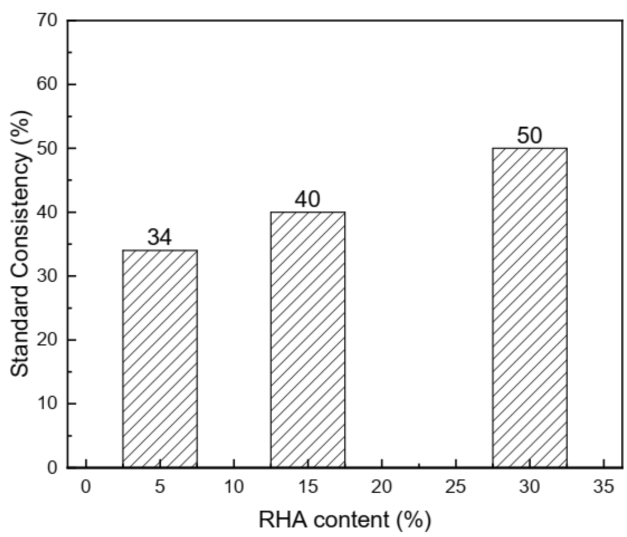

Figure 3: Variation of standard consistency

Variation of Setting Time with RHA content

The effect of RHA on setting time of cement mortar is shown in Figure 4.

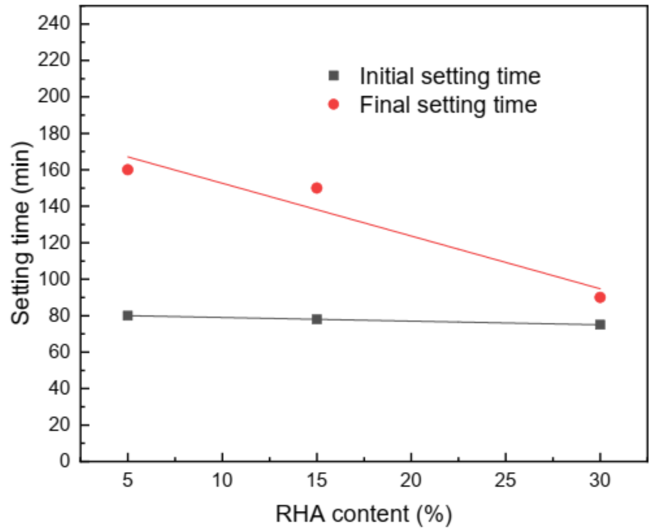

Figure 4: Variation setting time with RHA

It was noted that setting time varied inversely with increasing RHA content. The initial setting time varied between 75min and 80min, representing 6% increase for 5% RHA and 30% RHA , respectively. On the other hand, final setting time varied between 90min and 160min, representing 78% increase. The reduced setting time could be attributed to the high rate of hydration in the presence of high silica content in RHA (84 % see Table 1) , resulting in the faster calcium silicate hydrates (C-S-H) nucleation[16]. The minimum initial setting time for conventional cements recommended by BS EN 197-1:2011 is 75 min [17], thus the RHA blended cement in this study complied with the requirement.

Effect of RHA on the Compressive Strength

The effect of RHA dosages on compressive strength at various w/c ratio is shown in Table 3.

Table 3: Compressive Strength of Mortar with RHA

RHA Content %	Compressive strength MPa					
	Water-cement ratio (7 days)			Water-cement ratio (28 days)		
	0.5	0.55	0.6	0.5	0.55	0.6
5	20.8	22.7	20.2	30.3	34.2	19.2
15	14.2	15.3	13	20.9	22.7	18.9
30	4.7	6.7	5.3	17.1	18.9	11.6

It was observed that compressive strength reduced with an increase in RHA dosage for all w/c ratios. At least 40% loss in strength was registered with 30% RHA for all batches. The compressive strength registered maximum values at 0.55 w/c ratio for all RHA dosages. After 28 days of curing, the highest registered value was 34.2 MPa at 0.55 w/c ratio and 5% RHA content. The lowest value was 11.6MPa at 0.6 w/c with 30% RHA content. This loss in strength was obviously due to the dilution effect caused by the decreased amount of clinker in the mix.

Several researchers have reported similar trend and confirmed that 10% to 15% of RHA is optimal to achieve maximum long-term strength of RHA-blended cement. It was concluded that delayed pozzolanic activity of RHA is responsible for early-age compressive strength reduction [18, 19]. Segregation of aggregate in the cement mortar due to water in excess of the amount required for hydration is also a possible cause of low-strength development at high w/c ratio of 0.6 [20, 21]. According to BS EN 413-1:2011[22] specifications , specimens with 0.55 w/c at 5% and 15% RHA met strength requirement for masonry cement.

Table 4 compares the strength between three batches of masonry cements obtained from the retail outlets and RHA-blended cement prepared for this study. The results showed that RHA-blended cements had better strength performance than batches on the market, indicating potential application of RHA-based cement in the Malawian construction industry.

Table 4: Comparison of RHA-blended cement with masonry cement batches on the market.

Water-cement ratio	Compressive strength MPa					
	Masonry cement batches			RHA content %		
	MC1	MC2	MC3	5	15	30
0.45	19.2	*15.03*	10.6	30.3	34.2	19.2
0.5	18.9	*14.83*	10.4	20.9	22.7	18.9
0.6	11.6	*9.94*	7.0	17.1	18.9	11.6

Water Uptake Characteristics

The water absorption characteristics of RHA-blended cement mortar are shown in Figure 4.

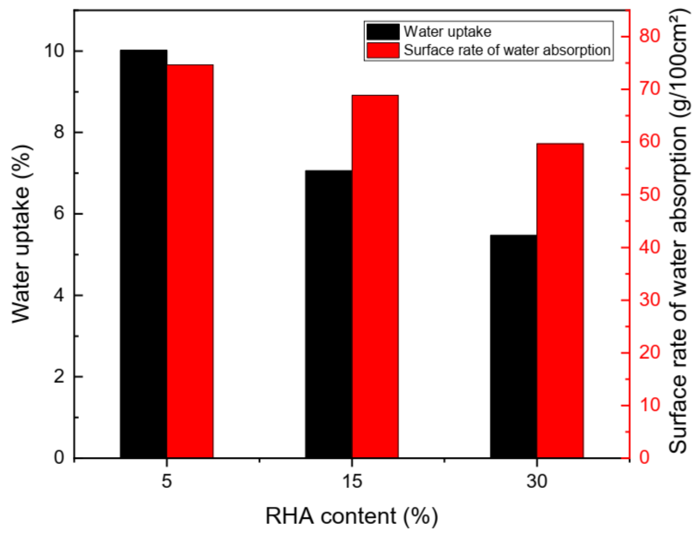

Figure 4: Water uptake characteristics

It was noted that the sorptivity of the cement mortar reduced with an increase in RHA content. A reduction of 45% at 30% RHA was registered. On the other hand, surface rate of absorption exhibited similar trend. Surface rate of absorption reduced by 20% at 30% RHA. Similar trend in the blended cementitious materials is reported in the literature [23, 24].

This decrease in the total water uptake in this study was attributed to the changes occurring in the pore size distribution as a result of using silica-rich RHA which could react with the calcium hydroxide to form C-S-H gel [24].

Degree of linear shrinkage

The evolution of shrinkage with RHA content is shown in Figure 5.

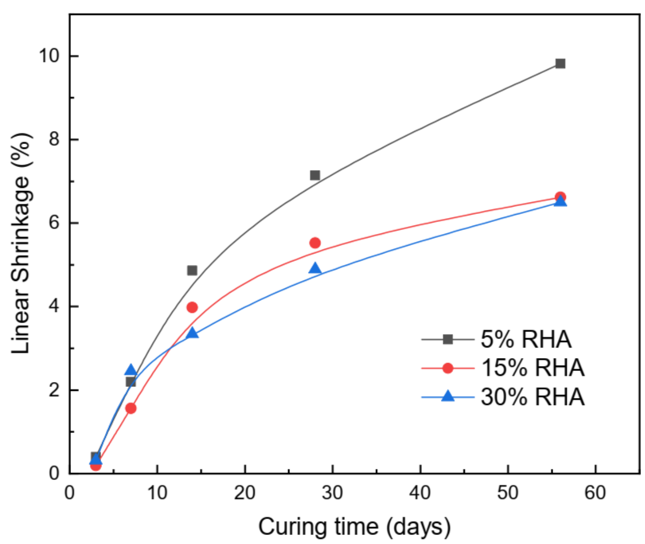

Figure 5. Linear shrinkage of RHA-blended cement

It was observed that evolution of linear shrinkage varied inversely with RHA content. After 56 days of curing, values of the percentage shrinkage were 9.8% ,6.6% and 6.5% for 5% ,15% and 30% RHA, respectively. This was due to the presence of more micro silica from RHA dosages in the cement paste that caused pore refinement, leading to low porosity and low shrinkage for RHA dosage. The similar trends were in the literature [25].

Resistance to Sulphate Attack

The resistance to sulphate of the RHA-blended cement is shown in Figure 6. The results showed that increase in the RHA content resulted in the decrease loss of strength, indicating enhanced resistance to sulphate attack. The specimens with 15% RHA and 30% RHA exhibited superior performance in resisting loss of strength (11% and 8%, respectively). The literature has reported that high RHA content enhances sorptivity of the cement mortar due to pore refinement and development of hydration products. In this case, low porosity inhibited penetration of sulphate molecules in the cement mortar, resulting in the resistance to the strength degradation [26].

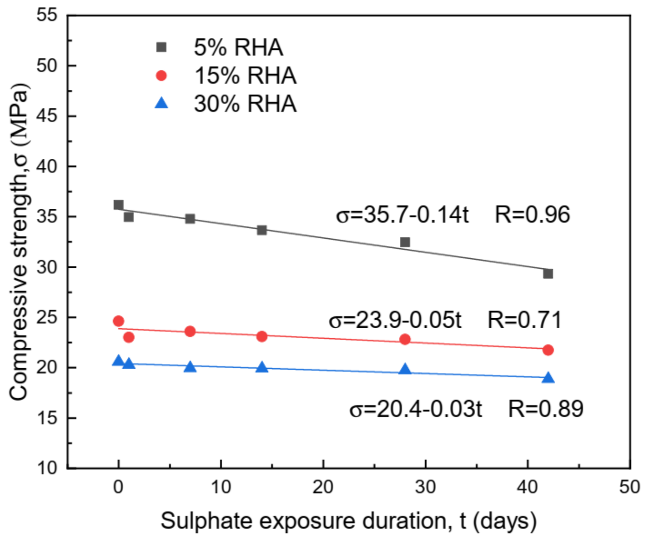

Figure 6: Strength degradation with sulphate exposure

4. Conclusions and Future Work

Based on the acquired results, the following conclusions were drawn:

- The RHA-blended cement demonstrated superior performance in strength compared to some batches of masonry cement on the Malawian market. Therefore, environmental sustainability as enshrined in Malawi 2063 agenda can be achieved by replacing energy intensive clinker with RHA to promote sustainable development with clean and secure environment.
- The maximum dosage of RHA in the blended cement should be 15% at 0.55 water to cement ratio.
- RHA-blended cement can performance well under sulphate exposures

- The reduced porosity (less than 10%) and shrinkage of RHA-blended cement are beneficial to achieve resilient and durable infrastructure.

It is recommended to establish rate of hydration of the RHA cement and associated phases that are substantiated by image analysis.

5. Acknowledgement

The authors acknowledge financial support from MUBAS to conduct this research

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Paper 17: Durability Properties of Limestone Calcined Clay Cement amended with natural pozzolan

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Abstract

The global construction industry is highly dependent on concrete. Cement is a major component of concrete which is manufactured through an energy intensive process that is responsible for 9% of global greenhouse gas emissions. Malawi 2063 agenda hinges on the infrastructure development with clean and secure environment. It is therefore imperative that the conventional methods of construction and the production of materials in Malawi are revolutionised to achieve this agenda. The advent of limestone-calcined clay cement (LC^3) is part of the change and Malawi stands to benefit due to the abundance of raw materials for LC^3 production. This paper presents an investigation on the performance of LC^3 in Malawi blended with natural pozzolan (NP) at the dosages of 10%, 15%, 20%, 25% and 45% and, water-cement (w/c) ratios of 0.45, 0.5 and 0.6, to explore the potential use of natural pozzolan as a filler in LC^3-50. Series of laboratory tests were conducted to determine standard consistency, setting time, compressive strength and water absorption of the blended LC^3-50. The strength results were compared with the performance of the masonry cement available on the Malawian market. It was revealed that NP dosages up to 25% caused marginal change in standard consistency. Rapid setting (55min) was observed for cement paste with 10% NP. Compressive strength reduced with an increase in NP dosage and w/c ratio. The optimum compressive strength was determined to be 21.9MPa with 25% NP at w/c ratio of 0.45. The water uptake reduced with an increase in NP content. The LC^3-50 blended cement mortar exhibited superior strength performance compared to masonry cement on the Malawian market, showing potential use of the blended cement in the Malawian construction industry.

Keywords: Standard consistency, setting time, compressive strength, water absorption, dosage

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1. Introduction

Concrete is the most widely consumed construction material in the world, due to its excellent properties, relatively low-cost and availability. It is used in almost all types of construction, ranging from residential housing, industrial and high-rise buildings roads, and infrastructure such as dams and bridges. Concrete industry untilises cement whose manufacturing process is energy intensive and contributes 9% of the global greenhouse gases. The growing global population and urbanisation in the developing countries directly increases demand for concrete. It is anticipated that global demand for concrete will exponentially rise by year 2050 [1, 2]. Therefore, there is a need to decarbonise concrete industry by exploring alternative ways of cement production that are both cost effective and environmentally friendly. This can be achieved by reducing clinker factor in cement, by direct replacement with cheaper and readily available cementitious materials that have comparatively good performance [3].

Research has shown that the use of supplementary cementitious materials (SCMs) to replace the clinker portion of cement is the most successful strategy to reduce CO_2 emissions in the global cement industry. Several researchers[4-8] have proposed the use of binary blended cement with supplementary cementitious materials (SCMs). The common SCMs that have proven to perform well are the industrial waste products such as fly ash, silica fume, and GGBS. however their availability to meet the growth in cement demand depends on the level of industrialisation [9].

Malawi's manufacturing industry is young and susceptible to economic shocks, hence the conventional SCMs are available in limited quantities which makes it difficult to replace clinker content at a large scale. However, Malawi has a large deposit natural pozzolans and clays containing kaolinite that can be calcined and produce an effective SCM. Limestone calcined clay cement (LC^3) is a newly developed cement with limestone and calcined clay as SCMs which fulfils all the requirements for low carbon footprint. LC^3 can reduce up to 40 % of Portland cement emissions by substituting 50 % of clinker content [10]. The literature has shown that LC^3 containing 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum (LC^3-50) possesses strength properties comparable to Portland cement [7, 11-14].

Comparatively, a conventional pozzolan-blended cement cuts down clinker factor to around 65-70%. Natural pozzolans include rocks of volcanic origin which are used in their raw state while others of sedimentary origin such as clays and shales undergo a process of thermal activation (e.g. calcined clays). These pozzolans increase late strength of concrete while also inhibiting alkali-silica reaction which is detrimental to concrete structures thereby improving durability [15].

As Malawi envisions to achieve sustainable wealth creation through resilient infrastructure development by year 2063, the use of locally available and sustainable construction materials is an integral part to realising the vision. This study aims to establish potential use of blended LC^3 with natural pozzolans through a series of tests for mechanical and physical properties. Of special interest are compressive strength and durability properties of the blended cement with various dosages of natural pozzolan.

2. Materials and Methods

12. Materials

The materials used herein were clinker, gypsum, calcined clay, limestone and natural pozzolan. Both clinker and gypsum were supplied by Lafarge cement manufacturers. Clay for calcination was collected from Lithipe in Dedza district. Natural pozzolan was collected from Senzani in Ntcheu district. Limestone was obtained from the Chenkumbi mining sites in Balaka district. The cement mortar was prepared using river sand with particle size distribution in conformity with EN-196-1.

13. Material Preparations

Limestone, gypsum, and clinker were ground separately to produce fine powder. The clay soil and natural pozzolan were initially pulverized and sieved using a 75 µm sieve. Calcined clay for LC^3 was produced by static calcination process in which 100g of clay was heated at 800°C in a muffle furnace for 30 min.

A binder system of was prepared with 50% clinker content, 5% gypsum and limestone to calcined clay ratio of 1:2. The system was subsequently blended with natural pozzolan at the dosages of 10%, 15%, 20%, 25% and 45%. The river sand for cement was graded to achieve particle distribution that conformed the grading of standard sand according to EN 196-1. The ground materials are shown in Figure 1.

Figure 1: Natural clay ,Calcined clay, Gypsum, Clinker, Limestone and Natural pozzolan.

The analysis of mineralogical composition of the materials was performed using X-ray Florescence (XRF) analyser. The summary of results is shown in Table 1a and b.

Table 1a:Mineralogical compositions of materials

Mineral	Mineral Composition %		
	Clay	Calcined	Gypsum
Na_2O	0.009	0.003	0.003
MgO	0.12	0.20	4.80
Al_2O_3	29.44	36.03	1.90
SiO_2	48.15	46.71	1.50
P_2O_5	0.06	0.06	0.00
SO_3	0.06	0.83	52.5
Cl	0.007	0.004	0.005
K_2O	0.3	0.35	0.01
CaO	0.44	0.71	32.01
TiO_2	0.40	0.43	0.02
MnO	0.02	0.02	0.004
Fe_2O_3	2.9	3.35	0.07
LOI	18.09	11.30	7.7

Table 1b :Mineralogical compositions of materials

Mineral	Mineral Composition %		
	Clinker	Limestone	Natural pozzolan
Na_2O	0.03	0.003	6.25
MgO	4.00	9.20	2.02
Al_2O_3	7.35	1.65	33.12
SiO_2	34.07	6.45	51.87
P_2O_5	0.36	0.034	0.07
SO_3	1.19	0.34	0.19
Cl	0.03	0.002	0.02
K_2O	0.65	0.05	0.25
CaO	52.17	47.26	7.56
TiO_2	0.3	0.057	0.15
MnO	0.004	0.018	0.02
Fe_2O_3	2.58	0.61	1.16
LOI	0.00	34.32	0.00

14. Experimental Programme

The cement mortar for testing physical and mechanical properties such as standard consistency, setting time and compressive strength was prepared at water-cement (w/c) ratios of 0.45, 0.5 and 0.6. The specimens were cured in the full water bath (see Figure 2) and the total of 45 specimens of dimensions of 50 mm x 50 mm x 50 mm were prepared for testing. Three batches of masonry cement available on the Malawian market designated as MC1, MC2, MC3 were randomly collected from the retail suppliers and tested to serve as reference for strength comparison.

Figure 2: Specimens' curing process

The summary of experimental programme is shown in Table 2.The optimum water-cement ratio was used to prepare specimens for water uptake , sulphate attack, shrinkage tests.

Table 2: Experimental design

Mix design %				Water-Binder ratio
Calcined clay and Limestone	Clinker	Gypsum	Natural Pozzolan	
35	*50*	5	10	0.45
30	*50*	5	15	0.45
25	*50*	5	20	0.45
20	*50*	5	25	0.45
0	*50*	5	45	0.45
35	*50*	5	10	0.5
30	*50*	5	15	0.5
25	*50*	5	20	0.5
20	*50*	5	25	0.5
0	*50*	5	45	0.5
35	*50*	5	10	0.6
30	*50*	5	15	0.6
25	*50*	5	20	0.6
20	*50*	5	25	0.6
0	*50*	5	45	0.6

15. Specimen preparation for compression, standard consistency and setting time tests

The specimens for compression test were prepared according to EN 196-1.The testing was performed after 7 and 28 days of curing. On the other hand, standard consistency and setting time were conducted in accordance with EN 196-3.

16. Specimen preparation for water absorption test

The batches of specimens that were cured for 28 days were initially oven dried and subsequently exposed to full water bath until saturation. The dry weight and saturated weight were recorded. The degree of water absorption (%) was determined using Equation 1.

$$W = \frac{M_2 - M_1}{M_1} \qquad (1)$$

where M_1 is dry weight of specimen and M_2 is saturated weight of specimen. The rate of absorption was measured and computed in accordance with ASTM C1585-13.

3. Results and Discussion

Variation of standard consistency and setting time

The variations of standard consistency and setting time are shown in Table 3.

Table 3: Standard consistency and setting time

Natural Pozzolan Content %	Physical properties		
	Standard consistency (%)	Setting time (min)	
		Initial	Final
10	33.3	55	120
15	32.7	72	140
20	32.3	80	149
25	32	92	160
45	26.7	119	180

It was worth noting that very marginal changes in standard consistency were observed in LC^3-50 paste with varying natural pozzolan (NP) content between 10% and 25%. An appreciable change (20%) was observed at 45% NP content. The standard consistency of 33.3% for 10% NP and 26.7% for 45% NP were registered. Rapid initial setting (55min) was observed at 10% NP content and 119 min for 45% NP. The setting time varied linearly with an increase in NP content. The same trend was exhibited for final setting time (from 120 min to 180min). The presence of reactive metakaolin in the LC^3 coupled with reactive silica in NP resulted in the high rate of hydration that was responsible for faster calcium hydrates nucleation, leading to the building up of bridges between cement particles. The delayed setting time at high NP content implied lower rate of hydration contributed by reactive silica in NP than that of metakaolin in LC^3 [16-18]. It should be acknowledged that the binder system with 10% NP did meet minimum requirement for initial setting time of 75min in accordance with BS EN197-1:2011[19].

Effect of Natural Pozzolan on Compressive Strength

The variation of compressive strength with NP dosages in the LC^3 system is shown in Figure 3 and Figure 4 for 7-day and 28-day strengths. The results showed an inverse relationship between compressive strength and natural pozzolan dosages. The maximum early-stage strengths were 17.3 MPa, 18.9MPa and 15.2MPa at 10% NP content, and 0.45, 0.5 and 0.6 w/c ratios, respectively. The highest early-stage strength loss was exhibited for cement paste with 0.6 w/c ratio at 45% NP dosage.

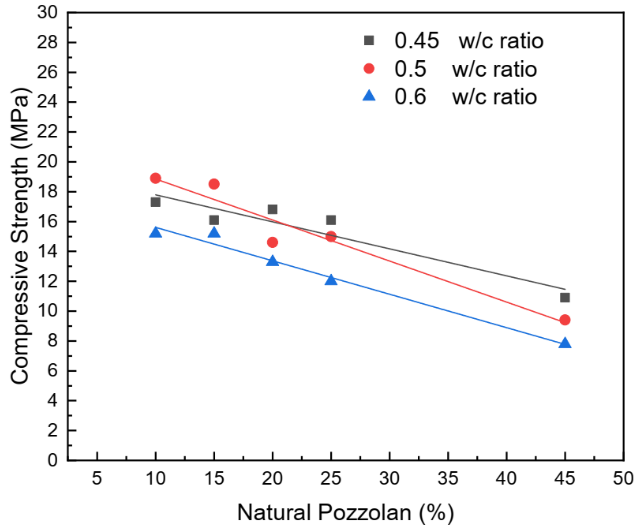

Figure 3: 7-day compressive strengths with NP dosages

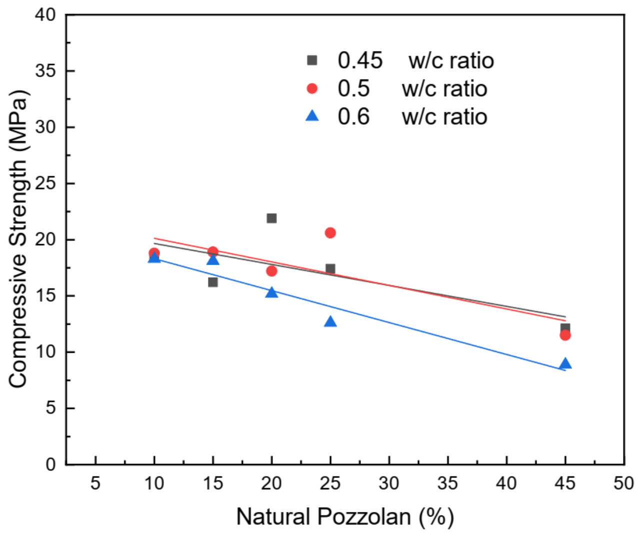

Figure 4: 28-day compressive strength

The maximum registered strength was 21.9MPa at 20% NP and 0.45 w/c ratio. The rate of strength development reduced at later stage as evidenced by the marginal difference between 7-day and 28-day compressive strengths. The retardation in strength development could be attributed to an increased amount of inert silica from natural pozzolan that resulted in the low hydration products, responsible for the improved strength of cement mortar.

In order to evaluate potential application of the binder system in the construction industry, batches of masonry cements obtained from retail outlets were tested for compressive strength and comparative analysis was performed. Tables 4 and 5 summarise the results.

Table 4: NP blended LC^3 versus masonry cement on the market

Water-cement ratio	Compressive strength MPa					
	Masonry cement batches			Natural Pozzolan content %		
	MC1	MC2	MC3	10	15	20
0.45	19.2	*15.03*	10.6	18.6	16.2	21.9
0.5	18.9	*14.83*	10.4	18.8	18.9	17.2
0.6	11.6	*9.94*	7.0	18.3	18.1	15.2

Table 5: NP blended LC3 versus masonry cement on the market

Water-cement ratio	Compressive strength MPa				
	Masonry cement batches			Natural Pozzolan content %	
	MC1	MC2	MC3	25	45
0.45	19.2	*15.03*	10.6	17.4	12.1
0.5	18.9	*14.83*	10.4	20.6	11.5
0.6	11.6	*9.94*	7.0	12.6	8.9

The results showed that NP-LC^3-50 at 0.5 w/c ratio had better strength performance than batches of masonry on the market, indicating potential application of NP-blended LC^3-50 in the Malawian construction industry

Water uptake characteristics

The water uptake characteristics of LC3-NP binder system are shown in Figures 5 and 6. It was noted that the sorptivity of the cement mortar reduced with an increase in NP content. A highest reduction of 15% at 45% NP with 0.5 w/c ratio was registered. On the other hand, surface rate of absorption exhibited similar trend. Surface rate of absorption reduced by 19% at 45% NPA. Similar trend in the blended cementitious materials was reported in the literature [20, 21].

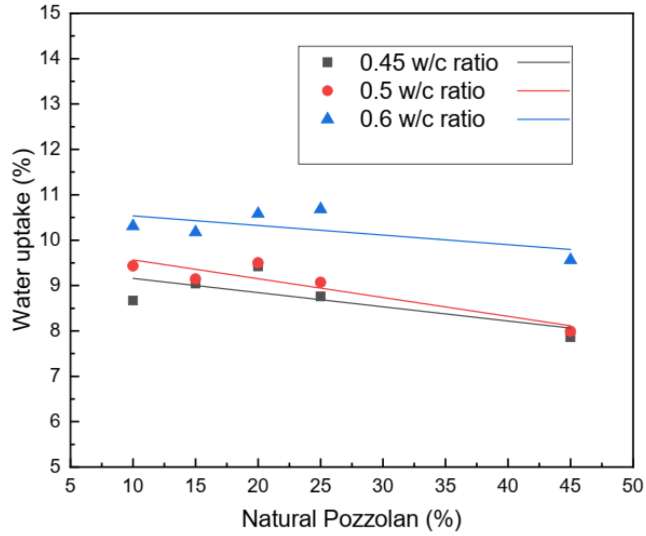

Figure 5: Saturated water absorption

This decrease in the total water uptake is attributed to the change occurring in the pore size distribution as a result of using silica-rich natural pozzolan which could react with the calcium hydroxide to form C-S-H gel [21].

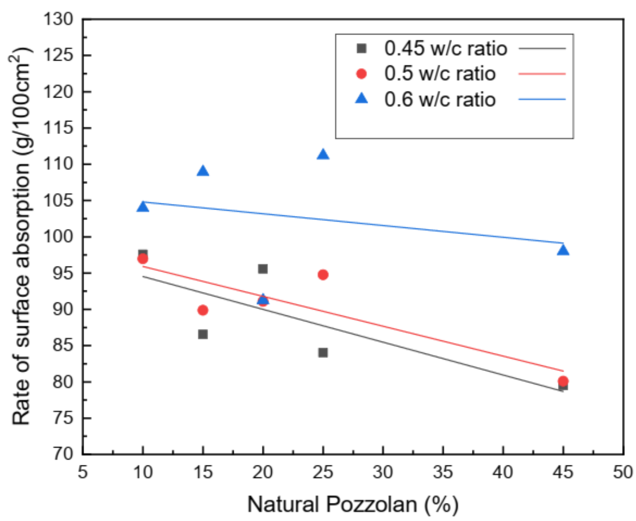

Figure 6: Surface absorption rate

4. Conclusions and Future Work

Based on the acquired test results, the following conclusion are drawn.

- The natural pozzolan can be incorporated in LC^3 binder system and the ultimate blended binder system exhibits superior performance in strength compared to masonry cement available on the Malawian market. Therefore, environmental sustainability as enshrined in Malawi 2063 agenda can be achieved by using natural materials like natural pozzolan in cement production to promote sustainable development with clean and secure environment.

- The optimum dosage of NP in LC^3 system should be 25% at 0.5 water to cement ratio to ensure cost effectiveness of the cement batch.

Further research is recommended to establish rate of hydration, phase diagrams, resistance to sulphate attack and chloride penetration.

5. Acknowledgement

The authors acknowledge financial support from MUBAS to conduct this research.

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Paper 18: Enhancing Sustainable Construction Practices through the Implementation of Building Information Modeling (BIM)

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Abstract
The construction industry's significant contribution to global greenhouse gas emissions and resource consumption necessitates the adoption of sustainable construction practices. Building Information Modeling (BIM) has emerged as a transformative technology with the potential to enhance sustainable construction. This study carried out a systematic review between 2010 and 2023 to examine the literature on the role of BIM in enhancing sustainable construction using the Scopus database. The findings of the study highlight the various ways in which BIM can contribute to sustainability, including but not limited to ensuring precise cost estimates, optimizing design to enhance quality of life, and enhancing the use of energy-efficient technologies. The study further categorized this into themes based on the three pillars of sustainability: economic, social and environmental. However, the study also identifies gaps in the existing literature, which predominantly focuses on the environmental and economic dimensions of sustainability within BIM implementation. To address these gaps, the study proposed that researchers delve deeper into the social aspects to ensure a holistic approach to sustainable construction. Finally, the study concludes by emphasising the significant potential of BIM to promote sustainable construction practices and provides strategies for its widespread implementation.
Keywords: BIM, Sustainability, Social, Economic, Environment

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1. Introduction

The construction industry plays a pivotal role in global greenhouse gas emissions, primarily due to its energy-intensive processes. These processes encompass raw material extraction, transportation, building construction, operation, maintenance, and demolition. Baloi (2003) corroborated this by asserting that buildings currently contribute to nearly 40% of the world's greenhouse gas emissions and account for approximately 36% of global energy consumption. Furthermore, buildings consume 16% of the world's water annually. Sev (2009) further emphasized that buildings alone account for about 50% of raw material consumption, underscoring the sector's substantial environmental impact. In response to these challenges, sustainable construction practices have emerged as a critical strategy. Sustainable construction practices can be viewed as a subset of sustainable development applied to the construction industry. Conte (2018) defined Sustainable construction as the practice of creating and responsibly managing a built environment that promotes the well-being of both occupants and the natural surroundings. It achieves this by conserving resources and effectively controlling pollution. This practice is aimed at reducing the environmental impact of construction activities while simultaneously promoting social and economic sustainability (Saka et al., 2021).

Several researchers have highlighted the possibility of technological innovation to address the issue of sustainable construction (Vergragt, 2016; Baloi, 2003; Aghimien et al., 2018). One of such transformative technology in the construction industry which has the capacity to greatly improve sustainable construction practices is Building Information Modeling (BIM). The advent of BIM in the construction sector has brought about a significant change with far-reaching implications throughout the lifecycle of a construction project (Azhar et al., 2012; Shirowzhan et al., 2020). Gana & John (2013) describe BIM as a digital model of a facility that contains all the information about the project in a structured manner that allows for the seamless sharing of data among stakeholders. The systematic approach of BIM allows for the organising and collecting of information about all stages of the facility's life expectancy, from feasibility studies to its final usage to the point it has elapsed over the expected duration in time and functionality (Russell & Elger, 2008). As a result, this modern project management technology has the potential to enhance the successful performance of construction projects by facilitating a seamless flow of information among stakeholders, improving stakeholder engagement by providing realistic visualisations, developing a better understanding of schedule and cost (4D and 5D), and early clash detection and mitigation (Gana & John, 2013). BIM offers a collaborative and information-rich platform that integrates various aspects of the construction process, from design and planning to construction and facility management (Matthew et al., 2018). According to Viscuso et al. (2019), BIM can provide many benefits to a project when properly implemented, including increased design quality through effective analysis cycles, increased innovation using digital design applications, greater prefabrication due to predictable field conditions, and improved field efficiency by visualising the planned construction schedule. Pinti et al. (2022) also added that to improve the overall performance of the facility or a portfolio of facilities, operators in asset management, space planning, and maintenance schedules can use valuable information obtained through BIM at the end of the construction phase. Additionally, BIM supports lifecycle assessment, allowing stakeholders to evaluate the environmental impact of construction materials and processes throughout a building's entire lifecycle (Kang et al., 2019; Azhar et al., 2011).

Recent studies have shown the potential of BIM in transforming the construction industry, but very limited studies have given a holistic approach to the potential of BIM in addressing sustainability issues in the construction industry using sustainability-related metrics. Santos et al. (2019) identified a significant gap in existing literature regarding the integration of economic, social, and environmental dimensions of sustainability within the context of BIM. Additionally, there are rare systematic reviews focusing on BIM implementation in achieving sustainable construction. Therefore, to promote a holistic approach to sustainable construction through BIM implementation and fill the deficiency in research articles and systematic review, this study aims to systematically examine the trends of literature on how BIM can effectively tackle sustainability issues considering the three pillars of sustainability and proposes strategies to improve its implementation within sustainable construction.

2. Materials and Methods

The study employs a systematic literature review methodology to explore current trends in existing literature regarding the role of BIM in sustainable construction. This approach ensures replicability, transparency, unbiasedness, and rigor, making it superior to other review methods (Boell & Cecez-Kecmanovic, 2015). Through meticulous selection of relevant primary studies, data extraction, and analysis, the study addresses specific research questions following a predetermined protocol and quality procedures (Munaro et al., 2020). Ultimately, this rigorous method evaluates, synthesizes, and documents the body of research produced by scholars and practitioners. The research followed procedures that were consistent with the work of similar research (Cao et al., 2022; Chong et al., 2017). Additionally, reliability checks were conducted throughout the entire process, with a particular focus on the reliability of study selection during search and the consistency of category coding during data gathering (Thomé et al., 2016).

Searching the Literature

The literature search aims to comprehensively and systematically identify relevant studies related to the study. The search will be conducted using the electronic database to identify peer-reviewed journal articles, conference proceedings, and other relevant publications. Scopus was chosen as the search database due to its comprehensive and interdisciplinary nature. According to Singh et al. (2021), Scopus covers a broad spectrum of scientific disciplines, including engineering, materials science, and environmental science. This wide coverage makes it an ideal choice for research that spans multiple subjects related to sustainable construction. Zhao et al. (2019) also concur that Scopus surpasses other significant databases like the Web of Science (WOS) in terms of coverage. Consequently, our study focused on research papers obtained from Scopus. Furthermore, recent systematic studies in sustainable construction have consistently utilized Scopus as their data source (e.g., Muller et al., 2017; Goh et al, 2020; Ogunmakinde et al., 2023). An advanced search tool was used to identify all articles published between 2010-2023 using variations of keywords such as “Building Information Modeling”, “BIM”, “Sustainable Construction”, “Sustainability”, “Social”, “Economic”, and “Environment”. Boolean operators (AND, OR) were used to effectively combine these search terms. The output of the search gave a total of 867 documents.

Study Selection

This stage ensures the study's reliability by filtering the identified publications based on predefined inclusion and exclusion conditions. Out of the 867 articles extracted from the database, 500 were removed because they included duplicates and papers lacking open access online. Furthermore, 59 articles were excluded because they were not written in English, lacked the peer review process or did not directly relate to the application of BIM in sustainable construction. Content analysis of the abstract was then carried out to verify whether it emphasized the role of BIM in sustainable construction and identify the specific dimension(s) around which the work was centred. In cases of uncertainty, the entire scientific work was thoroughly read to gain a better understanding of its focus. As a result, 83 papers were further excluded, leaving a total of 225 papers for in-depth examination. Through the abstract and full-text review, it can be summarized and categorised that BIM roles in sustainable construction are based on the three pillars of sustainability, including the social, economic, and environmental. Fig 1 shows the process used for the selection of the studies.

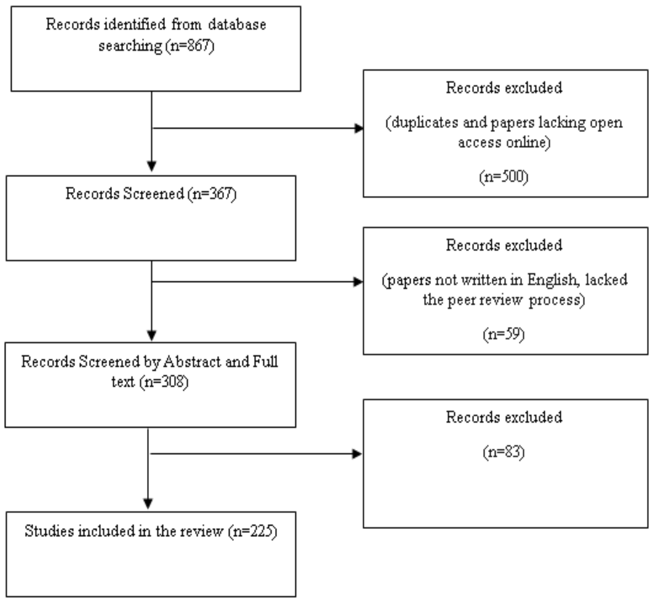

Fig 1: Flow chart showing systematic literature review

3. Results and Discussion

3.1 Descriptive Analysis

This section shows the distribution of the included research papers. The included papers were organized and categorized based on their publication year, publication type, and publication focus.

Figure 1 reveals a clear upward trajectory in the frequency of publications related to BIM's integration in sustainable construction. Initially, the figure shows a relatively low number of publications from 2010 to 2014, with only 1 to 3 studies publications annually. However, starting in 2015, there was a noticeable surge in publications. The years 2019 and 2020 witnessed a significant spike, with 40 studies published each year. This trend reflects a growing interest in BIM's role in sustainable construction, likely due to technological advancements, increased awareness of sustainability issues, and the demand for more efficient and eco-friendly construction practices. Despite a slight dip from the peak in 2021, the substantial number of publications in 2022 and 2023 underscores the continued relevance and significance of studies on BIM in sustainable construction.

Fig 2. Number of publications per year

Moreover, figure 2 reveals that the majority of publications concerning the integration of BIM into sustainable construction practices consist of articles. Out of a total of 225 publications, 154 are articles. This indicates a strong emphasis on disseminating research findings and conducting in-depth analyses of BIM applications in sustainable construction through peer-reviewed journals. In contrast, conference papers constitute a smaller portion, with 71 identified papers. Conference papers often present preliminary or ongoing research findings, practical case studies, and industry insights. This broader dissemination occurs across academic and industry conferences, reflecting a balanced approach to sharing knowledge. Articles provide detailed research outcomes, while conference papers serve as a platform for diverse perspectives and practical experiences in the field.

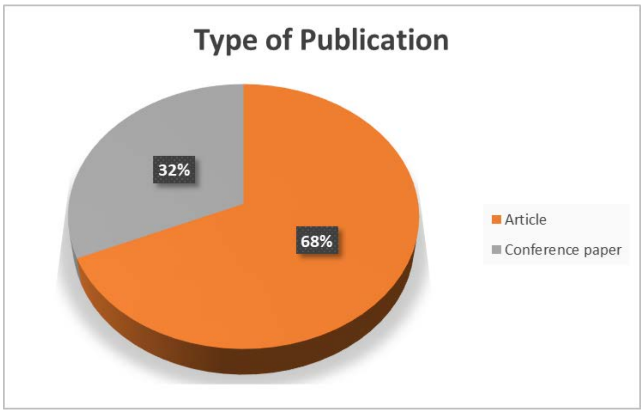

Fig 3. Type of publication

Furthermore, the findings in Table 1 below indicate that only 24 publications focus on the holistic approach to sustainability, indicating a significant gap in the literature. This gap suggests the need for more research and discussion on integrating economic, social, and environmental aspects into a comprehensive sustainability framework in BIM implementation for construction. These findings align with the research by Santos et al. (2019). Simultaneously, a smaller subset of publications delves into specific aspects, including economic, social, and environmental considerations. Environmental-focused publications, which are the most prominent (157 in total), stress the importance of reducing environmental impact, conserving natural resources, and mitigating climate change, while economic-focused publications (32 in total) emphasize cost-effectiveness and financial viability. However, the relatively lower emphasis on social-focused publications (12 in total) suggests that there may be opportunities to further explore the social impacts of BIM in sustainable construction, such as human well-being, preservation of cultural heritage and safety performance.

Table 1: Distribution of publication focus

Publication Focus	Frequency
Sustainability	24
Economic	32
Social	12
Environment	157
Total	**225**

3.2 Discussion

This section outlines the analysis of research findings from systematic literature regarding the role of BIM in sustainable construction Additionally, it explores strategies for enhancing the implementation of BIM. Table 2 indicates the categorization of the major roles of BIM in sustainability identified from the literature.

Table 2 Major roles of BIM in sustainable construction

THEMES	ROLE OF BIM IN SUSTAINABILITY	REFERENCES
ECONOMIC	Ensures precise construction cost estimates, thereby reducing overall project costs	Abdel-Tawab et al (2023); Juszczyk (2019); Alghuried (2023); Kaewunruen et al., (2020); Marzouk et al (2016); Alsaeedi et al., (2021); Biolek et al., (2019); Ismail et al., (2021)
	Promotes prefabrication, thereby Reducing project delivery time and promoting productivity	Kaewunruen et al., (2020); Lee et al., (2020); Liu et al (2019); Chen et al., (2019); Reizgevičius et al., (2018); Alghuried (2023);
	Evaluates renewable energy sources that reduce the cost of energy	Alwan & Jones (2014); Pučko et al., (2020); Lin (2020); Alghuried (2023); Khahro et al., (2021)
	Promotes financial and investment opportunity	Reizgevičius et al., (2018); Alghuried (2023); Qi et al., (2018)
	Ensures effective resource management, thereby reducing the wastage of materials	Liu et al. (2022); Olawumi & Chan (2019); Alghuried (2023); Zoghi & Kim (2020); Behun & Behúnová (2023)
SOCIAL	Lower health risks from chemicals linked to building energy usage, thereby enhancing healthy living	Abdelazim et al., (2021); Amoruso et al., (2019); Lin et al., (2019); Alghuried (2023); Lim (2015); Behúnová et al., (2021);
	Enhances ventilation and lighting effectiveness, thereby enhancing comfort	Abdelazim et al., (2021); Amoruso et al., (2019); Alghuried (2023); Kensek (2015)
	Ensures evaluation of water harvesting	Liu et al. (2019); Alghuried (2023)
	Enhances project safety and health performance	Manzoor et al., (2021); Alghuried (2023);
	Enhances the restoration, preservation and maintenance of historic buildings	Cinquepalmi & Tiburcio (2023); López et al., (2018); Priavolou (2020); Chiabrando et al., (2016)
ENVIRONMENT	Enhances evaluation of various design options for achieving a lower carbon footprint	Kaewunruen et al., (2020); Alwan & Jones (2014); Sameer et al., (2020); Vite et al., (2021); Behúnová et al., (2021); Bank et al., (2011); Veerendra et al., (2022)
	Encourages the use of clean, energy-efficient technologies	Alwan et al., (2015); Cinquepalmi et al., (2023); Watfa et al., (2021); Garyaev (2021)
	Promotes green building design, construction and management	Olawumi & Chan (2021); Liu et al., (2019); Marzouk & Thabet (2023); Panteli et al., (2020); Abdelazim et al.,

Environmental Themes

This theme encapsulates publications on BIM that focus on its role in promoting environmental sustainability in the construction industry. This covers studies on evaluating design options for a lower carbon footprint, promoting clean energy-efficient technologies, and advocating for green building design, construction, and management practices.

The most prevailing subject area under this theme is design evaluation for a lower carbon footprint. Kaewunruen et al. (2020) highlighted that designers can simulate different scenarios and assess their environmental impact, aiding in identifying the most sustainable solutions. By considering factors such as material choices, energy efficiency, and waste reduction, BIM helps minimize the carbon footprint of construction projects (Olawumi & Chan, 2019). Additionally, Alwan et al. (2015) emphasize the potential of BIM to provide tools for energy modelling and simulation, thereby encouraging the adoption of clean, energy-efficient technologies. By analyzing the energy performance of buildings, designers can select systems and technologies that reduce energy consumption and greenhouse gas emissions. Veerendra et al. (2022) demonstrated that through the use of BIM at the design stage, the environmental impact of a structure might be reduced by as much as 70%, thereby supporting the transition to a circular economy. This approach conserves natural resources, reduces waste, and contributes to a more sustainable future. Additionally, Kensek (2015) highlighted the potential of BIM in enhancing environmentally conscious design and energy consumption monitoring through the use of visual programming environments like Dynamo. Dynamo, which incorporates parametric geometries, can harness the interoperability quality of BIM software like Revit to enable virtual model responsiveness via light-level sensors and facilitate interactive updates to shading components on building facades based on solar angles.

The subject area of green building practices and sustainable resource management is another area of interest observed in this review. BIM goes beyond design and extends into the entire building lifecycle. It promotes green building practices during construction, operation, and maintenance. Sustainability principles are incorporated into every phase, leading to reduced environmental impact. For instance, Tirella et al. (2023) introduced a smart configuration procedure within the realm of BIM. This innovative approach seamlessly integrates elements of project automation and flexibility while addressing the critical requirements for energy efficiency and environmental sustainability for the green transition of building stock.

Economic Themes

This theme encapsulates publications on BIM that focus on its role in promoting economic sustainability in the construction industry. This covers studies that highlight the potential of BIM in improving cost savings, project efficiency and resource utilization.

Most of the literature identified under this theme focuses on enhancing precise cost estimation and budget management. BIM facilitates the development of detailed 3D models, incorporating data on materials, quantities, and labor requirements. These precise models enhance cost estimations, leading to reduced overall project costs by minimizing budgeting errors. When project budgets are based on dependable data, the risk of cost overruns significantly decreases, leading to enhanced project outcomes and financial performance (Kaewunruen et al., 2020; Marzouk et al., 2016). Throughout the project lifecycle, BIM ensures efficient budget management by empowering stakeholders to monitor costs, track resource allocations, and make informed decisions based on real-time data (Liu et al., 2022). This not only improves cost control but also enhances project efficiency and overall economic viability (Olawumi & Chan, 2019).

Numerous studies have also underscored the potential of BIM in enhancing economic sustainability through prefabrication, a practice that significantly influences project economics (Kaewunruen et al., 2020; Lee et al., 2020). Prefabrication involves manufacturing building components off-site, leading to accelerated construction timelines and reduced labor costs (Liu et al., 2019; Chen et al., 2019). Liu et al. (2019) stated that prefabricated buildings offer numerous advantages that align with the strategic requirements of national sustainable economic development, making them a key development direction for the construction industry. BIM plays a pivotal role in unlocking these benefits through the creation of detailed 3D models that accurately represent the prefabricated elements, facilitating better visualization and coordination among stakeholders. The prefabrication process of building components off-site is able to reduce the construction time and labour costs significantly. It also promotes financial and investment opportunities by enabling faster occupancy and revenue generation (Reizgevičius et al., 2018; Alghuried 2023).

Furthermore, BIM's intricate characteristics allow for the visualization of construction sequencing and phasing, which help optimize project workflows. This guarantees timely delivery of materials to the construction site, minimizing the chances of material damage or wastage due to incorrect timing.

Social Themes

This particular theme remains relatively underexplored in the context of BIM and sustainability. It encompasses research publications that specifically delve into BIM's impact on advancing social sustainability within the construction industry. These studies encompass various aspects, including evaluating practices that enhance the well-being of building occupants, the preservation and maintenance of cultural heritage, and project health and safety performance.

One of the most significant aspects of this theme that is prevalent in literature is the potential of BIM to facilitate the design of energy-efficient buildings that reduce the use of harmful chemicals and improve indoor air quality. Abdelazim et al. (2021) confirmed that effective BIM implementation helps designers increase the performance of buildings, thus maintaining the life cycle of cities and achieving a suitable quality of life for the inhabitants. Behúnová et al. (2021) designed a methodology and database for intelligent designs through BIM, where BIM technologies were used to develop digital models of buildings, incorporating knowledge about sustainable materials and construction practices. These models served as a basis for creating databases that could be used in future research and projects, enabling the implementation of environmental materials such as recycled polyvinyl butyral in building designs. This contributes to occupant satisfaction and well-being, which are crucial aspects of social sustainability.

Additionally, a few literature have highlighted the contribution of BIM to social sustainability by supporting the evaluation and integration of water harvesting systems in building designs. Rainwater harvesting systems gather and store rainwater for diverse purposes, including irrigation, toilet flushing, and cleaning. When integrated into building designs, BIM plays a crucial role in curbing water consumption and addressing water scarcity challenges, particularly in regions grappling with water stress or scarcity (Liu et al., 2019). The social benefits are manifold, encompassing enhanced access to clean water for building occupants, reduced reliance on centralized water supplies, and advancement of sustainable water management practices.

BIM plays a crucial role in enhancing project safety and health performance by allowing the simulation of safety procedures and the identification of potential hazards during the design phase (Manzoor et al., 2021). This proactive safety approach significantly reduces the risk of accidents and ensures a safer working environment for both construction workers and building occupants. Furthermore, BIM contributes to restoring, preserving, and maintaining historical buildings, thereby promoting cultural sustainability (Cinquepalmi & Tiburcio, 2023). By capturing detailed information about historical structures, BIM actively supports the restoration, preservation and maintenance of cultural heritage and fosters sustainable urban development.

Overall, the findings of the content analysis indicate that BIM plays a pivotal role in advancing sustainable construction practices, considering the holistic dimension of economic, social, and environmental sustainability. BIM significantly contributes to economic sustainability by providing precise construction cost estimates, advocating for prefabrication to reduce project delivery time, and enhancing resource management. In terms of social sustainability, BIM positively impacts occupant health and comfort by mitigating health risks associated with building energy usage, improving ventilation and lighting effectiveness, and promoting safety and health performance. Furthermore, BIM supports environmental sustainability by evaluating design alternatives to minimize carbon footprints, encouraging the adoption of clean, energy-efficient technologies, and endorsing green building design, construction, and management practices. However, the implementation of BIM can be made possible by increasing the level of awareness through training, workshops, and seminars. Moreover, there is a need to develop well-defined BIM standards and protocols within the organization that guarantee uniformity and effectiveness in BIM adoption.

4. Conclusions and Future Work

The aim of this study is to perform a systematic review of the role of BIM in sustainable construction. In this study, 225 publications were used to perform the systematic review and content analysis. The study highlights the diverse ways in which BIM positively impacts sustainability. These include cost reductions, enhanced quality of life and project performance, and environmental advantages. The research further advocates for increasing the level of awareness of BIM and developing well-defined BIM standards and protocols so as to elevate sustainability practices within the construction sector.

Beyond the theoretical implication of this study, the study impacts professionals involved in the construction process with the sufficient knowledge required to incorporate innovative technology like BIM to enhance sustainability in their projects. Also, it serves as a basis for policymakers to develop regulations and incentives to encourage sustainable practices. Moreover, the research revealed the most frequently explored sustainability dimensions in relation to BIM, which are mainly the environmental and economic themes. This shows an evident gap in understanding the role of BIM in social sustainability. Therefore, further exploration is recommended, particularly in areas like water harvesting and cultural heritage preservation. Despite the gap in existing literature, the study underscores the importance of ongoing innovation and research to fully leverage the advantages of BIM in sustainable construction.

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Paper 19: A Systematic Review of Causes of Road Project Delays in Sub-saharan African Countries: A Case of Malawi

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Abstract
The Malawian economy heavily relies on agricultural practices, making optimal-quality road infrastructure crucial for its development. However, road projects face persistent delays, slowing down economic growth. The study used a systematic literature review methodology, examining 16 relevant scholarly articles from a literature pool identifying fourteen major causes of project delays. The articles were selected based on critical constructs and publication dates. Content analysis revealed the significant causes of road project delays, highlighting similarities among Sub-Saharan African countries. The most critical causes were challenges in project financing, slow payment processes, slow decision-making, client delays in giving instructions, and poor project planning and scheduling. The results revealed that the identified challenges affect not only Malawi but also other Sub-Saharan African countries. These findings are crucial for the Malawian construction industry as the road sector can develop/adopt solutions that would benefit the industry and achieve Malawi Vision 2063 of expanding the road network and having world-class roads that are adequately maintained. In response to the challenges, the study recommended using practical project management technologies, such as integrated project management (IPD), lean project management, and building information modeling (BIM), to improve project management practices, communication, and collaboration. Furthermore, collaborating with the private sector through public-private partnerships (PPP) would enhance road project efficiency and attract foreign and private sector investment in road projects.

Keywords: Sub-Saharan; Malawi; Road Construction; Project Delay; Project Management
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1. Introduction

In Sub-Saharan countries, high-quality road infrastructure contributes to economic development. In the case of Malawi, whose economy is strongly dependent on agriculture (mainly tobacco), the primary mode of transport is the road. For agriculture to impact the economy, there must be good road infrastructure (Edriss & Chiunda, 2017). The road network in Malawi is in terrible condition (Mwamvani et al., 2022). Therefore, Malawi's inadequate road infrastructure contributes to the country's slow economic development.

Malawi has an extensive road network of about 15,451 km, of which about 26% is paved. The remainder of the road network (74%) consists of dirt/gravel pavement. A study carried out in 2005 identified approximately 10,000 km of undesignated road network connecting rural areas (Malawi Roads Authority, n.d). After the entry into force of the new classification, the total public road network will, therefore, be around 25,000 km. The Malawi Roads Authority (RA) is responsible for constructing, rehabilitating, and maintaining this road network. In line with the Malawian government's priorities and medium-term strategic framework, the 2022/2023 national budget allocated K211.74 billion for transport and ICT infrastructure, accounting for 7.5% of the total budget. Of all the allocated funds, K155.44 billion was allocated to the Road Fund Administration (RFA) to rehabilitate and maintain the road network across the country (Malawi Roads Authority, n.d). This investment aims to improve transport networks, reduce travel costs and increase mobility while expanding regional trade. Given that road infrastructure development is crucial for Malawi Vision 2063, which is essential for socio-economic growth, connecting the rural and urban areas to international and local markets by expanding the road network and having world-class well-maintained roads, this large allocation of funds to road projects is unsurprising. It is through the infrastructure and construction industry that societies achieve their rural and urban development goals (Hussain et al., 2022).

However, like many other Sub-Saharan countries, Malawi faces significant road construction project delays that hinder project delivery and impede progress in the road sector (Mwamvani et al., 2022). Different scholars have identified some of the causes of project delay, which include difficulties accessing finance, inflexible credit terms, late payments to contractors, lack of technology, skills shortage, corruption, and mismanagement (Akomah & Jackson, 2016; Khair et al., 2018; Kullaya et al., 2022; Stević et al., 2022). These delays in or disruptions to project completion pose risks to the country's economic development and affect the delivery of services to its citizens and resilient infrastructure. Project delays pose significant risks to the country's growth and can threaten the economy. Gbahabo and Samuel (2017) found that project delays have a negative impact on projects, resulting in time overruns, reduced productivity, increased costs and contract cancellations, and continue to pose significant challenges for developing countries. Therefore, it is imperative that countries give serious attention to delay threats, especially in Sub-Saharan Africa, where financial resources are limited and critical social sectors must be prioritised.

Over the years, the Malawian construction industry has introduced measures to try and mitigate these project delivery challenges. The government and other industry stakeholders have been attempting to improve project planning and coordination, enhance collaboration, and promote effective information management. The Malawi government has introduced policies and regulations (most recently, the Public Roads Act 2022), Malawi Vision 2063, and the National Transport Master Plan 2017-2037 to streamline the road sector and encourage professionalism and sustainability in the delivery of infrastructure projects. These efforts aim to improve project governance, increase transparency, and ensure compliance with quality standards (Chilipunde, 2010; Kululanga, 2012). In addition, industry and professional associations have been established to provide training and development programs for construction professionals and equip them with the skills needed to meet industry challenges (Nyemba et al., 2019).

Furthermore, the construction industry, including the road sector, has increasingly recognised the importance of information management systems, adopting computerised systems for documentation, project tracking and financial management (Emuze & Kadangwe, 2014; Nkhata, 2014). Although these efforts have resulted in some improvements, the industry still struggles with project delivery challenges hindering efficiency and effectiveness (Hussein, 2019; Ngoma et al., 2019). Hence, this study aims to identify the significant causes of road construction project delays in Malawi.

2. Materials and Methods

The issues that hinder infrastructure development were identified after looking at the slow development of the Malawian economy and the low output of research publications. Also, with road infrastructure playing an integral part in helping to shape the economy, the authors decided to explore the major causes of delays in road infrastructure projects. This is because the road infrastructure in Malawi is in bad condition, and the road network does not link the country well (Kamanga & Steyn, 2013; Mukasera, 2016). Hussain et al. (2022) state that road infrastructure is the heart of economic development in developing countries. Rodrigue (2020) adds that good road infrastructure offers a country economic benefit, but inadequate infrastructure impairs a country's overall economic growth. Thus, for Malawi to improve its road infrastructure, it is wise to identify the major causes of the problems that hinder efficient project delivery before developing sustainable innovative solutions.

To meet the study objectives, the study adopted a systematic literature review methodology. A systematic literature review is the foundation for understanding a study field (Xiao & Watson, 2019). It facilitates the development of valuable theories for both academic and industrial research. Ayman et al. (2020) justify that a systematic literature review gives a comprehensive review by highlighting the gap in knowledge of existing literature within a well-defined research scope. Schryen (2015) mentions that systematic review is characterised by three unique stages (i.e., literature search and selection, synthesis and interpretation, and examination of extracted data/analysis). Therefore, this methodology has been proven to satisfy all stages of the study; hence, it was adopted (see Figure 1).

The framework in Figure 1 illustrates the stages of the study. The following keywords were used to extract literature from Google Scholar regarding the causes of road construction project delays in Malawi: "Malawi, road construction, projects, and delays." After eliminating some studies based on publication date, duplicates, and full-text review, only five papers were selected for the analysis (see Table 1). In determining scholarly articles in the context of Sub-Saharan Africa, the following keywords were used: "Developing countries, Africa, Road construction, projects, and Delays." After elimination, 11 papers were selected for the analysis (see Table 2). The study comprises 16 academic papers, including journal articles, a thesis, and conference proceedings.

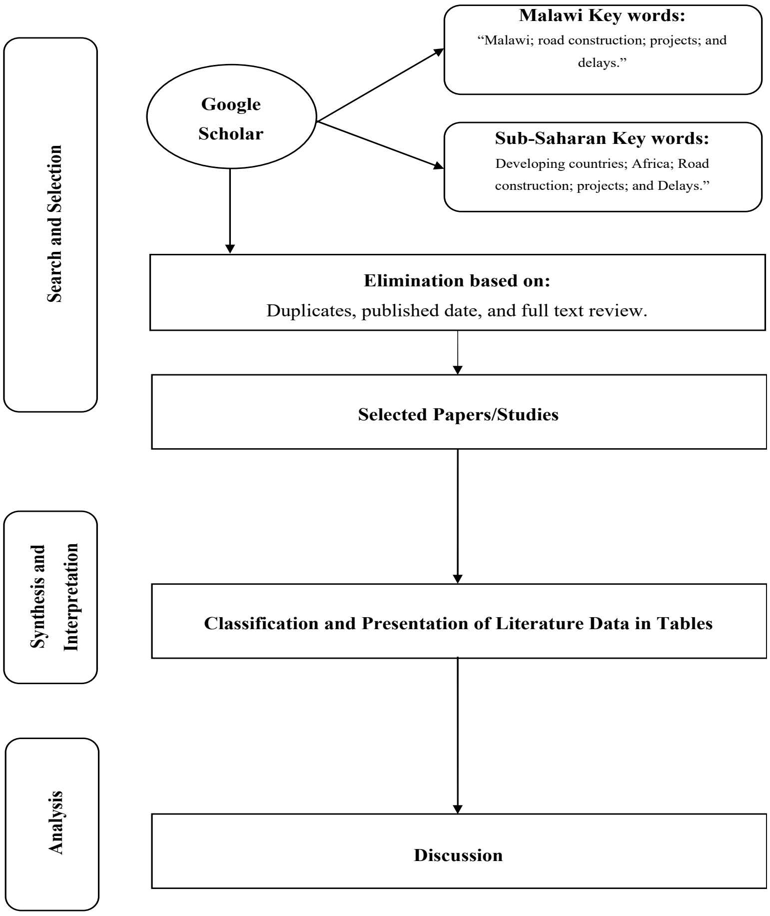

Figure. 32: Systematic Literature Review Framework

Table 14: Causes of Road Construction Project Delays in Malawi

S/N	Causes	Reference
1	Poor project planning; lack of funds from the client, changing scope; client delay in issuing instructions; and shortage of construction equipment and materials.	Mwamvani et al. (2022)
2	Shortage of fuel; difficulties in financing projects; shortage of foreign currency; slow payment procedure adopted by the client in paying progress payment; insufficient equipment	Kamanga and Steyn (2013)
3	Delayed payment from clients; lack of well-trained and skilled human resources; rising costs of materials; poor project management; scope changes	Emuze and Kadangwe (2014)
4	Inadequate planning; inability to pre-finance projects; delay in processing contractor payment; delayed mobilisation to project sites	Mukasera, 2016
5	Political situation; payment delay by owner; lack of coordination between construction parties; frequent change orders; unexpected ground condition and terrain	Mahamid, 2017

A deep understanding of the major causes of road construction project delays is vital when adopting sustainable construction methods and trying to improve the Malawi economy. However, a better understanding of the causes of construction delays can be achieved by a holistic evaluation of some of the prevailing causes in countries of similar economies. Thus, table 2 presents the top five causes of road construction delays in every selected country in Sub-Saharan Africa. Rivera et al. (2020) reviewed over 25 developing countries, including 7 Sub-Saharan African countries, to understand the significant causes of delays in road construction projects across developing countries. Several researchers have reviewed literature from countries of similar economies to understand the major causes of delays in their countries (Kamanga & Steyn, 2013; Kassa, 2020; Khair et al., 2018). Furthermore, Mejía et al. (2020) state that countries of similar economies or developing countries share similar causes of road construction project delays, although they have different effects. Therefore, this study used a similar approach to identify the key/major causes of road construction project delays in Malawi.

Table 15: Causes of Road Construction Project Delays in Sub-Saharan Africa

S/N	Causes	Reference	Country
1	Local community unrest; work interruption by the construction mafias; regulatory approval process delays; inadequate community participation, and local community project rejection.	Vahed et al., 2022	South Africa
2	Client's late payment; client organisation's delayed decision-making and bureaucracy; poor planning and scheduling; and rain.	Atibu, 2015	Kenya
3	Payment certificates that were not honoured on time; adverse weather; unfavourable site conditions; changes that the consultant made; and a delay in instructions from consultants.	Akomah & Jackson, 2016	Ghana
4	Problems of cash flow; difficulties in project financing; material inflation; poor site management; Ineffective planning, scheduling, controlling and quality monitoring.	Khair et al. 2017	Sudan
5	Project funding; slowness during the client-endorsed payment; scarcity of professional personnel; delay in indemnifying reimbursement (land-owners); price escalation.	Stević et al. 2022	Benin Republic
6	Poor project management and coordination; right of way issues; inaccurate forecasting of schedule; psychological biases; political interest	Kassa (2020)	Ethiopia
7	Harsh or unfavourable weather brought on by floods and severe rains; changes in the project's scope; the cost of environmental protection and mitigation measures; and strikes.	Kaliba et al. 2009	Zambia
8	Inexperienced contractor/subcontractor; financial difficulties; poor site management and supervision; poor	Shimete and Wall (2017)	Namibia

	prospection and planning; contract termination.		
9	Inadequate access to finance and delayed payment for completed work; financial problems or difficulties; unwillingness or inability to sustain operations for an extended period without payment; unrealistic program of works; inadequate site management.	Kullaya et al. 2022	Tanzania
10	Changes to the scope of work; delayed payment; poor monitoring and control; high cost of capital; political insecurity and instability.	Alinaitwe et al. 2013	Uganda
11	Client's financial difficulties; cash flow during construction; political influence; government regulations; inclement or bad weather.	Toriola-Coker et al. 2022	Nigeria

3. Results and Discussion

A total of 14 significant causes were found across five studies based on the Malawi road sector. These causes were then matched with the causes affecting Sub-Saharan Africa. Table 3 shows various causes of road construction project delays; each matched with references from Malawi and Sub-Saharan Africa.

Table 16: Major Causes of Road Construction Project Delays

S/N	MAJOR CAUSES OF DELAY FACTORS	MALAWI					SUB-SAHARAN AFRICA
		Mwamvani et al. (2022)	Kamanga & Steyn (2013)	Emuze & Kadangwe (2014)	Mukasera (2016)	Mahamid (2017)	
1.	Poor Project Planning and Scheduling	√		√	√		Atibu (2015); Khair et al. (2017); Kassa (2020); Shimete & Wall (2017); Kullaya et al. (2022)
2.	Changing Scope	√		√		√	Akomah & Jackson (2016); Kaliba et al. (2009); Alinaitwe et al. (2013)
3.	Client Delay in Issuing Instructions	√		√	√	√	Atibu (2015); Akomah & Jackson (2016)
4.	Shortage of Construction Equipment and Materials	√	√	√			Khair et al. (2017);
5.	Shortage of Fuel	√					
6.	Difficulties in Financing Projects	√	√	√	√	√	Khair et al. (2017); Stević et al. (2022); Kaliba et al. (2009); Kullaya et al. (2022); Alinaitwe et al. (2013); Toriola-Coker et al. (2022)

7.	Shortage of Foreign Currency		√				Steviç et al. (2022);
8.	Slow Payment Procedure Adopted by Client in Paying Progress Payment	√	√	√	√	√	Atibu (2015); Akomah & Jackson (2016); Steviç et al. (2022); Alinaitwe et al. (2013)
9.	Lack of Well-Trained and Skilled Human Resources			√			Steviç et al. (2022); Shimete & Wall (2017)
10.	Delayed Mobilisation to Project Sites				√		Atibu (2015); Khair et al. (2017); Kassa (2020); Shimete & Wall (2017); Kullaya et al. (2022)
11.	Slow Decision Making/lack of communication	√	√	√	√	√	Toriola-Coker et al. (2022); Atibu (2015); Vahed et al. (2022)
12.	Political Situation					√	Kassa (2020); Alinaitwe et al. (2013); Toriola-Coker et al. (2022)
13.	Lack of Coordination Between Construction Parties					√	Khair et al. (2017); Kassa (2020); Shimete & Wall (2017); Kullaya et al. (2022); Alinaitwe et al. (2013)
14.	Natural Forces					√	Atibu (2015); Akomah & Jackson (2016); Kaliba et al. (2009); Toriola-Coker et al. (2022)

From the analysis, fourteen causes for road construction project delays were identified, which included shortage of construction equipment and materials, change of scope, shortage of fuel, shortage of foreign currency, lack of well-trained and skilled human resources, delayed mobilisation to the project site, political situation, lack of coordination between construction parties among others. Inferring from Table 3, this paper discusses only the most frequent major causes of road construction project delays across Sub-Saharan Africa and Malawi.

Difficulties in Financing Projects

The issue of financing projects appears to be predominant in all the studies across Sub-Saharan Africa. Traditionally, in most developing countries, road projects are financed by the government or the public sector. However, governments in most of these countries have found it challenging to provide this infrastructure mainly due to budget constraints. Rondinelli (2017) states that the Malawi government's limited financial resources restrict the country's ability to invest in infrastructure development, resulting in delayed or stalled projects. Moreover, Asomani-Boateng (2015) add that insufficient funding hampers the maintenance and rehabilitation of existing infrastructure, leading to deterioration over time.

Slow Payment Procedure Adopted by Client in Paying Progress Payment

To ensure smooth delivery of construction projects, it is critical to ensure swift payment to contractors and consultants without delays. The payment challenge is prominent in most Sub-Saharan countries due to a lack of forex and access to credit facilities, where contractors find it difficult to sustain project operations for an extended period (Kullaya et al., 2022). Also, the lengthy process of processing payment in the public sector, which requires authorisation at different management levels before final approval, affects timely payment to contractors or consultants. In addition, Ullah et al. (2019) stated that the absence of automated processes, digital tools, and building information modelling (BIM) restricts the construction industry's ability to streamline project workflows, enhance collaboration, improve approval processes, etc., thus improving overall project performance, including efficient payment procedures.

Lack of Communication and Client Delay in Issuing Instructions

Effective communication has been identified as a management practice ensuring the smooth delivery of construction projects. It is essential to have a clear communication framework right at the project's planning stage to ensure changes to the scope of the work or possible risks are communicated right in time. Ineffective communication contributes to many other causes of delays (i.e., Slow payment procedures, issues of instructions, etc.), which affects the project schedule, thus leading to cost overrun and low quality of work.

Poor Project Planning and Scheduling

The construction industry has a shortage of adequately trained and skilled professionals across various disciplines, which hampers the industry's ability to meet project requirements and impacts the quality and efficiency of construction projects (Chilipunde, 2010; Kamanga & Steyn, 2013). This shortage undermines project planning, design, and implementation, affecting the industry's ability to deliver projects on time and within budget (Chilipunde, 2010). Since all road projects are handled by the government in Malawi, this adds to the limited capacity of the public sector, limiting the sector's ability to effectively plan, regulate, and implement construction projects, leading to delays in project delivery.

4. Conclusion

This review has uncovered that the causes of road construction project delays are similar in Sub-Saharan Africa but have different effects. In Malawi, the major causes of delays in road projects can be attributed to five major factors: difficulties in financing projects, slow payment procedures adopted by clients for payment of progress, lack of communication, client delay in issuing instructions, and poor project planning and scheduling. However, the findings reveal that financial difficulties and poor project planning and scheduling are the roots of almost all other problems faced during project delivery. Therefore, it is suggested that addressing these factors would help resolve project delays in Malawi, thereby improving project efficiency and productivity. Furthermore, it is worth mentioning that addressing these factors requires a comprehensive and tailored strategy for the Malawian construction industry.

5. Recommendations

To mitigate delays in road projects, the road sector should leverage the benefits of practical project management technologies and collaborate with the private sector through public-private partnerships (PPPs). The technologies include but are not limited to integrated project management (IPD), lean project management, BIM, change management, etc. These tools could significantly improve communication and collaboration between diverse stakeholders in road construction projects. BIM, in particular, can enable the creation and management of a virtual representation of a construction project, integrating design, construction, and operational information, leading to improved project visualisation, enhanced decision-making, and streamlined project processes. This kind of technology can help not only the road sector but also the entire construction industry mitigates the challenges that the industry faces. However, such solutions can be accomplished and thoroughly relished through adopting project management technologies and revising institutional, legal, and regulatory processes and agreements supporting PPPs on fair and favourable terms for both private and public bodies.

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Paper 20: Review of Bridge Washaways and Design Criteria in view of Incremental Weather

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Abstract

In recent years, the world has been experiencing excessive flooding that affects transport infrastructure such as bridges and road embankments. Malawi has not been spared and since 2015 there have been a number of tropical cyclones including Gombe and Freddy. The design and construction of bridges and embankments consider natural and human factors. It is this interaction of natural and human factors that will provide a resilient structure. Flooding and collisions fall in either of the factors. Design factors in design standards and manuals have been informed by studies on historical failures and laboratory testing. This review has analysed photos from bridge and embankment failures that have occurred due to recent flooding to establish correlation with design and construction practice to inform future design and construction methods.

Keywords: Bridges, Road Embankments, Tropical Cyclones, Resilient, Design Standards

1. Introduction

Malawi 2063 Agenda fruition is dependent on transport infrastructure. Transport infrastructure is dominated by road infrastructure which are basically road embankment and bridges. Road embankment and bridges are affected by natural and human factors. Natural factors include cyclones, floods, droughts, scour, earthquake, wind and landslides. Human (manmade) factors include design and construction, overloading, collision and lack of inspection and maintenance. Malawi and the world have recently started experiencing unprecedented road embankment and bridge failures leading to road closures which has a direct bearing on movement of passenger and cargo traffic. The question that needs to be addressed is, has anything gone wrong? There is therefore need to establish existing design and construction standards, investigate failure patterns due to cyclones and then compare and contrast to determine the cause and hence propose a solution.

2. Materials, Methods and Literature Review

The materials and methods used in this study included review of current standards, codes of practice and design manuals followed by field observations covering photos and measurements and then a full analysis.
Malawi road and bridge design and construction is informed by national and international best practice which consider natural and human factors. National standards are mostly two – 'Highway Design Manual' and 'Road and Bridge Specifications' which were produced in 1978 (Malawi Govt, 1978). International standards are mainly SATCC (2000), Road Notes, RSA Drainage Manual and AASHTO. Supporting documents include traffic estimation, maximum design flood estimation, earthquake magnitudes and maximum wind speed estimation. Of interest in these standards are Incremental Weather of Cyclones and Scour Considerations. Are these standards/manuals/supporting documents still relevant/adequate?
The SATCC Design of Road Bridges and Culverts defines an action as an assembly of concentrated or distributed forces (direct actions), or imposed or constrained deformations (indirect actions) applied to a structure due to a single cause. An action is considered to be a single action if it is stochastically independent, in time and space, of any other assembly of forces, or imposed or constrained deformations, acting on the structure. Qualitatively, actions are classified as permanent actions, variable actions or accidental. The variability of the actions on a structure is taken into account by defining the actions in terms of characteristic values. Where the necessary data are available, these characteristic values are based on a statistical interpretation of the data; where data are not available, appraisal of the values is based on experience and, possibly, forecasts of the implications of future developments.
A bridge design life of 100 years is assumed throughout the SATCC Code whereas for the Malawi standard it is 50 years. The design life is that length of time for which the structure will continue to be serviceable with adequate and regular inspection and maintenance. The assumption of a design life does not necessarily mean that the structure will no longer be fit for its purpose at the end of that period. In general, the design flood return-period guides the design life.
In general, standards/codes provisions cover, methods of calculation, coefficients and design criteria, extent of theories versus application, modelling and analysis of drainage problems, planning (economic and legal) and design of road structures, hydrology/Hydraulic design and maintenance of river crossings – peak rate of run-off dependent on weighted run-off coefficient, average rainfall intensity and drainage area (Re-calibration of these factors), design manual for standard box culverts, site selection for bridge location and selection of structure.
The following are considered best practices for road embankments: preparation of the foundation surface to remove loose and permeable material, use of low permeability soils in the

embankment (clayey or silty gravel, clayey or silty sand, clay or silt), batter slopes of three horizontal to one vertical (3H: IV), minimum crest width of 4.0 m and allowance for secondary flow paths.

The following figures illustrate the best practice for bridge site location, bridge alignment, scour challenges and wing walls.

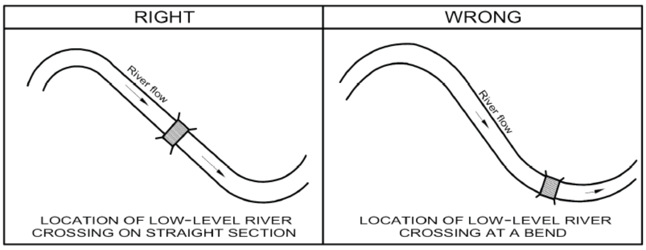

Figure 1: Location of LLRC in river

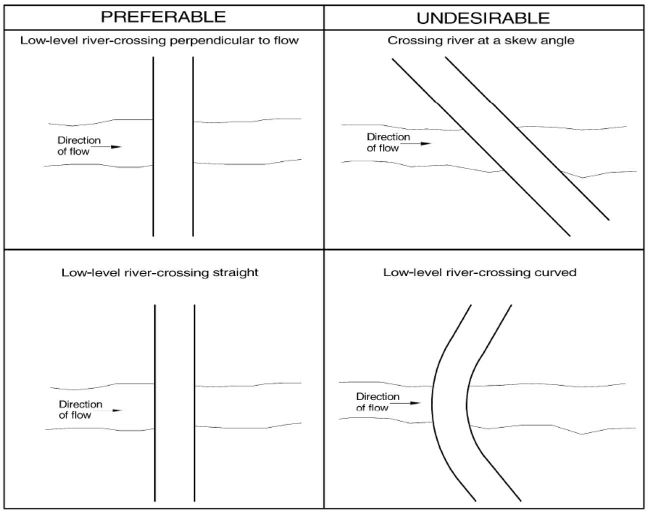

Figure 2: Avoid skew or curved LLRCs

Figure 3: Scour undermines bridge performance

Figure 4: Typical wing wall

3. Results and Discussion

The following photos illustrate the bridge failures as a result of incremental weather and absence of proper interventions.

The Chapananga bridge failure is an example of poor site location and lack of approach embankment protection as shown in figure 5.

Figure 5: Chapananga bridge failure

The bridge on Chikwawa to Chapananga road as shown in figure 6 is typical bad alignment choice. The bridge will be subjected flood forces for both piers and embankments.

Figure 6: Bad bridge alignment

The Ruo river bridge failure between Seven and Makhanga shown in figure 7 is a typical problem of lack of river morphology investigations. The Ruo river has been changing course which was not given ample time to find the best bridge location.

Figure 7: River morphology investigations

Figures 8, 9 and 10 show bridge failures due to poor wing wall provision.

Figure 8: No wing wall on Nsanje - Marka

Figure 9: Failure due to lack of wing wall

Figure 10: Failure due to lack of wing wall

Figure 11: Lack of proper backfill of wing wall

The other issue that emerged from field investigations is lack of provision of impermeable surface on bridge crossings. Figures 12 and 13 show typical failures due to permeable surfaces at bridge crossings.

Figure 12: Impermeable surface at bridge crossing

Figure 13: Pavement failure at bridge crossing

The lack of monitoring of river approach to bridge structures or river training can lead to bridge failure. Reeds growth on river approach to bridge structure can lead to river flow changing course and hence missing the bridge opening and go to hit the road embankment. Figure 14 shows the situation at Lifidzi bridge.

Figure 14: River training (reeds removal)

The incremental weather has led to some road sections being submerged or overtopped during flooding. This has seen road embankments being eroded due to lack of proper slope. Figure 15 shows embankment failure on the Thabwa – Kamuzu bridge road section.

Figure 15: Road Embankment Failure. Batter slopes to three horizontal to one vertical (3H:1V) or plant vetiver grass.

Scour of piers and abutments can lead to bridge collapse as shown in figure 16.

Figure 16: Scour at South Lunzu bridge

Figure 16 shows that the South Lunzu bridge also suffered overtopping. This is a clear sign to consider an increased free board in light of incremental weather.

4. Conclusions and Future Work

The field investigations have demonstrated that Incremental weather is causing damage to bridges and embankments (nature). It has shown that poor road/bridge to river alignment exacerbates the problem (manmade). It has been shown that lack of investment in planning can lead to poor location of bridge structure (manmade). The choice of embankment protection method can cause bridge failure (manmade). It has also been shown that lack of full impermeable road surface at bridge crossing causes embankment failure (manmade). The lack

of river training can cause river diversion (manmade). Inadequate embankment slopes can lead to embankment erosion and inadequate freeboard can make road impassable (nature).
It is therefore clear that there is an urgent need to revisit the practices both for design and construction.
There is also need to do research on best materials for various applications.

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SESSION 3B: ICT, AI, Water and Health

Paper 21: Automatic fish species identification using an artificial intelligence system

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Abstract

The fishing industry is a vital component for developing countries like Malawi as it enhances the economy thereby contributing significantly to employment and export revenue. The manual fish sorting processes employed by key Malawi fish industries like MALDECO Fisheries result in operational inefficiencies and increased costs. This paper therefore proposes an artificial intelligence-powered system capable of accurately identifying diverse fish species. A convolutional neural network model was built from over 10,000 images using Keras, comprising Conv2D layers, MaxPooling2D layers, and Dropout layers to prevent overfitting. The model was trained using the fit method and evaluated using metrics such as accuracy, precision, recall, and F1-score on an independent testing set. The deployment involved web application development and Flask backend server implementation to handle image classification requests. The system underwent unit, integration, system, acceptance and performance testing to ensure functionality and stability in real-world scenarios. The results depict a classification accuracy of 90% in fish species identification using an evaluation dataset and the web application provided a user-friendly interface for end-users. The system will enhance operational efficiency, reduce costs, and contribute to the sustainability of Malawi's fishing industry. Future work includes classification accuracy improvement, enhancing the model to be resistant to illumination and picture quality and incorporating more fish species in the training dataset.

Keywords: convolution neural network, deep learning, classification accuracy, model loss, machine learning

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1. Introduction

MALDECO Fisheries is the largest commercial fishing and processing fishing and processing company in Malawi and thus the largest single supplier of both fish in Malawi. The annual catch amounts to over 70% of the total commercial catch and about 7% of the total Lake Malawi catch, which fluctuates between 26000 tons and 47000 tons. The company currently processes whole fresh fish, gutted, fillet smoked, frozen and sun-dried fish such as *Nkholokolo, Samwamowa, Kadyakolo, Mpasa, Mbaba, Bombe, Chambo, Makakana, Mcheni, Kampango, Ndunduma, Utaka, Sawasawa* and *Mlamba* [1].

In the context of Malawi's thriving fishing industry, the need for accurate fish species identification has become paramount. With the country's reliance on Lake Malawi's diverse aquatic life, effective sorting of caught fish species has gained significant importance. The existing manual sorting process employed by MALDECO Fisheries presents challenges that hinder operational efficiency [1], [2]. As the largest commercial fishing and processing company in Malawi, MALDECO Fisheries plays a crucial role in the country's economy [2], [3]. However, the manual sorting process is plagued by inefficiencies and increased operating costs. Relying on temporary workers for sorting results in inconsistencies, errors, and heightened operational expenses. The need for a more streamlined, accurate and cost-effective solution has led to the initiation of this work. By addressing the inefficiencies of the current manual sorting process, the automated fish species identifier promises a range of benefits including improved efficiency, increased accuracy in species identification and cost reduction.

Several works attempted to address the manual sorting problems. Authors in [4] developed a Dried Danggit Sorter is a machine vision-based system, that utilises machine vision technology to sort dried Danggit fish. The underlying theory behind this system is the use of image processing techniques, such as Euclidean colour filtering and blob detection, to identify and classify fish based on visual features. However, the weaknesses of this system include the reliance on manual feeding of the dried Danggit to the sorter, which limits its level of automation and efficiency. Additionally, the system may face challenges in accurately distinguishing fish with similar visual characteristics or variations due to factors like lighting conditions or fish orientation.

The WikiFish mobile app in [5] utilises deep convolutional neural networks for fish species recognition. The underlying theory behind this app is the use of deep learning techniques to extract meaningful features from fish images and classify them based on learned patterns. Weaknesses of this approach include the reliance on a limited dataset primarily focused on fish varieties found in the Mediterranean Sea, which may limit its effectiveness in identifying fish species from other regions. Additionally, challenges may arise in dealing with variations in fish appearance due to factors such as age, gender, or environmental conditions. Expanding the dataset to include a wider range of fish species and improving the robustness of the deep learning model to handle diverse variations would be crucial to enhancing the app's accuracy and applicability.

In the realm of citizen science, authors in [6] created a comprehensive library of annotated fish images for machine learning applications. The underlying theory behind this work is the use of machine learning algorithms, such as deep convolutional neural networks, to recognise and classify fish species based on annotated images. The weaknesses of this approach include potential biases in the annotated dataset, limitations in dataset diversity and representativeness, and challenges in handling the wide variety of fish species that exist globally. These factors may impact the accuracy and generalizability of the identification system, particularly for fish species that are underrepresented or poorly annotated in the dataset.

The main objective of the work in this paper is to design and develop an Artificial Intelligence(AI)--powered fish species identifier that accurately identifies different fish species to facilitate the sorting process. Once the system identifies the species of a particular fish, that information can be used to sort the fish into appropriate categories or groups based on their species.

The specific objectives are as follows: (1) develop a computer vision algorithm that can accurately identify the different species of fish caught during fishing activities, (2) create a user-friendly web application interface that enables users to easily input images of the caught fish and receive real-time identification results and (3) build a database of fish species information that the system can compare the analysed images against, to ensure accurate identification.

The rest of the contents of this paper is organized as follows. Section 2 describes the methodology starting from field visits to model training. The research findings are presented in Section 3 and finally, Section 4 concludes the paper.

2. Materials and Methods

This section describes in detail the methodology used to develop the proposed system whereby mobile device users can capture images of fish. The mobile device has a web application installed that allows capturing fish images using the camera. This application provides an interface for the user to take photos of the fish and submit them for processing. Once the user captures the fish image using the web application on the mobile device, the data is transmitted to a machine-learning model. This transmission occurs through the internet via the hypertext transfer protocol secure (HTTPs), which is a secure method for transmitting data over the internet.

A machine learning model is responsible for performing the necessary processing on the fish image. The model is hosted on a local server and analyses the fish image to determine the species of the fish in the image. Once the model has completed processing, it couples the result with the name of the fish species. The result includes information about the fish species. The machine learning model transmits the results of the processing back to the user who made the initial request. This transmission occurs through the internet using an appropriate Application Programming Interface (API) to the mobile phone. The API provides a simple and easy-to-use interface for the user to view the results of the processing. Figure 1 shows the system architecture for the developed system.

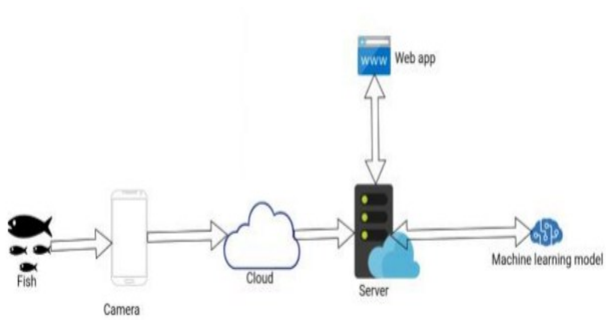

Figure 1: System Architecture

2.1. Data Collection

The first step required field visits to MALDECO Fisheries retails as well as Limbe Market to purchase five fish species that are commonly captured there, namely: *Chambo, Utaka, Makakana, Mcheni and Ndunduma.* Using a high-resolution camera, 2,000 images per fish species were captured while ensuring that the dataset represented various angles and lighting conditions. The total size of all the captured images amounted to 10GB and realizing the potential strain on computational resources during training, a python script was employed to compress the images from 10GB to 750MB.

2.2. Data Annotation

The second step is that every image in the dataset was labelled with corresponding fish species using manual annotation as shown in Figure 1 up to Figure 5.

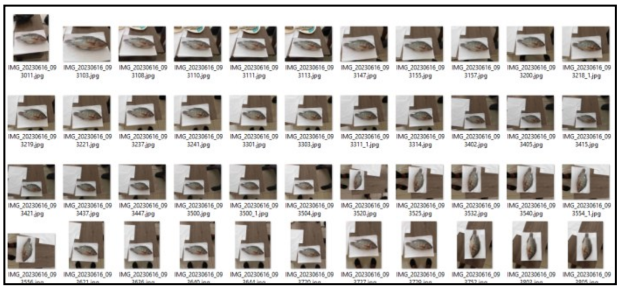

Figure 2: Collection of Chambo images

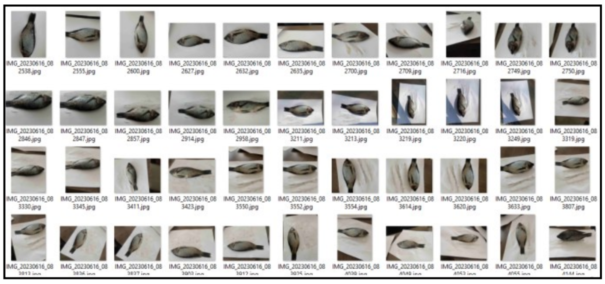

Figure 3: Collection of Makakana images

Figure 4: Collection of Mcheni images

Figure 5: Collection of Ndunduma images

Figure 6: Collection of Utaka images

2.3. Building Dataset

During the third step, the processed data was divided into three datasets—training, validating, and testing.

Firstly, the training set was used to initially train the algorithm and teach it how to process information. This set defined model classifications through parameters. Secondly, the validation set was used to estimate the accuracy of the model. This dataset was used to fine-tune model parameters. Lastly, the testing set was used to assess the accuracy and performance of the models. This set was meant to expose any issues in the model. Applying techniques such as rotation, scaling, flipping, and adding noise to create additional training samples.

2.4. Data Augmentation

Furthermore, ImageDataGenerator from Keras Framework was used to perform data augmentation. This technique was used to increase the effective size of the dataset [7], [8].

2.5. Building the Convolutional Neural Network (CNN) Model

Using Keras, a sequential CNN model was developed and the model comprised several Conv2D layers with Rectified Linear Unit (reLU) activation functions, MaxPooling2D layers as well as Dropout layers to prevent overfitting. The dense layer with softmax activation was the final layer used to produce the classification probabilities for the five fish species [7].

2.6. Model Training

Then, the model was trained with 40 epochs or iterations to increase the accuracy of the model on Google using the fit method together with the training data generator. ModelCheckpoint and EarlyStopping were used to save the best model and stop training early if the validation accuracy is not improving.

2.7. Web Application Development

After successfully training the system, a web application was developed to provide an interface with the targeted users of the system. This stage involved coding and programming using a HyperText Markup Language (HTML) template that creates a user-friendly web interface for the fish identification application. Java has also been used to provide dynamic behaviour of the application.

2.8. Flask Backend Server Implementation

The backend server was implemented to handle image classification requests. A Python script was used to define the server using the Flask, load the trained model, and define routes to handle image classification and image compression [9], [10]. Figures 7 and 8 show the web app's home section and predict section respectively.

Figure 7: Web App "Home" Section

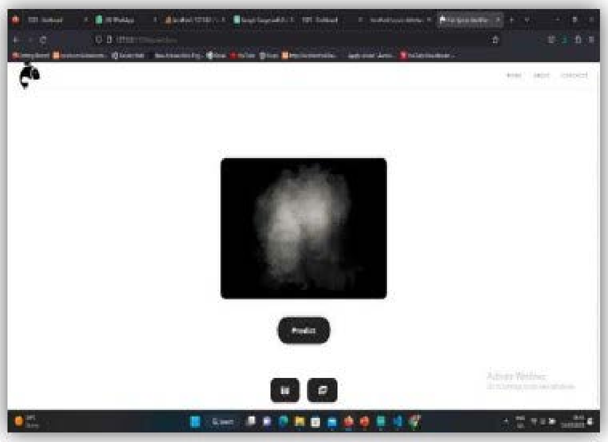

Figure 8: Web App "Predict" Section

3. Results and Discussion

The results of the model training were plotted in the graphs of Figures 9 and 10.

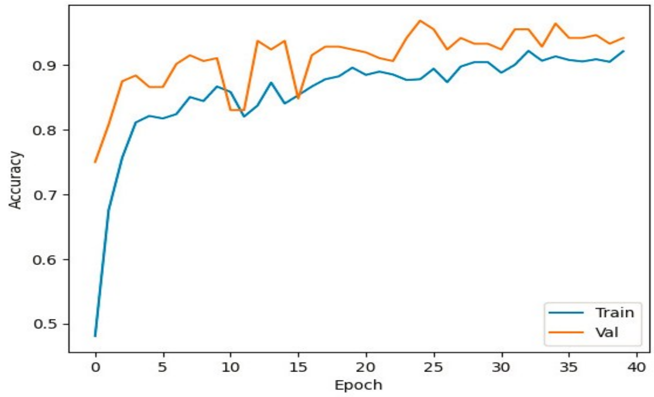

Figure 9: Classification Accuracy

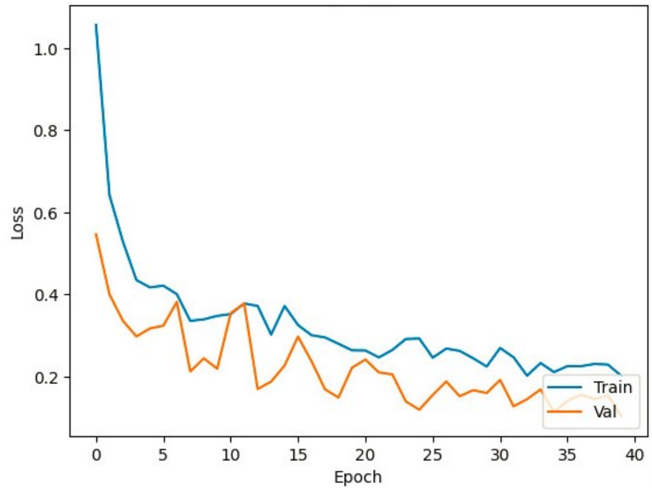

Figure 10: Model Loss

According to the results from the graphs, as the iterations were increasing, the classification accuracy was increasing and the model loss was decreasing.

The performance of the model was also evaluated through a classification report and confusion matrix as depicted in Figures 11 and 12, providing insights into the accuracy, precision, recall and overall effectiveness of the classification. This evaluation helped to understand how well the model generalises to new data. The confusion matrix visualised the performance of the model by detailing the number of true positive, true negative, false positive and false negative predictions. This ensured to identification of which classes the model might struggle with.

Classification Report:

	precision	recall	f1-score	support
0	0.75	0.68	0.71	302
1	0.76	0.72	0.72	303
2	0.75	0.77	0.70	315
3	0.74	0.78	0.71	304
4	0.77	0.76	0.75	301
accuracy			0.75	1840
macro avg	0.75	0.75	0.75	1840
weighted avg	0.75	0.75	0.75	1840

Figure 11: Classification Report

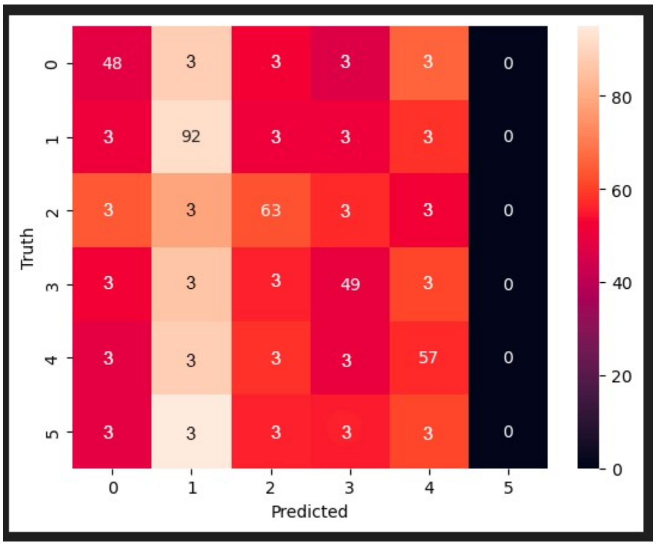

Figure 12: Confusion matrix

According to the Classification report and the confusion matrix, the model was evaluated to be good due to the high overall accuracy, a balanced trade-off between precision and recall, diagonal dominance in the confusion matrix and consistency in the F1- score, precision and recall.

Figures 13 to 15 show the results of the testing done on the new fish and this testing verified the accuracy of the trained model of 90%.

Figure 13: Chambo Identification

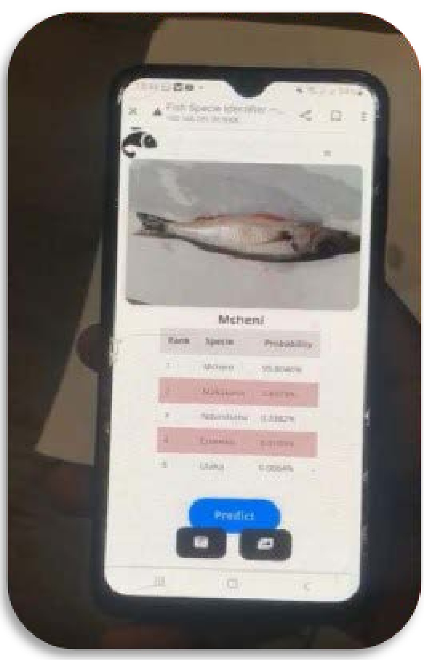

Figure 14: Mcheni Identification

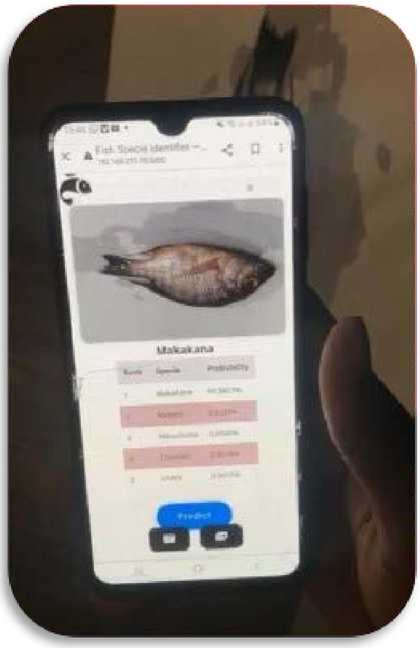

Figure 15: Makakana Identification

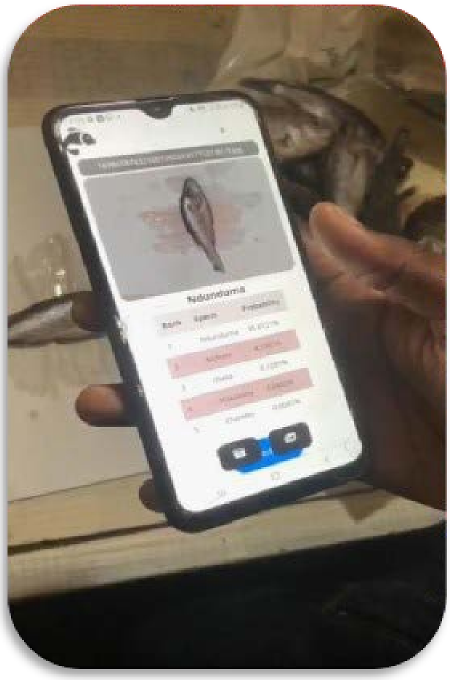

Figure 16: Ndunduma Identification

During this work, it was noted that the laptop used for the model training slowed down model training and optimization. The use of a cloud-based solution called Google Collab to leverage its computational resources to expedite model training and experimentation would thus be ideal. Also, all of the five fish species that were supposed to be used in the model were not readily available at MALDECO Fisheries since fish harvesting activity does not take place every day and even if it does, there is a low probability that all five fish species would be caught. To resolve this, there was a need to outsource from other fisheries as well as local fishermen to make sure that during the training and testing phases, all these five fish species were available.

4. Conclusions and Future Work

In conclusion, the fish species identifier has achieved substantial advances in automated fish species detection and categorization. It has proved its potential to revolutionize several parts of fisheries management, biodiversity monitoring, and ecological research through the use of computer vision techniques, machine learning models, and data-gathering initiatives. This fish species identifier has successfully developed a machine-learning model that can properly identify fish species from images. The model was trained on a dataset of over 10,000 photos of fish from over 5 distinct species. On the test set, the model had an accuracy of more than 90%. A lot of challenges must be solved in future efforts. The challenge is to increase the model's accuracy for difficult-to-identify fish species, such as some species that are almost similar and hard to differentiate. Another challenge is making the model more resistant to changes in illumination and picture quality. The model should also be developed to incorporate more fish species from across Malawi.

Acknowledgements

First and foremost, we want to express our gratitude to MUBAS through the Electrical Engineering Department for funding the work and also assisting in scrutinising this work. Also, we would like to thank MALDECO for providing the information we required to proceed with this work. Lastly, we are grateful to Beaton Ndawa and Dr Timothy Chadza for their unwavering advice and technical assistance.

Nomenclature

AI	Artificial Intelligence
API	Application Programming Interface
CNN	Convolutional Neural Network
Conv2D	Convolutional 2D layer in neural networks
Flask	Web Framework for Python.
Keras	High-level neural networks API, written in Python.
MALDECO	Malawi Development Corporation
MUBAS	Malawi University of Business and Applied Sciences
Python	High-level, interpreted programming language
ReLU	Rectified Linear Unit
Softmax	A function, used to convert the output of a neural network to a probability distribution.

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Paper 22: Techno-Economic Evaluation of the Rooftop Solar Power Generation at Malawi University of Science and Technology

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Abstract
Like many other universities, the Malawi University of Science and Technology faces the difficulty of enormous utility power expenditures, as such, there is a need to explore alternative sources of energy for onsite power generation. Thus, the purpose of this study was to examine rooftop solar generation potential. To achieve this, the size of the available rooftop was measured directly; the energy consumption was calculated using data gathered through loads physical examination; and the System Advisor Model (SAM) was used to assess the system's technical and financial performance. According to the technical analysis, the university's rooftop area is 14,738 m2, with an average daily global radiation of 5.17 KWh/m2. The rooftop can accommodate a 2.8 MW solar PV system, which produces 3,314.62 MWh of electricity annually against 1,819.4 MWh of electricity consumed annually that cost the university approximately $67,624.17 every year. The university will have a surplus of 1,495.22 KWh of electricity annually. An economic analysis of the system using SAM shows that an investment cost of $4,140,640 will be required; the cost of the energy produced will be 17cents/KWh, the net present value of the project will be $232,300 and the project is expected to have a payback period of 9.7 years, which means the project is worth the investment. Therefore, MUST should consider investing in rooftop solar PV system, which can be done with support from the bank or in partnership with industries, such as, milk processing companies located close the university that also demand more cooling energy.

Keywords: System Advisor Model, Solar PV System, Rooftop, electricity, Malawi University of Science and Technology.

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1. Introduction

Access to reliable energy is a requirement for attaining high quality education in institutions of higher education (Jabbar et al., 2020). But Malawi still struggles with an unstable power supply, which has a detrimental effect on universities like the Malawi University of Science and Technology (MUST). Activities that require energy as an input are interrupted as a result of these inadequacies in the energy supply (Gamula et al., 2014). Given the many functions that consistent power may offer in the classroom, it is regrettable when educational facilities lack it (UNDESA, 2014). The demand for energy in Malawi is likely to rise over the next ten to twenty years, and it is anticipated that the country's current ability to generate it would not be able to supply it (World Bank, 2020). EGENCO is facing challenges in achieving its goals of raising generation capacity, one of which being the impact of climate change on hydropower production (JICA, 2022).

Already it is predicted that there would be a decreasing capacity of hydropower with climate changes (McCauley et al., 2022). This will present a major challenge for Malawi, a country that is dependent on hydropower (McCauley et al., 2022; USAID 2019). Due to the national energy supply utility company's inconsistent energy supply, a considerable number of commercial and industrial businesses have erected their own diesel and gasoline-powered (Gamula et al., 2014). These are, nevertheless, urgent measures given that the cost of liquid fuels is still rising and that their supply is unstable due to a shortage of foreign exchange (MoE, 2023). Universities must play a significant role in the development and promotion of sustainability and renewable energy. One way that universities may show their dedication to this cause is by incorporating sustainable development into every aspect of campus life (Tarigan, 2018). The majority of these institutions' yearly budgets are already devoted to paying increasing electricity bills, so it is imperative that they make an investment in on-site power generation if they hope to wean themselves off of this burden (Jabbar et al., 2020).

Already it is widely believed that mini-grids will play a significant role in realising the national energy goal (MERA, 2019), which is "To increase access to affordable, reliable, sustainable, efficient and modern energy for every person in the country." The policy outcomes among other is diversified energy sources(Ministry of Natural Resources, Energy and Mining, 2018).

Solar energy, which is one of the most popular harnessed form of renewable energy in the globe will play a key role in achieving the policy goal (IRENA, 2019; Tarigan, 2018). The usage of photovoltaics has evolved tremendously over the past decades from a niche of small-scale applications such as running a basic calculator or a torch light to a fully emerged mainstream source of electricity (Sivaraman & Rawool, 2019). The solar PV systems has had its advancement in technology over the years, and it has been observed that the weighted average levelised cost of electricity (LCOE) from solar PV has declined by 77% between 2010 and 2018 (IRENA, 2019).

According to Zalengera et al. (n.d.), Malawi has a potential for solar energy ranging from 1642.5 to 2555 kWh/m2 annually on a horizontal surface. Between 2007 and 2017, installed capacity in Malawi increased from 0.2 MW to 5.7 MW (Buckland et al., 2017). One of the renewable energy resources that Malawi has in abundance is solar energy. On a horizontal surface, the country's average daily solar irradiation is 5.8 kWh/m2, and its potential for solar energy ranges from 1,642.5 to 2,555 kWh/m2 annually. Like most third-world countries, most of Malawi's renewable energy comes from solar energy, but this resource is not fully utilized (Mohan et al., 2019).

Using a roof area is a very good choice for reducing the demand for additional land, as installing a solar PV system requires an open space for mounting PV modules to maximize capturing of solar irradiation (Tarigan, 2018). The rooftop solar system offers numerous benefits because of the significantly smaller size of the power plant-style components (Jabbar et al., 2020). However, the placement of a solar plant on the roof of a building or integration of it into some architectural parts of the buildings or structures is complicated by the fact that the latter do not always function in an optimal mode, as unusual conditions of placement lead to the panels not always being installed optimally in relation to the Sun (Belenov et al., 2016; Tarigan, 2018; Belenov et al., 2016). Among others optimal performance of the rooftop solar PV can be achieved by proper initial design (Buckland et al., 2017). Another global trend that is unavoidable is the use of design and simulation software to maximize solar electricity. Currently, many research institutes and solar cell manufacturers have been developing the software such as PVsyst , Solar Pro, Sunny Design, PV*SOL, TRNSYS, PVFORM, INSEL, PHANTASM, P-Spice, PVsyst, PV-DesinPro, PVcad, and SolarGIS PV Planner, which effectively be used to properly design a solar PV Systems (Tarigan, 2018; Nguyen & Van, 2021). Therefore, this study involved assessing the potential of rooftop solar power generation at MUST campus using the System Advisor Model (SAM).

2. Materials and Methods

2.1 Study Area.

The research project was conducted at the MUST, a public university that is located in Thyolo District, Malawi. The university was established on 17th December 2012 by the Malawi Act No. 31 of 2012 as the fourth public University. The MUST was established to promote the development, adaptation, transfer and application of science, technology, and innovation (STI) for macro- and micro-economic development of Malawi. Figure 1 shows the MUST campus, where the study was undertaken.

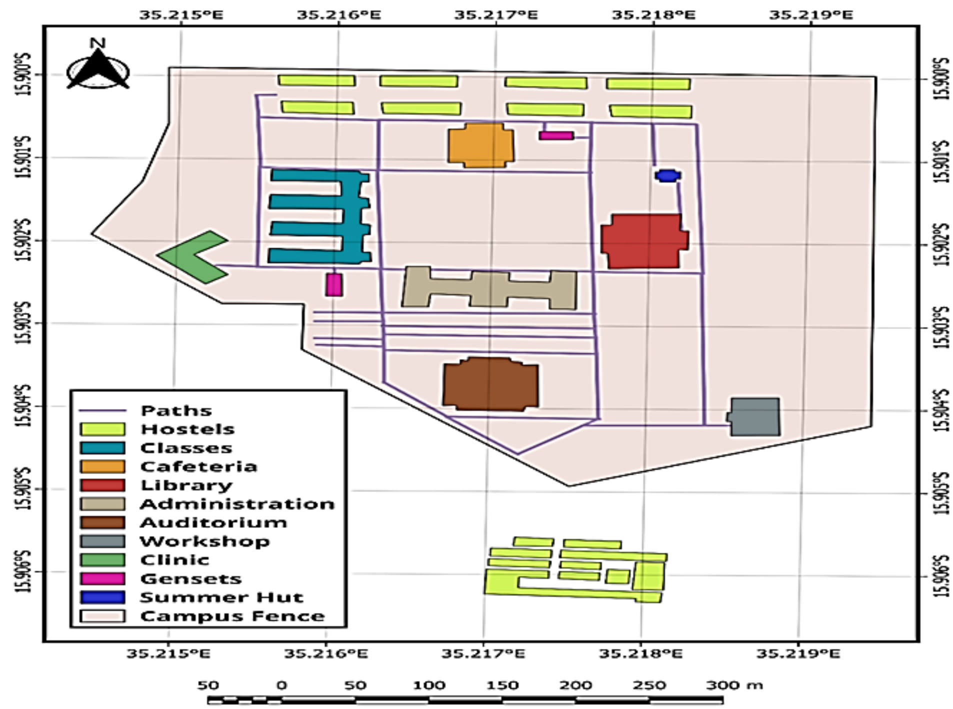

Figure 33: The Malawi University of Science and Technology Campus in Thyolo District.

2.2 Specific Methods Used.

2.2.1 Determining energy demand of the university.

All the university buildings were inspected at the campus to identify energy the loads and its operating hours. The collected data was used to determine energy intensity areas of the university as well as the daily energy demand of the university. Apart this Key Informant Interviews were done, where personnel from the university accounts and estate departments were interviewed to collect relevant data on energy consumption and the associated bills.

2.2.2 Sizing the available rooftop area of the university.

Rooftop space measurements were done for all buildings on campus using a tape measure and putting into consideration the roof type, roof pitch, orientation and access for installation & maintenance. The process was aided with drone camera. The rooftop area for all buildings was added together to get the total rooftop space that can be used for the installation of the Solar PV System.

2.2.3 Technical and economic analysis of the Rooftop Solar PV System.

The sizing and economic analysis of the rooftop Solar PV System was done using system advisor model (SAM) based on the collected data. SAM is a free desktop application for techno-economic analysis of energy technologies. It is used by project managers and engineers, policy analysts, technology developers, and researchers to investigate questions about the technical, economic, and financial feasibility of renewable energy projects. SAM can model many types of renewable energy systems such as Solar Photovoltaic Systems, from small residential rooftop to large utility-scale systems; Battery storage with Lithium ion, lead acid, or flow batteries for front-of-meter or behind-the-meter applications. SAM combines time series weather data and system specs to calculate the electricity production of a potential renewable energy system. Next, the model uses system cost, compensation, financing, and incentive data in an annual cash flow to calculate levelized cost of energy, net present value, payback period, internal rate of return, and revenue of the potential project.

2.2.4 Data collection and analysis.

The research project involved the collection of qualitative data on energy demand, rooftop space available the MUST campus, and the radiation received. The data collection for determining the MUST campus rooftop size was done physically by measuring the dimensions of the available rooftop space using a tape measure. Estate and Finance Departments were interviewed and their records on energy consumption and bills were collected. Weather data regarding the temperature and solar radiation received was collected from the Department of Meteorological Services, which was validated using the satellite date. The data was analysed using SAM to determine the techno-economic performance of the rooftop Solar PV System.

3. Results and Discussion

3.1 MUST Energy Demand.

Using the data for power load and the average operating hours of each equipment on a daily basis. It was found that on average MUST consumes 4, 984.7 KWh per day. Of this energy it was determined that Administration Block, Hostels, Cafeteria, Library, Clinic, Auditorium, Classrooms, Sewer Treatment and Workshop Block accounted for 35%, 26%, 8%, 15%, 3%, 2%, 7%, 3% and 1%, respectively. These statistics show that higher consumption of the energy is at the administrative block. This administrative block could become an area of focus when considering a rooftop solar power system in case the implementation of the project is to happen in phases depending on the available financial resources. The university pays about 8,987.91 USD (MWK15, 768, 267.67) per month on average for utility power. However, variations were observed considering that during some months students are on holiday. Figure 2 shows energy consumption by different building blocks at the MUST.

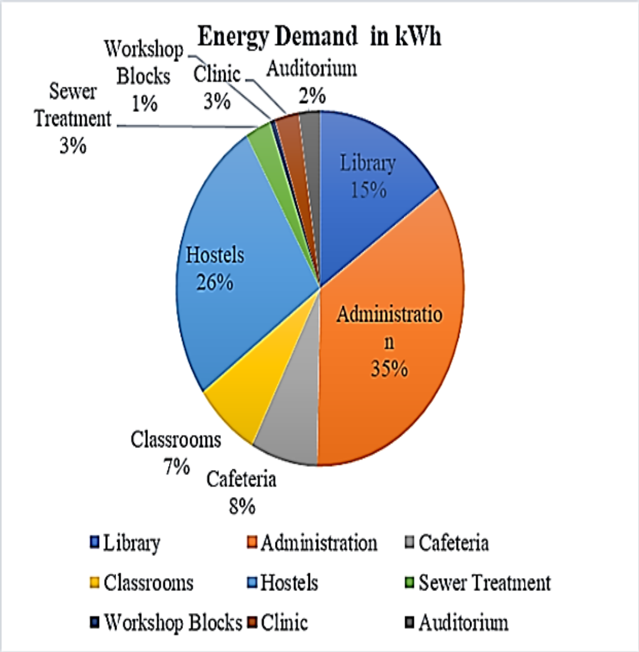

Figure 34: Energy Consumption by Blocks at the MUST.

3.2 MUST Rooftop area.

The MUST campus has a number of building blocks, which can be considered for rooftop Solar PV installation. The roofs are of different designs and orientation, which may also affect the design of the Solar PV System where it be difficult to adopt an optimal tilt angle of the solar modules on some buildings. The finds showed that workshop, Hostel at Extension Wing, Hostels, Cafeteria, Classes, Clinic, Library, Administration and Auditorium Blocks had a rooftop areas of 800m^2, 2,692m^2, 3,432m^2, 800m^2, 2,596m^2, 416m^2, 1,320m^2, 2,044m^2, and 638m^2, respectively (Figures 3a & 3b). The total rooftop area for Solar PV generation was found to be 14,738m^2.

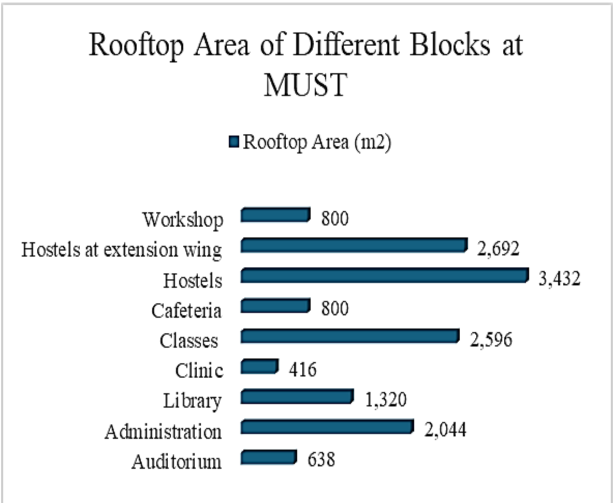

Figure 35a: Rooftop Area of Different Building Blocks at MUST Campus.

Figure 3b the Rooftop Area of MUST campus captured using a drone.

3.3 MUST Campus Weather Information.

3.3.1 Must Solar Irradiance.

The simulation results using SAM indicates that the MUST receives solar irradiance that varies according to months. The Diffuse irradiance ranges from 38 kW/m^2 to 70 kW/m^2 per month. On the other hand, the beam irradiance had ranges of 88 kW/m2 to 195 kW/m^2 per month. The global irradiance, which is the total irradiance from the sun on horizontal surface was determined to be ranging from 120 kW/m^2 to 198 kW/m^2 per month. Based on this global irradiance it was observed that the MUST campus receives more radiation from January to around April, then from August to December. However, the location receives less solar radiation from May to July. Therefore, it should be anticipated that the installed Rooftop Solar PV System will be generating less power during these months. However, designing of the Solar PV System usually is based on the months of least solar radiation, which helps to ensure that there is adequate power generation throughout the year to meet the load demand. Figure 4 shows diffuse, beam and global irradiance of MUST campus in Thyolo District.

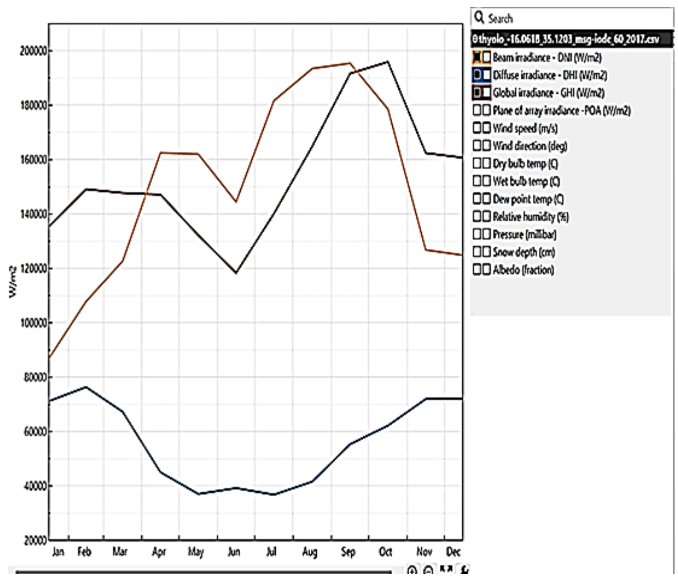

Figure 36: Solar Irradiance at MUST, Based on the SAM analysis.

3.3.2 Temperature at MUST Campus.

Temperature has a significant impact on the performance of the Solar PV System. Solar panel efficiency is measured under standard test conditions (STC) based on a cell temperature of 25°C, solar irradiance of 1000W/m^2 and Air Mass of 1.5. Therefore, the solar modules considered for installation at MUST may not perform the same. The results of the SAM simulation showed that higher temperatures of above 30˚C are expected during the months starting from September to December. The lowest temperatures were observed from April to August. It can be noted that these temperatures are in line with the amount of radiation received in a particular month. For instance, June and July having the lowest irradiance also experiences lower temperatures. Therefore, from September to December, where the temperatures are mostly above 25 °C, the solar modules will not be performing according to manufacturers' specifications. Figure 5 shows temperature of MUST throughout the year.

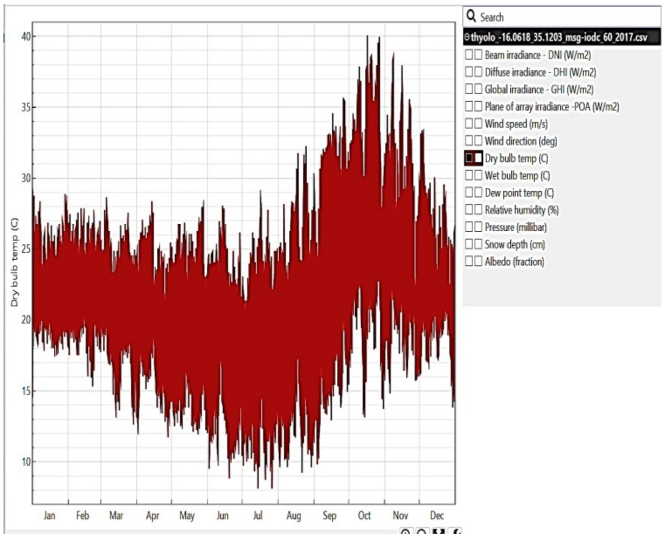

Figure 37: Temperature at MUST campus.

3.4 Rooftop Solar PV System Size for MUST.

According to the SAM simulation results, based on the roof surface area, the university can install a Rooftop Solar PV System with the following specifications: total capacity of 2.8 MW, with a DC to AC ratio of 1.15; an inverter size of 2434.78KW with 96% efficiency; and a fixed roof mount of an array tilt 20 degrees. The rooftop Solar PV System will have a total power loss of 14%, the system will be degrading at rate of 0.8% per year. The summary of the system capacity is shown in the table below:

Table 17: Technical Specifications of the Rooftop Solar PV System.

Performance Model

PV System Specifications	
System nameplate size	2,800 kW
Module type	0
DC to AC ratio	1.15
Rated inverter size	2,434.78 kW
Inverter efficiency	96 %
Array type	fixed roof mount
Array tilt	20 degrees
Array azimuth	180 degrees
Ground coverage ratio	N/A
Total system losses	14 %
Shading	no

Performance Adjustments	
Availability/Curtailment	none
Degradation	0.8 %/yr
Hourly or custom losses	none

3.5 Energy Output of the Rooftop Solar PV System.

SAM simulations results indicated that highest energy of above 300MWh will be generated by the rooftop Solar PV System from September to December. These are the months which the MUST campus receives highest radiation. On the other hand, the system will generate less energy of bellow 200MWh during the months of May and June. On average, the location has an average solar radiation of 4.41 kWh/m2/day, which will allow the university to generate 3,314.6MWh of energy per year using the rooftop Solar PV System.

Table 18: Monthly and Annual Energy Output of the Rooftop Solar PV System.

Results	Solar Radiation	AC Energy
	(kWh/m2/day)	(kWh)
Jan	4.38	277,631
Feb	5.15	298,650
Mar	4.29	276,916
Apr	3.96	247,448
May	3.09	198,726
Jun	2.74	170,635
Jul	3.14	202,771
Aug	4.08	264,216
Sep	5.47	337,636
Oct	5.93	373,949
Nov	5.39	329,179
Dec	5.3	336,856
Year	4.41	3,314,618

3.6 MUST load Versus Energy Output and Potential Bill Savings.

The SAM simulation results showed that the energy demand for MUST about 150 MWh of energy per month. However, energy output of the Solar PV System per month is above the load demand except for the month of June, when the system is expected to generate less energy because the location receives the least radiation. The analysis shows that the university will be generating an excess of between 50 MWh to 200 MWh depending on the month of the year (Figure 6). The MUST has a daily energy demand of 4, 984.7 kWh per day, which translates to 1,819.4 MWh of energy annually assuming that the demand is constant. However, the rooftop Solar PV System has the capacity to generate 3, 314.6 MWh. This means that there is a surplus of 1,495.2 MWh of energy, which can be sold to Electricity Supply Corporation of Malawi (ESCOM).

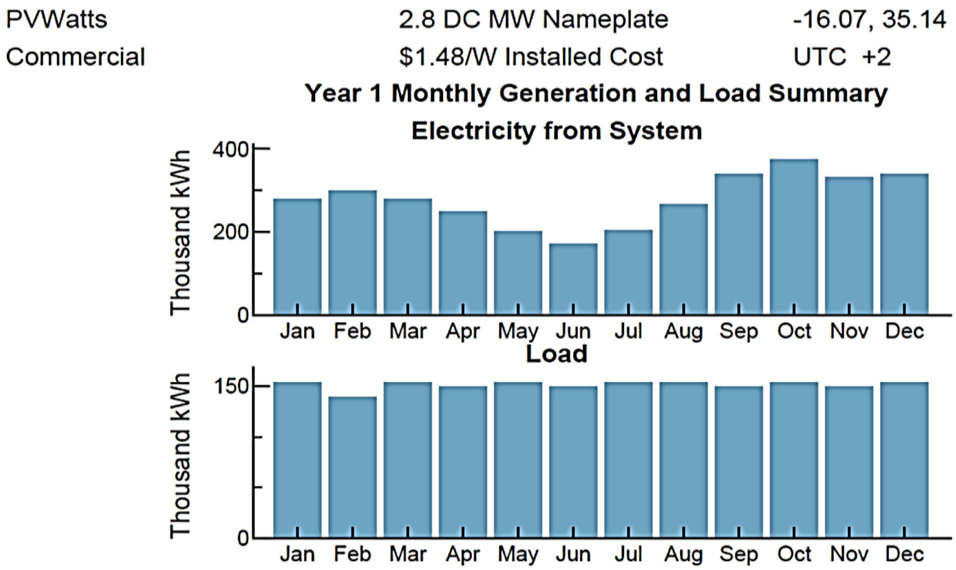

Figure 38: Rooftop Solar PV System Energy Output Versus Demand.

3.7 Economic Performance of the Rooftop Solar PV System.

The simulation results showed that the proposed rooftop Solar PV System that has a lifespan of 25 years will require an installation cost of $4,140,640.00. The salvage value of the system (i.e., estimated value of the system at the end of its useful life) will be $910,940. It is anticipated that the Levelized Cost of Energy (LCOE) will be 17¢/kWh. The payback period of the project will be 9.7 years and having a Net Present Value of $232, 300 (Figure 7).

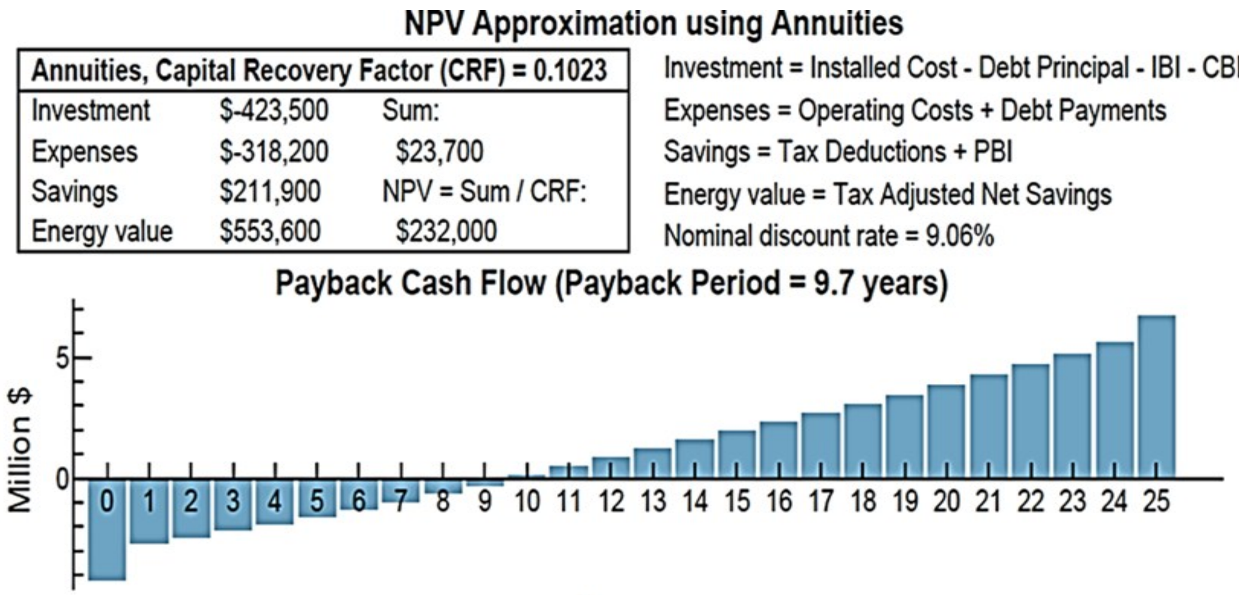

Figure 39:NPV Approximation Using Annuities.

4. Conclusions.

This study investigated the potential of rooftop solar power generation at the MUST. Specifically, the technical and economic performance of the system was assessed. The study involved determining the energy demand of the university, where energy consumption in different building blocks were assessed. In addition, the size of the rooftop was assessed to understand its space that can be used to install a Solar PV System. Using SAM, the Rooftop Solar PV System was analysed to determine its technical and economic performance. The results indicated that the rooftop of the MUST campus is large enough to allow the university generated more than demanded energy. Except for June, all the months are expected to have surplus energy of between 50-200MWh, which can be sold to ESCOM. The rooftop Solar PV System will have a lifespan of 25 years, and the LCOE is expected to be 17¢/kWh. The payback period of the project will be 9.7 years and having a Net Present Value of $232, 300.

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Paper 23: Data-driven Modeling of Optical turbulence in Near-Maritime Free Space Optical Communication Links

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Abstract
Atmospheric turbulence significantly impacts free space optical communication (FSOC) links by causing rapid fluctuations in the local refractive index. These fluctuations cause optical turbulence, resulting in wavefront distortion as the optical beams propagate through the atmospheric medium. The refractive index structure constant, C_n^2, quantifies the turbulence's intensity. However, modelling C_n^2 remains challenging due to its dependence on local topography and meteorological conditions. Macro-meteorological models, based on weather data, often struggle to predict rapid variations in C_n^2, especially in near-maritime environments. To address these limitations, this work explores data-driven approaches, specifically, machine learning (ML) techniques. The study begins with feature selection, to identify impactful meteorological parameters for modelling C_n^2, using measured C_n^2 values and environmental parameters from publicly available dataset. Subsequently, two ML models based on Random Forest and a proposed Radial Basis Function Neural Network are trained using the selected features. Additionally, these ML models are trained employing features used in one of the literatures, providing a baseline for comparison, and demonstrating the role of feature selection on this task. Results demonstrate that while ML models offer good candidates for C_n^2 prediction, effective feature selection plays a crucial role in developing models where even higher accuracies could be attained. This approach offers a promising solution that can be included in the ML pipeline to accurately estimate optical turbulence in FSOC links.

Keywords: Free space optical communication (FSOC) links, Machine learning (ML), Macro-meteorological models, Refractive index structure constant.

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1. Introduction

Free-space Optical Communication (FSOC) emerges as a transformative technology in our interconnected, data-driven world, offering secure and energy-efficient networks capable of high-capacity data transmission at low costs. Unlike traditional radio frequency communication, FSOC uses optical beams for data transfer, which, while efficient, are susceptible to atmospheric disturbances like cloud cover, particle scattering, and optical turbulence. The latter, arising from the atmosphere's turbulent mixing, leads to rapid refractive index changes, distorting the optical beam and impairing electro-optical system's performance in the FSOC terminal. Therefore, accurate prediction of optical turbulence profiles is vital for the development of adaptive optical systems that can mitigate these effects. The refractive index structure constant, C_n^2, is a crucial metric for quantifying these spatial fluctuations. Influenced by both local environmental factors and broader atmospheric forces, C_n^2 is directly related with the turbulent structure of the atmosphere. At lower altitudes, air temperature gradients are the primary cause of optical turbulence [1], [2]. Additionally, macro-meteorological models, consider local weather factors such as air temperature, pressure, humidity, wind speed, and the weight of temporal hours to significantly impact C_n^2 predictions [3], [4], [5]. For FSOC links to be reliable and effective, it is imperative to measure or model optical turbulence conditions accurately, considering the dynamic nature of atmospheric conditions and geographical variations to enhance electro-optical system's performance.

In modelling C_n^2, several solutions have emerged in the literature. These solutions range between traditional physically based techniques such as the Offshore-updated model, the ANOVA macro-meteorological model and Sadot macro-meteorological [6], [7], [8] to machine learning (ML) models. To this end ML models have shown superior performance in modelling C_n^2 in near maritime environments.

Pierzyna et al. propose Π-ML, a ML framework based on dimensional analysis, to estimate optical turbulence in the atmospheric surface layer [9]. It uses gradient boosting and an ensemble of models for robust predictions, highlighting the normalized variance of potential temperature as a key feature. The methodology is tested using data from the Mauna Loa Observatory study, which includes meteorological measurements and estimated turbulence values. The findings suggest that simpler measurement setups might be sufficient for accurate turbulence estimation, potentially impacting the design of free-space optical communication links.

Cuicui et al. [10] present a novel hybrid neural network model, combining a backpropagation (BP) neural network with a genetic algorithm (GA), to estimate optical turbulence profiles in marine environments. The study introduces a GA BP model that estimates atmospheric turbulence profiles, validated against balloon-borne microthermal measurements. It emphasizes the lack of systematic direct measurements of optical turbulence in marine climates and proposes a solution using the GA-BP model. The model's performance is compared with traditional physically based models and validated through a field campaign at the Haikou marine environment site. Their findings suggest the GA-BP model can effectively characterize vertical distributions of optical turbulence, offering valuable data for adaptive optics systems in marine settings.

Bolbasova et al. explore the application of ML to predict optical turbulence in the surface layer at Baikal Astrophysical Observatory [11]. The work utilizes the group method of data handling (GMDH), a deep-learning technique, to forecast the refractive-index structure constant from atmospheric parameters. Achieved correlation coefficients ranging from 0.79 to 0.91 for stable atmospheric conditions, indicating a strong agreement between predicted and measured values. This demonstrates the effectiveness of the GMDH approach in predicting optical turbulence, which is crucial for optimizing telescope operations and scheduling observations.

The work in [12] presents ML informed macro-meteorological models including linear model with polynomial regression, random forest model and Boosted regression tree model for predicting optical turbulence in near maritime environments. Seven months of field measurements were collected along an 890 *m* scintillometer link over the Severn River in Annapolis, Maryland, augmented with local meteorological data. Existing macro-meteorological models were analyzed and compared with new ML models trained using the collected data. The new models demonstrated higher overall prediction accuracy for optical turbulence under most conditions, suggesting potential for further improvement with additional tuning and architectural changes.

Based on existing studies, ML techniques have shown promise in predicting C_n^2 in near maritime environments. However, feature selection is not apparent in these studies. Selecting the right features for ML models is crucial, as these features directly impact model accuracy. While training a model with all meteorological variables may seem convenient, some features may add complexity without contributing valuable information. To address this, this work explores data-driven approaches: one based on correlation and the other on Mutual Information (MI). Additionally, we propose a hybrid approach that combines the strengths of both methods to strike a balance.

The rest of the paper is organized into the following sections: Section 2 discusses about the dataset used in this study; Section 3 details feature selection methods; Section 4 described the models considered under our study; Section 5 discusses the results obtained from simulation and Section 6 concludes the work.

2. Dataset

In this study, the effectiveness of a proposed methodology is explored by analyzing experimental data collected along an 890-meter propagation path established over the Severn River in Annapolis, Maryland [13]. The study spanned from January 1, 2019, to March 31, 2020. During this time, various environmental parameters to capture the intricacies of the propagation path were recorded. The collected data resulted in two datasets:

- **Hourly Averaged Data**: This dataset provides aggregated information over hourly intervals.
- **10-Minute Averaged Data**: This dataset captures measurements at 10-minute intervals, allowing for finer temporal details.

This study utilizes the 10-minute dataset. The dataset encompasses several meteorological variables, each contributing to the overall understanding of the propagation environment. The variables include:

- **Air Temperature**
- **Relative Humidity**
- **Dew Point Temperature**
- **Wind Speed**
- **Pressure**
- **Rain**
- **Solar Radiation**
- **UV Index**
- **Air Density**
- **Depth**
- **Season**
- **Temporal Hour Weight**
- **Air-Water Temperature Difference**

From the dataset, three days (December 14, 2019; March 9, 2020; and March 29, 2020) were selected to be used for interrogating the trained models while the rest of data was used for training.

3. Feature Selection for C_n^2 Modelling

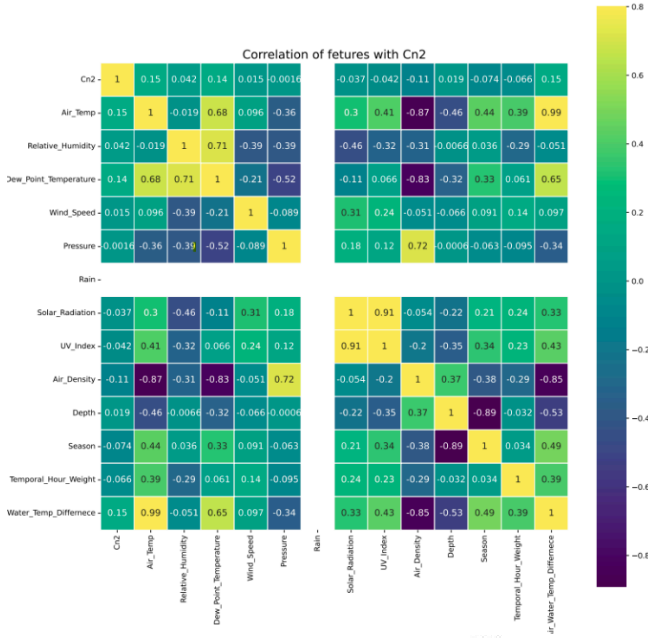
Choosing appropriate features during the development of ML models is essential for creating a well-generalized model. In the context of estimating C_n^2 using ML techniques, researchers have used various meteorological variables in literature. Table 1 offers a concise summary of these variables. These variables have been reported to provide good models for estimating C_n^2, however, the criteria that informs the choice of appropriate features is not well defined. For analysis and comparison, this research focuses on features presented in [12]. Our work establishes a data informed procedure that could be employed in deciding the appropriate features by assessing the relationship between features and the target variable. In this regard two distinct approaches are explored: MI and correlation. MI quantifies the dependence between random variables, making it valuable for evaluating relationships between labels and features, as well as among different features. It excels at capturing complex dependencies and handling non-linear relationships. On the other hand, correlation focuses on linear relationships between continuous variables. It detects linear dependencies between features, making it useful

Table: 1 Features employed in previous studies.

Article	Meteorological Variables	Number of Features
Cuicui et al. [10]	height, pressure, temperature, wind speed, wind shear, and temperature gradient	6
Jellen et Al. [12]	air temperature, air-water temperature, relative humidity, wind speed, solar radiation and pressure	6
Wang et al. [14]	temperature, relative humidity, pressure, potential temperature gradient, and wind shear	5
Wang et al. [15]	temperature, wind speed, temperature gradient, relative humidity, soil temperature, net radiation, water content	7
Bolbasova et al. [11]	temperature, relative humidity, pressure, wind speeds (Vx, Vy, Vz), wind directions (Fi and Vh)	8

for trend detection and dimensionality reduction. However, correlation does not account for non-linear dependencies and may miss important non-linear associations. To strike a balance, this paper further explores a hybrid approach that combines both MI and correlation methods.

A correlation matrix is firstly computed to identify features that are strongly correlated (both positively and negatively) with the target (C_n^2) variable. Figure 1 illustrates this matrix, revealing relationships between



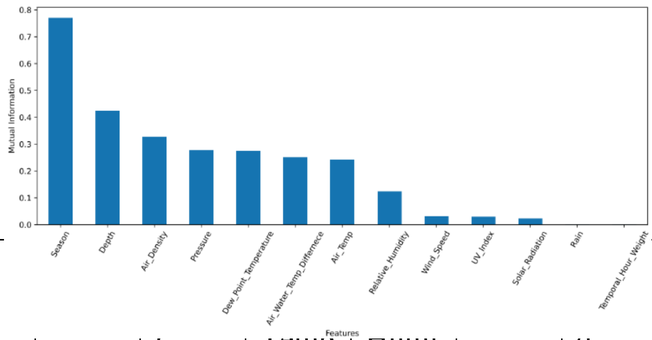
the meteorological features and the C_n^2, as well as inter-feature correlations. Specifically, the following observations emerge from the correlation analysis:

- **Positive Correlations**: Mean air temperature, air-water temperature difference, mean dew point temperature, mean relative humidity, depth, and mean wind speed exhibit positive

Fig. 1. Shows the correlation matrix depicting the relationship between the target variable (C_n^2) and features, as well as the relationship between the features themselves.

correlations with coefficients of 0.154011, 0.151726, 0.142070, 0.041882, 0.018961, and 0.014724, respectively.
- **Negative Correlations**: Conversely, mean pressure, mean solar radiation, mean UV index, temporal hour weight, season, and mean air density show negative correlations with coefficients of −0.001633, −0.036714, −0.042435, −0.066368, −0.074403, and −0.106032, respectively.

Interestingly, no relationship is observed between C_n^2 and rainfall when correlation approach is employed.



		Temp Diff	Temp	dity		d	Press ure	Solar Radia tion	Uv Index	Temp oral Hour Weig ht	Seaso n	Air Densi ty	Rain
Norm Corr.	1.000	0.9852	0.9225	0.2719	0.1231	0.0956	0.0106	0.2384	0.2755	0.4309	0.4831	0.6885	0
MI	0.2405	0.1288	0.2777	0.0314	0.2772	0	0.0236	0.0269	0.3312	0.4229	0.7711	0	0.2503
Prod.	0.2405	0.1269	0.2562	0.0085	0.0341	0	0.0002	0.0064	0.0912	0.1823	0.3725	0	0

The discrepancy is attributed to the fact that the weather station failed to accurately measure the amount of rain over each 10-minute time interval [12]. Despite lack of correlation between C_n^2 and rainfall rainfall exhibits some correlation with C_n^2. Using the correlation method resulted into the following features as important: Air Temperature, Air Water Temperature Difference, Dew Point Temperature, Air Density, Season and Temporal Hour Weight. It can be observed that there is a strong correlation between Air Temperature and Air Water Temperature Difference. It is advisable to avoid using highly correlated features during model development, as they may not contribute additional information. To address this, Air Water

Fig. 2. Shows the mutual information between each feature and the target variable (C_n^2), sorted in descending order.

Temperature Difference is replaced with the next feature in the ranking: UV Index. By doing so, feature diversity is maintained, and the model's predictive power is enhanced.

Next, MI between each meteorological feature and C_n^2 is assessed. High MI values indicate strong statistical dependence, suggesting that the features hold predictive power for C_n^2. Figure 2 displays the MI scores for each meteorological feature, providing insights into their informativeness. Feature ranking using MI scores, identifies the following highly ranked features for predicting C_n^2: Season, Depth, Air Density, Pressure, Dew Point Temperature and Air Water Temperature Difference.

Finally, a metric that combines both the correlation coefficient and MI scores is defined.

Table 2: Parameter ranking.

This is done by multiplying the normalized absolute correlation coefficient with MI scores. Table 2 shows the ranking parameter. Taking the first six features highly ranked according to this criterion makes Season, Dew point temperature, Air temperature, Temperature hour weight, Air Water Temperature Difference and UV index. This approach also includes both Air Temperature and Air Water Temperature Difference in the selected features. However, to avoid redundancy, Air Water Temperature Difference is replaced with Depth, which follows in the ranking. This adjustment ensures a diverse set of informative features for training the models.

4. Considered Machine Learning Models for C_n^2 Estimation

After establishing the features as per this work's criteria, the next step is to develop the models. Firstly, models are developed on the selected features, after that the same model architectures are trained using features used in one of the previous studies.

4.1. Random Forest

A Random Forest is an ensemble of decision trees. It combines predictions from multiple individual trees to mitigate over fitting and enhance accuracy. Each tree in the forest is trained on a distinct subset of the dataset (referred to as a sub-sample). By using random subsets of the data (with replacement), the random forest prevents over fitting. The average of the predictions from all the individual trees represents the ensemble's prediction, resulting in robustness and improved generalization. Additionally, each tree within the forest employs the best split strategy, akin to passing splitter='best' to the underlying decision tree regressor. Random Forest has been reported to perform better in estimating C_n^2 Jellen et al. [12]. Inspired by this finding, it was chosen as the baseline model for analysis in this research work. The task now becomes tuning the hyper-parameters for the model. Table 3 shows optimal hyper-parameters for the Random Forest obtained through Bayesian optimization.

Table 3: Optimized Parameters for Random Forest Model.

	Number of trees	Min Leaf Size
Correlation	27	75
MI	63	30
Combined	144	62
Paper [12]	59	127

The Combined technique requires a larger number of trees (144) compared to the other techniques, indicating that this technique results in features which may have more complex relationships with target variable C_n^2. The MI method requires a smaller minimum leaf size (30), which suggests that it identified more informative features that require fewer samples to make accurate C_n^2 predictions.

4.2. Radial Basis Function Neural Network

This work also proposes Radial Basis Function (RBF) neural network for estimating C_n^2. The choice of RBF neural network is driven by its ability to make accurate local approximations for nonlinear input-output mappings. Additionally, RBF neural networks do not encounter the problem of local minima, which is often a challenge in feedforward neural networks trained by gradient descent. As a result, it is anticipated that RBF neural networks will exhibit better generalization capabilities. Basically, the RBF neural network is a feedforward neural network with two layers: the hidden layer and the output layer. In the hidden layer, nonlinear transformations of input data occur using radial basis functions (such as the Gaussian function). These functions produce outputs that are dependent on the distance between input data and predefined centers. The output layer linearly combines the transformed features to map nonlinearity into a new space.

The centers of hidden layer neurons can be obtained using several approaches which include Randomly selecting training data points as the centers for the RBF neurons, while simple, it may not always yield the best centers. An alternative approach is to use clustering techniques such as K-means or K nearest neighbors (KNN), to identify representative centers. KNN selects data points that are close to each other in feature space as the RBF centers. Clustering ensures that centers capture relevant patterns in the data. Another method finds the centers using Orthogonal Least Squares (OLS). OLS is an optimization-based approach that ensures the selected centers significantly contribute to the network's performance.

Ideally the centers of the hidden layer neurons are represented by their weights. These weights play an important role in determining the behaviour of the network. Once the centers are obtained, the Euclidean distance between the input vector set and the weights is calculated. The distance measurement helps to quantify how similar or dissimilar the input vectors are to the centers. The result of this distance calculation is then multiplied with the bias to manipulate the sensitivity of the neuron. If the Euclidean distance between the input vector and the centers of the Gaussian function is very large, the output from the RBF neuron will be close to zero. Conversely, if the input vector is near the centers, the output will be closer to one.

The second layer in the neural network shares similarities with the multilayer perceptron (MLP) neural network. The layer weight in this case can be obtained through two methods:

- **Inverse Matrix Operation**: A straightforward approach that involves using an inverse matrix operation to determine the layer weights.
- **Learning Algorithms**: Alternatively, learning algorithms such as radial distance and the Levenberg-Marquardt (Lm) algorithm can be employed to find the optimal weights.
- The popular used method is the OLS learning algorithm.

The OLS algorithm iteratively adds RBF centers to construct a network that minimizes the error. All training examples are considered as candidates for RBF centers. The one that reduces the mean square error, or any specified cost function becomes the new hidden unit. OLS has dual role, not only does it determine the weights of the output layer but also identifies the number and positions of RBF centers.

The spread parameter plays a vital role in training RBF neural networks. The spread determines how many Gaussian neurons are needed to smoothly approximate a function. A larger spread results in a smoother function approximation. While a large spread leads to smoother approximations, it also requires a substantial number of neurons. Conversely, a small spread necessitates fewer neurons but risks over fitting and poor generalization. The spread term is part of the Gaussian function formula used by RBF neurons. It influences the shape and width of the Gaussian curve. In determining a good spread term, the average distances between data points may at times be considered, as this approach may ensure effective function approximation without over fitting.

In the development of the RBF neural network model, we utilize the Gaussian function, the maximum number of neurons in the hidden layer is set to 10 and the centers are obtained using the OSL learning algorithm. The primary focus then lies in determining the optimal spread value while employing various feature selection techniques. The training data is randomly split into an 80% training set and a 20% validation set. For each random split, the spread parameter is varied from 0.1 to 2. To ensure statistically meaningful insights, this procedure is repeated 100 times and average mean squared error values on validation set are computed. The spread value with minimum mean squared error value is chosen to be the optimal one. The graphs that follow depict the mean squared error performance on the validation set, considering different spread values and feature selection methods. Figure 3 shows the error on the validation set when correlation is employed for feature selection and a spread value of 0.5 is found to be optimal. The use of MI in feature selection resulted into an optimal spread value of 0.4 as shown in Fig. 4. When both correlation and MI are used for feature selection, the optimal spread value is found to be 0.8 this is shown in Fig. 5. Employing feature used by Jellen et. al [12], a spread value of 0.4 is found to be optimal as portrayed by Fig. 6.

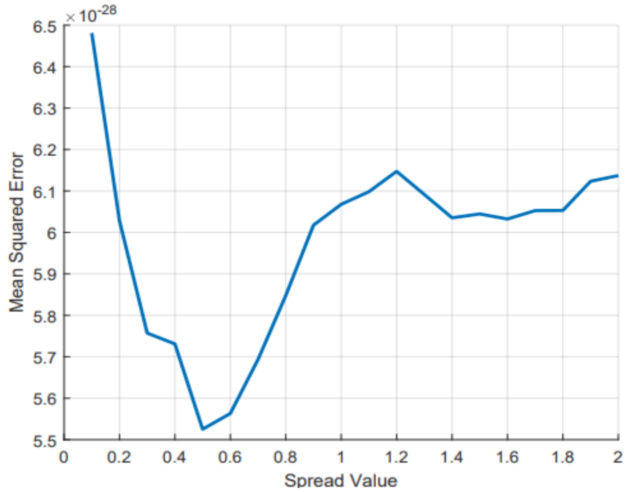


Fig. 3. Shows the relationship between the MSE (in 10^{-28}) and spread value when meteorological features selected based on correlation coefficients are used.

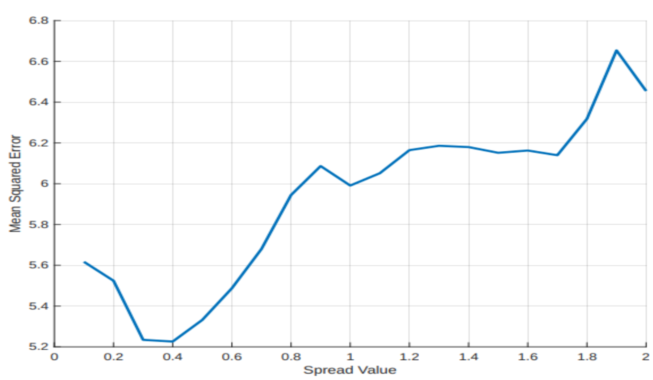


Fig. 4. Shows the relationship between the MSE (in 10^{-28}) and spread value when meteorological features selected based on mutual information are used.

Fig. 5. Shows the relationship between the MSE (in 10^{-28}) and spread value when meteorological features are selected based on combination of correlation and mutual information.

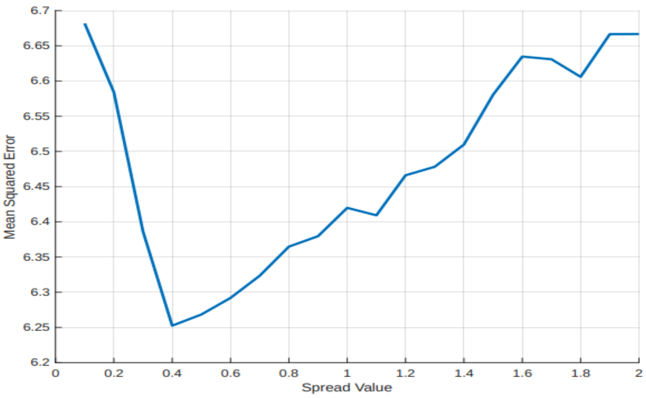


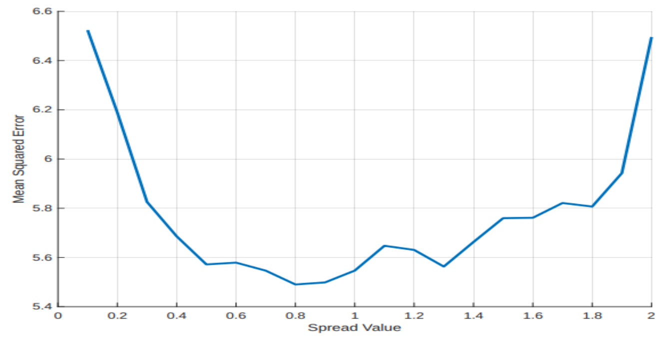
Fig. 6. Shows the relationship between the MSE and spread value when employing meteorological features used in [12].

Low spread values result when features are selected using correlation and MI as well as using features employed in [12]. This implies that models developed with these features tend to be more stable. However, they might miss extreme cases (outliers) due to their conservative nature. High spread value as observed in the combined technique implies that the developed model might capture extreme cases but could be less stable.

5. Results and Discussion

As pointed out in Section 2, three days are set aside to be used for testing the developed models and the feature selection procedure. These days are December 14, 2019; March 9, 2020; and March 29, 2020. Tables 4, 5 and 6 show the mean squared error performance for each test day.

Using correlation as a feature selection technique resulted in the least performance. This limitation may stem from its inability to capture nonlinear relationships. While MI



performed better, ranking second on December 14, 2019, and March 9, 2020, it did not fare well on March 29, 2020.

Table 4: Mean Squared Error Comparison for December 14, 2019.

	Number of trees	Min Leaf Size
Correlation	3.6685×10^{-14}	1.9119×10^{-14}
MI	2.2736×10^{-14}	1.2114×10^{-14}
Combined	3.4910×10^{-14}	3.2714×10^{-14}
Paper [12]	1.7097×10^{-14}	1.3979×10^{-14}

Table 5: Mean Squared Error Comparison for March 9, 2020.

	Number of trees	Min Leaf Size
Correlation	3.4711×10^{-14}	3.4455×10^{-14}
MI	3.2819×10^{-14}	3.3516×10^{-14}
Combined	3.0338×10^{-14}	2.9189×10^{-14}
Paper [12]	3.4687×10^{-14}	3.4135×10^{-14}

Table 6: Mean Squared Error Comparison for March 29, 2020.

	Number of trees	Min Leaf Size
Correlation	4.6512×10^{-14}	4.2032×10^{-14}
MI	4.3010×10^{-14}	4.0535×10^{-14}
Combined	3.7418×10^{-14}	4.1555×10^{-14}
Paper [12]	3.9459×10^{-14}	4.1106×10^{-14}

Interestingly, combining correlation and MI yielded fairly good results across all three days. The results suggest that much as feature selection plays a vital role in building good performing ML models, one single method may not give conclusive solution. Probably, making a hybrid approach would help to leverage the strengths of distinct methods, also, having domain knowledge regarding the impact of meteorological factors on C_n^2, would enhance the choice of features. A similar analysis is applied to the RBF Neural Network, the combined MI and correlation approach yielded poor results on December 14, 2019, for this model.

When compared to Random Forest, the RBF neural network demonstrates approximately the same performance.

Despite being simpler in architecture with only 10 nodes in the hidden layer, it achieves comparatively similar results as the more complex ensemble nature of random forest. This validates its candidacy in C_n^2 estimation problems.

6. Conclusion

This study demonstrates the potential of ML models for predicting the refractive index structure constant (C_n^2) for optical turbulence prediction. By leveraging environmental parameters and effective feature selection, accurate modelling becomes feasible. In this study, the RBF neural network emerges as a promising choice for C_n^2 prediction. Further research in this area could enhance the predictive capabilities of the RBF neural network bringing it closer to its integration in adaptive optics for free-space optical communication. Since the presented feature selection procedures rely on data, it implies that if the data collection procedure is inaccurate, the approaches may suffer limitations.

Acknowledgment

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Paper 24: Assessment of Central Hospital's infrastructure quality and performance in Malawi

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Abstract

Hospital infrastructure in Malawi is not in good condition. This is attributed to a lack of data on the current state of hospital infrastructure due to a lack of evaluations. Evaluations of infrastructure are important as they fill the knowledge gap, as such the study aimed to understand the quality and performance of central hospitals in Malawi. A concept called total building performance that uses both objective and subjective data was used with the following performance mandates: air, spatial, thermal, acoustic, illuminance quality, and building integrity. Objective and subjective data were collected using questionnaires and analyzed using software called R. A total of 200 participants were enrolled in all the central hospitals. Overall, the participants were not satisfied with the quality The acoustic quality range was between 22.1 dBA to 97.7 dBA above the standards set by the World Health Organization (0-35 dBA) and the Malawi Bureau of Standards (40,50 dBA), while the thermal quality, the temperature ranged from 22.6°C to 36.8°C, above the standards set by SHRAE (20°C to 26 °C) and 21°C to 24°C by the American Institute of Architects. The humidity range was between 33.1 and 84.6% and air velocity was 0–1.2 m/s, above standards. For air quality, all parameters met standards excluding $PM_{2.5}$ which ranged from 0.6 to 383.8 g/m^3. For illuminance, the range was between 39.65 and 1428 Lux, and out of 35 wards, 19 (54.3%) met the standards and 16(45.7%) did not meet the minimum standard of 300 Lux recommended by the World Health Organization. For spatial quality, bed space was between 4 m^2 and 5 m^2, below the standard of 7.43 m^2 by the Facility Guidelines Institute, and the average space between beds was 940 mm against the standard of

1200 mm. Out of 35 wards, 3 (8.6%) met the standards and 32 (91.4%) did not meet the spatial standards. The data collected exposes the challenges in hospital infrastructure in Malawi. This calls for the need for policies and procedures to ensure that standards are met. Policies should provide a mandatory framework for central hospitals to meet minimum standards.

Keywords: Central Hospital Infrastructure, Performance, Quality, Total Building Performance, Evaluations.

1. Introduction

The role of healthcare facility infrastructure as a major component of healthcare systems can not be underestimated (Scholz, Ngoli, & Flessa, 2015). World Health Organization (WHO) Alliance for Health Policy and Systems Research considers the hospital infrastructure as one component of the six building blocks of healthcare systems that offer service delivery (Harrington & Voehl, 2016) and they form a critical part of health service delivery in any country(Mavalankar, Ramani, Matel, & Sankar, 2005) as they are primarily intended to provide healthcare functions such as curative nursing and rehabilitation as such they're supposed to be in good condition (Wong, AbdulLateef, & Lim, 2021).

Poor hospital infrastructure can lead to poor service delivery which can lead to resource wastefulness and it affects positively the health and welfare of the patients(Mavalankar et al., 2005). It is important to evaluate the hospital infrastructure condition to see its conditions in offering services. Building performance evaluation emerged because of systematically evaluating the performance of buildings after they have been completed and occupied (Ukpong & Ackley, 2019).

The concept of building performance evaluation was used to evaluate a New Hospital building in the UK to assess the performance of the hospital against the industry standards and design intents(Jain et al., 2021).

The evaluation process produces data that can be used by stakeholders to improve the infrastructure. However, in Malawi, no study has been conducted to evaluate the performance and quality of infrastructure in the central hospitals, which has led to the unavailability of data. Understanding the performance of Malawi's healthcare infrastructure is critical as it will improve healthcare service delivery since the information collected will help the government and all stakeholders manage the infrastructure.

2. Methods

The total building performance (TBP) concept was used. TBP is a framework that simultaneously uses objective and subjective field evaluations in all performance areas (Wong & Jan, 2003). It is a holistic, performance-based, user-oriented building diagnostic and appraisal tool as the performance mandate connotes a set of users' preferences and responses regarding the spaces created (Abiodun, Oluseye, & Abiodun, 2017). The concept has six performance mandates, thermal, air quality, acoustic, illuminance, spatial and building integrity performance mandate.

2.1. Study design

A quantitative study assessing the performance of central hospital infrastructure in Malawi was conducted using TBP. The research was conducted the research using two research strategies, the experimental strategy in which electronic devices were used to collect objective data, and a survey was used to collect subjective data from users on their perception of quality and performance of the infrastructure in which the participants filled a questionnaire.

2.2. Setting

The study was conducted in Malawi's central hospitals, namely, Kamuzu in Lilongwe, Zomba Central in Zomba, Mzuzu Central in Mzuzu, Queen Elizabeth Central Hospital in Blantyre and Zomba Mental in Zomba**.** Data collection was done between December 2022 and February 2023 in 35 wards across all the central hospitals. Electronic devices were placed in each ward for 24 hours.

2.3. Study size

Sample size estimation was conducted in R using the power Prop (R Core Team, 2022). The aim was to estimate a sample size that was statistically powered (80%) to detect a minimum difference (30%) in satisfaction levels between any two eligible hospitals at a 5% significance level and a sample size of 40 participants determined per hospital. Figure 40 below shows the graph used for the computation of sample size.

$$N = \frac{\left(Z\frac{\alpha}{2}+Z\beta\right) 2*(P1(1-P1)+P2(1-P2))}{(P1-P2)^2} \text{(Chadha, 2006)}$$

$$Z\frac{\alpha}{2} = 1.96$$

$$Z\beta = 0.85$$

P1 is the estimated minimum difference between two central hospitals and equals 0.3 *and the P2 is the corresponding.*

$$N = 39.485$$

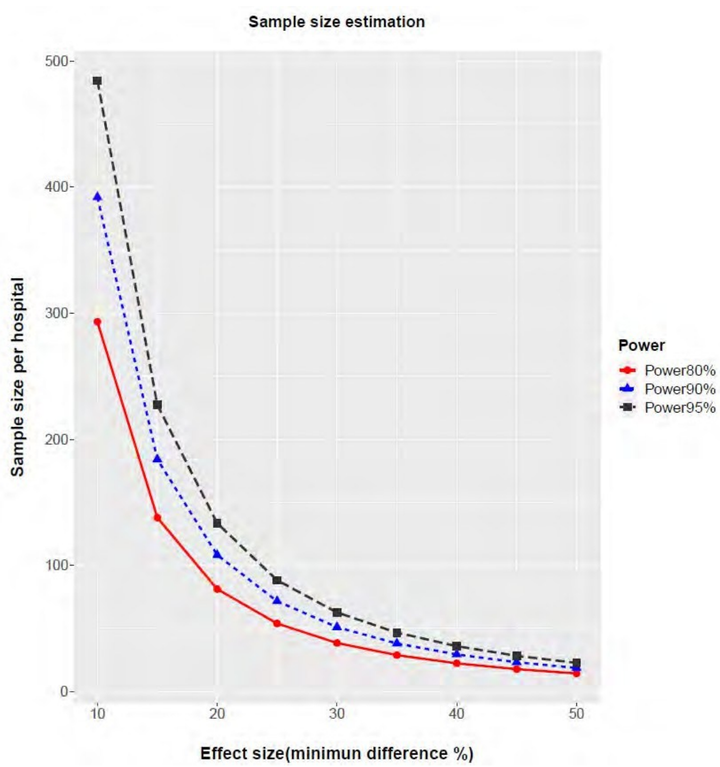

Figure 1: Sample Size Estimation graph

2.4. Participants

The study recruited a total of 200 participants, 40 health workers, and hospital infrastructure managers at each central hospital. To be eligible for the study the participants were supposed to be nurses, doctors, hospital administrators, and maintenance personnel. The study did not include lab and pharmacy personnel as the devices were placed in wards where nurses and doctors usually work. All participants gave informed consent.

Participants were given a questionnaire to fill in on how they perceive the quality of the central Hospitals in the areas of acoustic, spatial, thermal, building integrity, air quality, and illuminance.

2.5. Data measurement

Objective data in the wards was collected using calibrated equipment with a precision of less than +/- 5%. For thermal performance parameters, a Temtop M100 (Temtop, China) which measured air temperature in ºC. For humidity (%) and velocity (m/s), an Anemometer was used (Major Tech, South Africa). Temtop M100 was used to collect air quality parameters which are, Particular matter (PM_{10} and $PM_{2.5}$), the Air Quality Index (AQI), and carbon dioxide in parts per million (PPM).

For Illuminance, an MT 942 LED Luminaire Light Meter (Major Tech, South Africa) was used to measure illuminance parameters in Lux. A digital Sound Level meter (Major Tech, South Africa) to collect acoustic parameters in decibels (dBA). For spatial data, a digital measuring tape (Major Tech, South Africa) was used in which ward sizes in meters and ward areas in square meters were measured. Building integrity performance, a building checklist was used to assess the quality of the wards in the central hospitals by the researcher.

2.6. Statistical methods

Analysis used R (R Core Team, 2022) with 0.05 as an indicator of statistical significance. For objective numerical data, median, mean, range, and standard deviation were computed and the Kruskal Wallis test was used to determine whether there was statistical significance between the medians of performance parameters in the central hospitals.

For subjective data, mean, median, mode, range, variance, and standard deviation were computed and the Chi-Square test was used to determine if the distribution of the data was statistically different.

2.7. International standards

The World Health Organization states that for patient ward rooms, the minimum light level is supposed to be 300 Lux (Bholasingh & Bholasingh, 2017), for acoustic levels in the wards, it states that it should not exceed 35 dB LAeq (World Health Organization, 2020). For Air quality parameters the WHO states that maximum $PM_{2.5}$ is 15 ug/m^3 and PM_{10} is 45 ug/m^3 and maximum carbon dioxide levels are 1260 mg/m^3 – 700 (American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE)., 2009). Air quality index standards is supposed to be between 0 and 50 (EPA, 2023). For thermal quality, the American Society of Refrigerating Engineers (ASHRAE) states that the range for the patient ward is supposed to be between 20 – 26 degrees Celsius (ASHRAE, 2003), for humidity, it is supposed to be between 30% and 60%. For spatial quality, the standard square meters per patient station is (7.43 square meters) and 1.52 meters between adjacent patient beds and a minimum clearance of 1.22 meters (Facility Guidelines Institute, 2014).

3. Results

3.1. Participants and demography

A total of 200 participants were recruited across all the central hospitals, of which 105 (52.5%) were nurses, 75 (37.5%) were doctors and 20 (10%) were hospital infrastructure managers. Out of the 200, 95 (47.5%) were diploma holders, 87 (43.5%) were educated to degree level, 16 (8%) had master's degrees and 2(1%) had doctorate degrees. On work experience, 65 (32%) had >5 years' experience, 46 (23%) had 3-5 years, 52 (26%) had 1-2 years, and 37 (18.5%) participants had worked for less than a year.

3.2. Acoustics

The objective acoustic quality range was between 22.1 dBA to 97.7 dBA and the median was 56.9 dBA. The acoustic quality in the hospitals was statistically different P-Value<0.001 (Figure 2). The subjective acoustic result shows that 79 (39.5%) participants agree that the noise quality in the central hospital is good, while 46 (23%) participants and 75 (37.5%) participants neither agree nor disagree, which means participants are satisfied with the quality of the sound in the wards with P-value >0.155, which means that the values are similar in all the central hospitals. Figure 3 shows the distribution of acoustic satisfaction levels in the central hospitals.

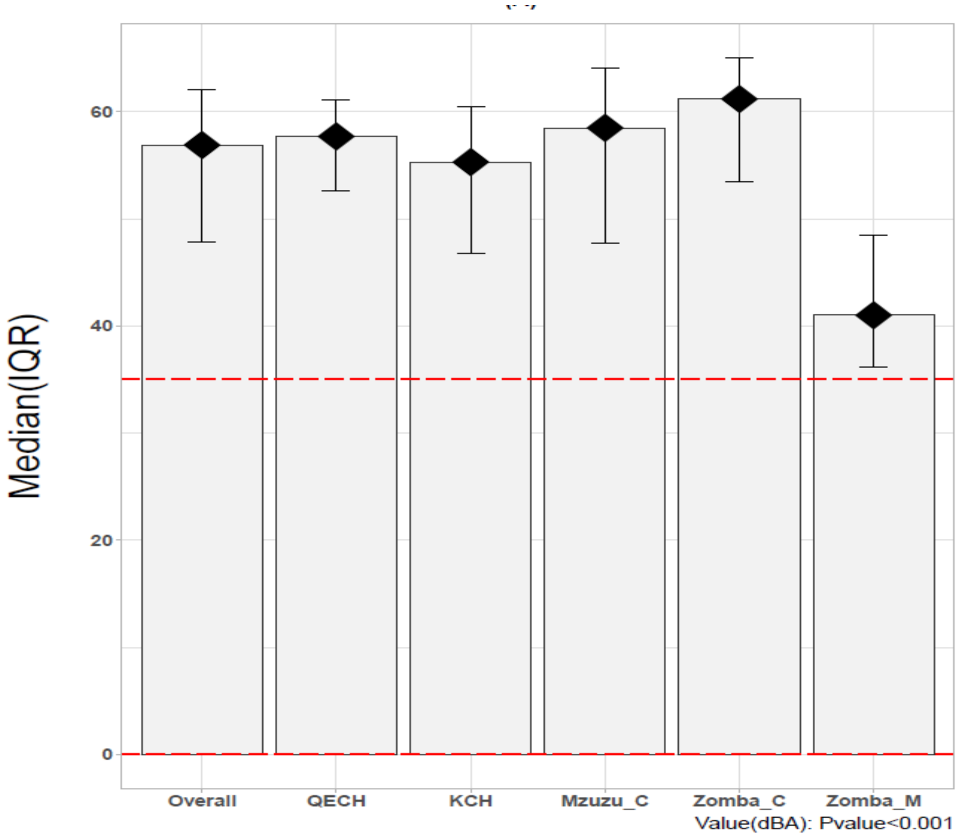

Figure 2: Violin and Box Plot Acoustic Quality

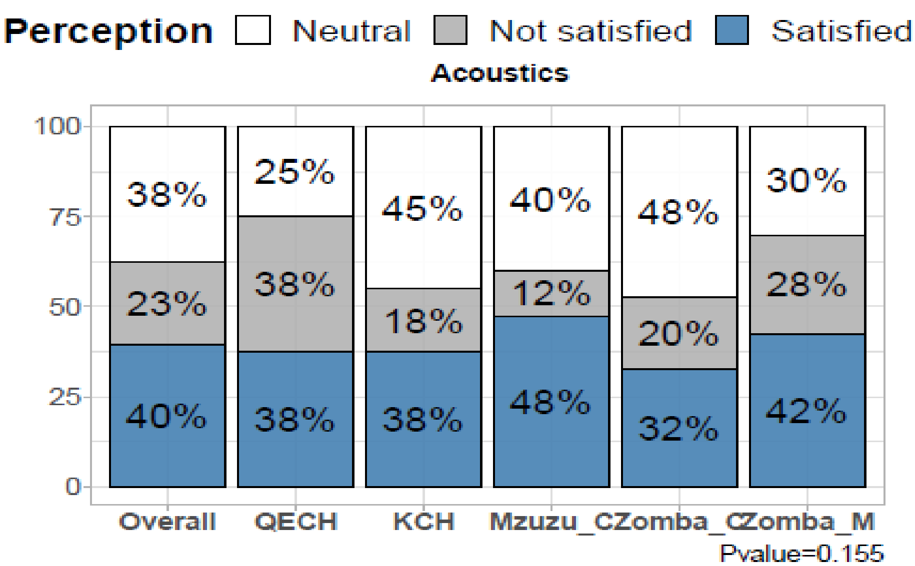

Figure 3: Subjective Acoustic satisfaction quality

3.3. Thermal quality

For objective thermal quality, the range of temperature was from 22.6 degrees to 36.8 degrees Celsius with a calculated median of 28.5. The humidity ranged between 33.1% to 84.6% with a median of 58.9 and air velocity ranged from 0 to 1.2 m/s. All the parameters were not within the standards. The P-value < 0.001, (Figure 4) shows statistical differences in the measured values in central hospitals. The subjective thermal results show that forty-six participants (23%) are satisfied with the thermal quality in the wards, eighty-eight (44.0 %) are dissatisfied with the thermal quality, and sixty-six (33%) are neither satisfied nor dissatisfied with the thermal quality, with calculated P-value = 0.055. The results show health workers are dissatisfied with the thermal quality. Figure 5 shows the distribution of thermal satisfaction levels in the central hospitals.

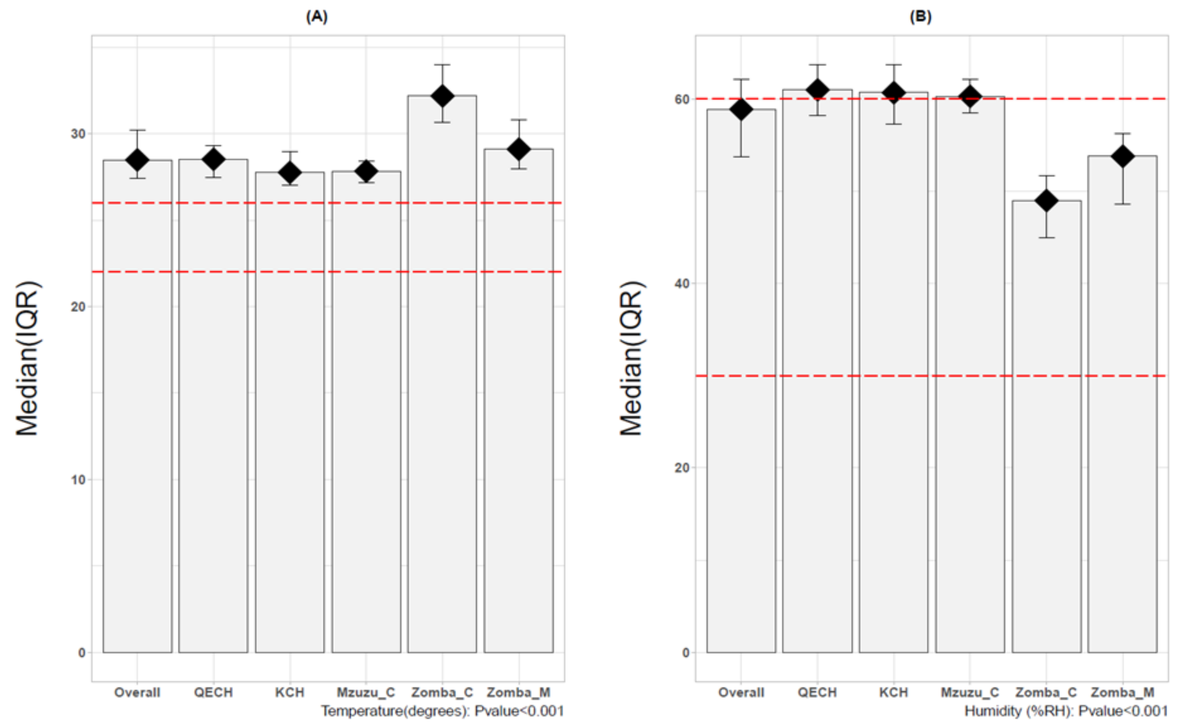

Figure 4: Box Plot for Thermal Quality

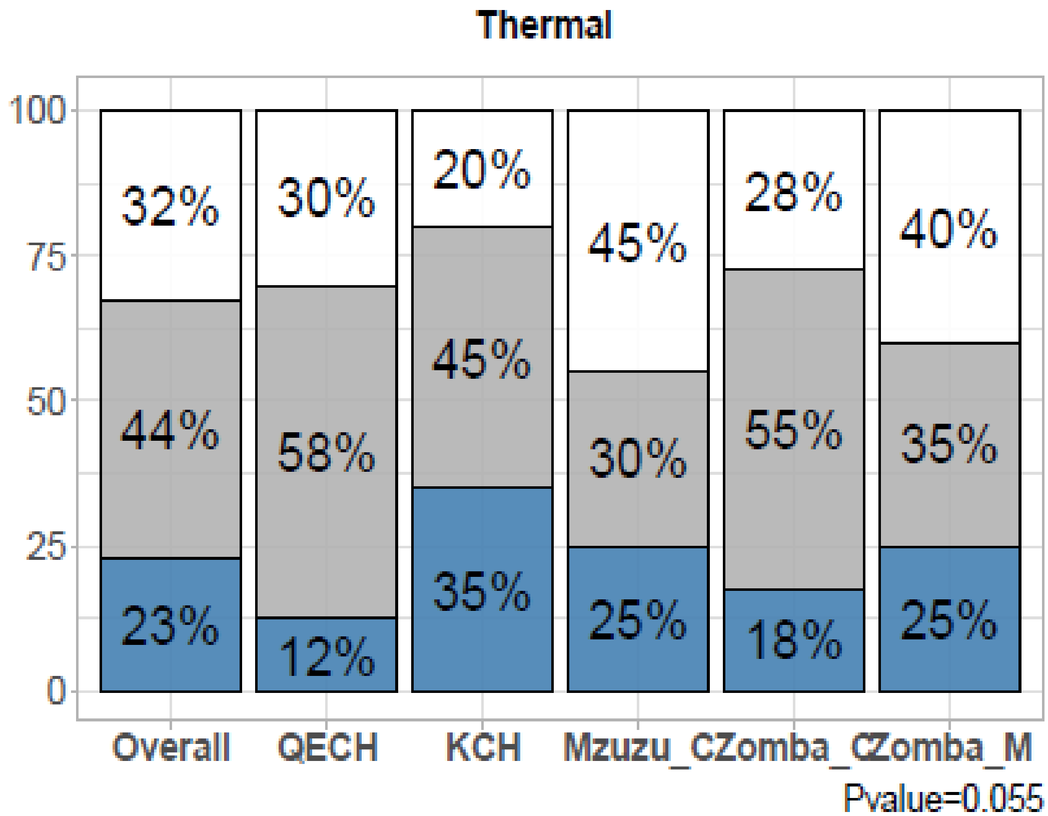

Figure 41: Subjective Thermal Quality Satisfaction Graph

3.4. Air quality

For objective air quality, the range for PM $_{2.5}$ was 0.6 ug/m^3 and 383.8 ug/m^3 and the upper and lower percentile was 16.1 ug/m^3 and 5.8 ug/m^3 with a median of 9.4 ug/m^3. The range for PM $_{10}$ was 0.9 ug/m^3 and 647 ug/m^3 respectively, the upper and lower percentile was 26.1 ug/m^3 and 9.5 ug/m^3 and the calculated median was 15.2 ug/m^3. The air quality index range was from 22 and 500, and the upper and lower percentile were 59 and 24 with a median of 41. The maximum and minimum range for CO_2 was 2109 ppm and 369 ppm respectively, the upper and lower percentile were 604 ppm and 467 ppm the median was 518 ppm. The PM $_{2.5,}$ PM $_{10}$, air quality index and carbon dioxide range are above the standards, however, carbon dioxide upper and lower percentiles are within the standards. The measured P-value< 0.001, which means the calculated values are different in all the central hospitals (Figure 6). The subjective air quality shows that seventy-nine participants (39.5%) are satisfied with the air quality in the wards, seventy-three (36.5 %) are not satisfied with the air quality, and forty-eight (24%) are neither satisfied nor dissatisfied with the air quality. The results show that the participants are satisfied with the air quality in the ward despite that objective measurement shows that the air quality is not meeting international standards. The subjective results are similar in all central hospitals as the P-value is 0.251 which is more than 0.005. Figure 7 shows distribution of air quality satisfaction levels in the central hospitals.

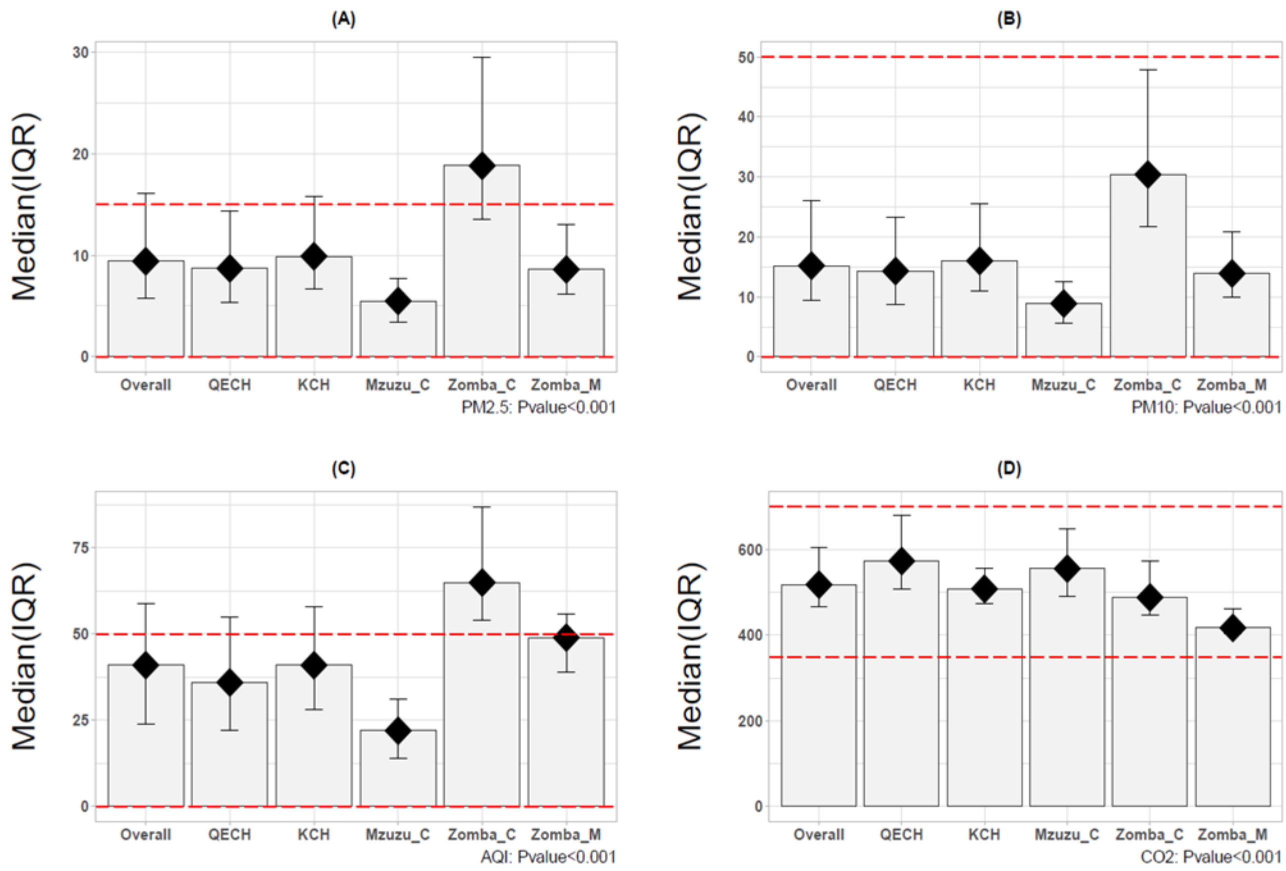

Figure 42 : Violin and Box Plot graph for Air Quality

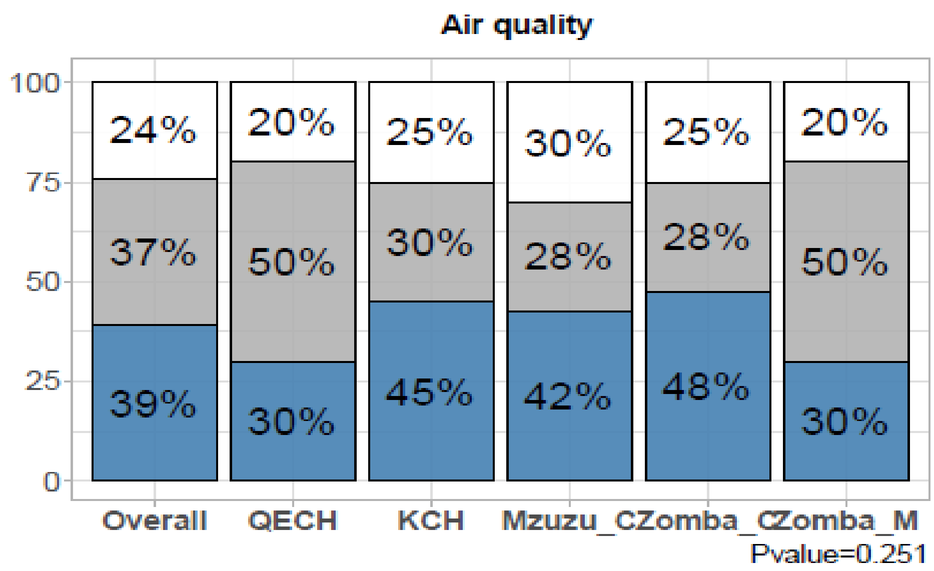

Figure 43: Subjective Air quality satisfaction Graph

3.5. Illuminance quality

For the night the range was between 10 Lux and 300 lux, for the day the objectively measured illuminance range was between 39.65 Lux to 1428 Lux. From 35 wards,19 wards met the international standards representing 54 percent and sixteen wards representing 46 percent did not meet the standards. For subjective illuminance quality, hundred 107 (53.5%) are satisfied with the illuminance quality in the wards, 45 (22.5 %) are dissatisfied with the illuminance quality, and 48 (24%) are neither satisfied nor dissatisfied with the illuminance quality, which means overall people are satisfied with the illuminance levels. There is no statistical difference in the subjective results of the central hospitals as the P-value is at 0.454, which means the results are the same in the central hospitals. Figure 8 shows the distribution of air quality satisfaction levels in the central hospitals.

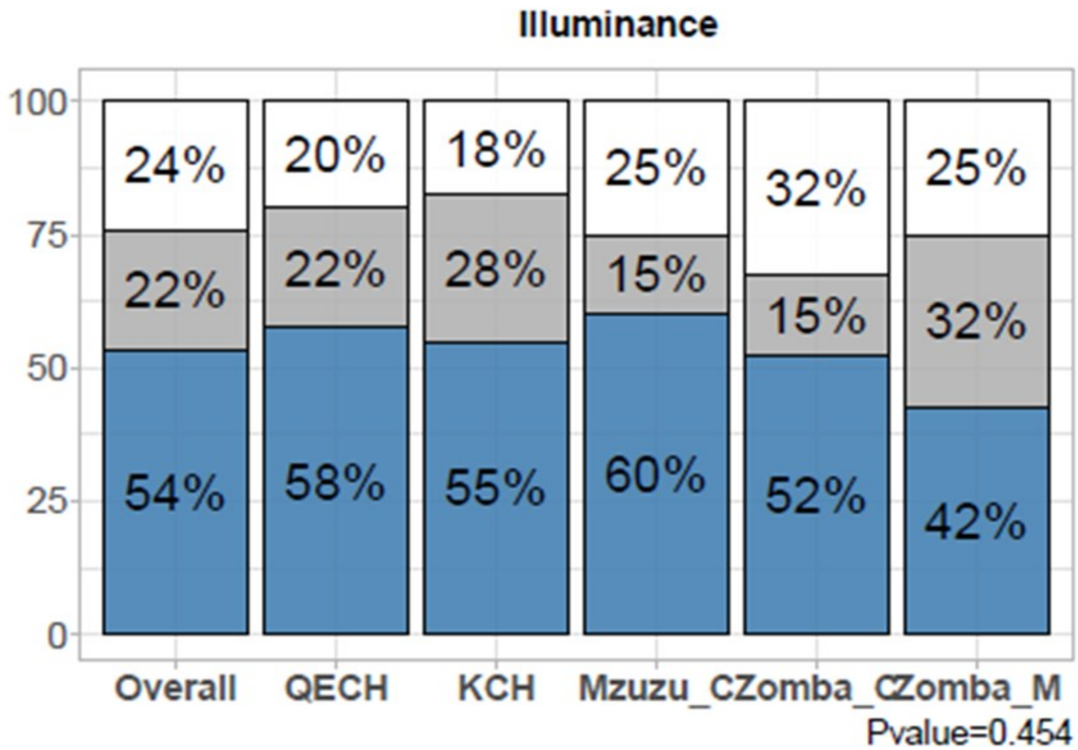

Figure 44: Subjective illuminance Quality satisfaction graph

3.6. Spatial quality

For spatial quality, 32 (91.4%) ward's bed space area was below the recommended space of 7.43 m^2 in which bed spaces were between 4 m^2 and 5 $m^{2,}$ and the measured average space between beds was 940 mm against the standard of 1200 mm. The subjective results show that Ninety-one participants (45.8%) are not satisfied with the spatial quality in the wards, thirty-eight (39%) are satisfied with the spatial quality, and thirty-two (15.4%) are neither satisfied nor dissatisfied with the spatial quality. The P-value is more than 0.199, which means that the values are similar in all the central hospitals. Figure 9 shows the distribution of spatial quality satisfaction levels in the central hospitals.

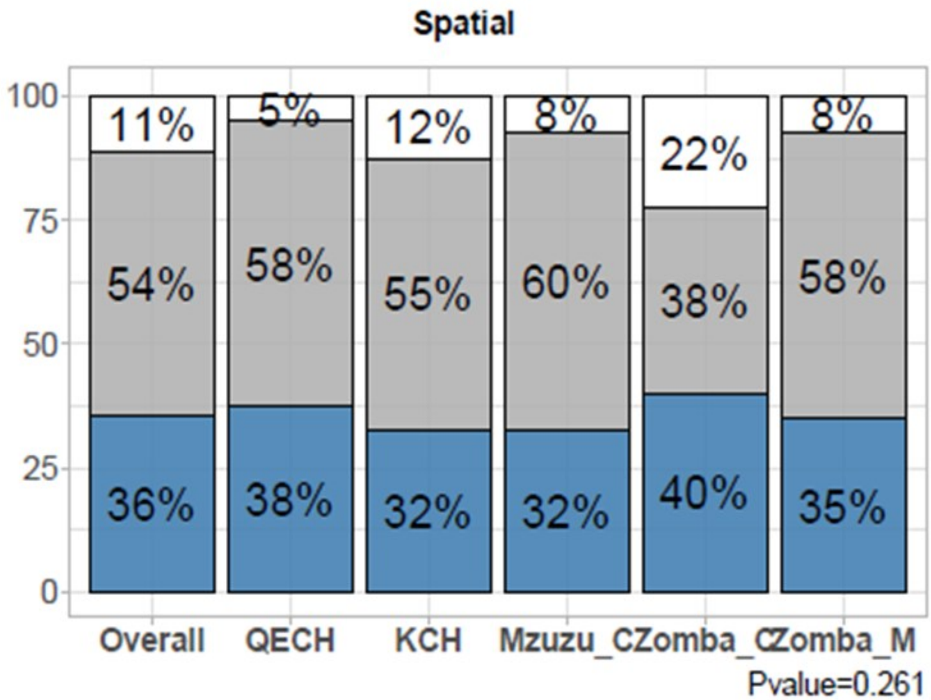

Figure 45: Objective Spatial quality satisfaction graph

3.7. Building integrity

Overall, the building integrity in Malawi's central Hospitals shows that the buildings are in good condition, however, there are some hospital wards in the central hospitals where defects were identified using the checklist. Zomba Mental Hospital tops the list with almost all the wards having defects. Hundred and eleven respondents (55.5%) are satisfied with the building integrity quality, forty-five (22.5 %) are dissatisfied with the building integrity, and forty-four (22 %) are neither satisfied nor dissatisfied with the building integrity. The results are similar in all central hospitals as the P-Value is 0.004 more than 0.001. Figure 9 shows the distribution of spatial quality satisfaction levels in the central hospitals.

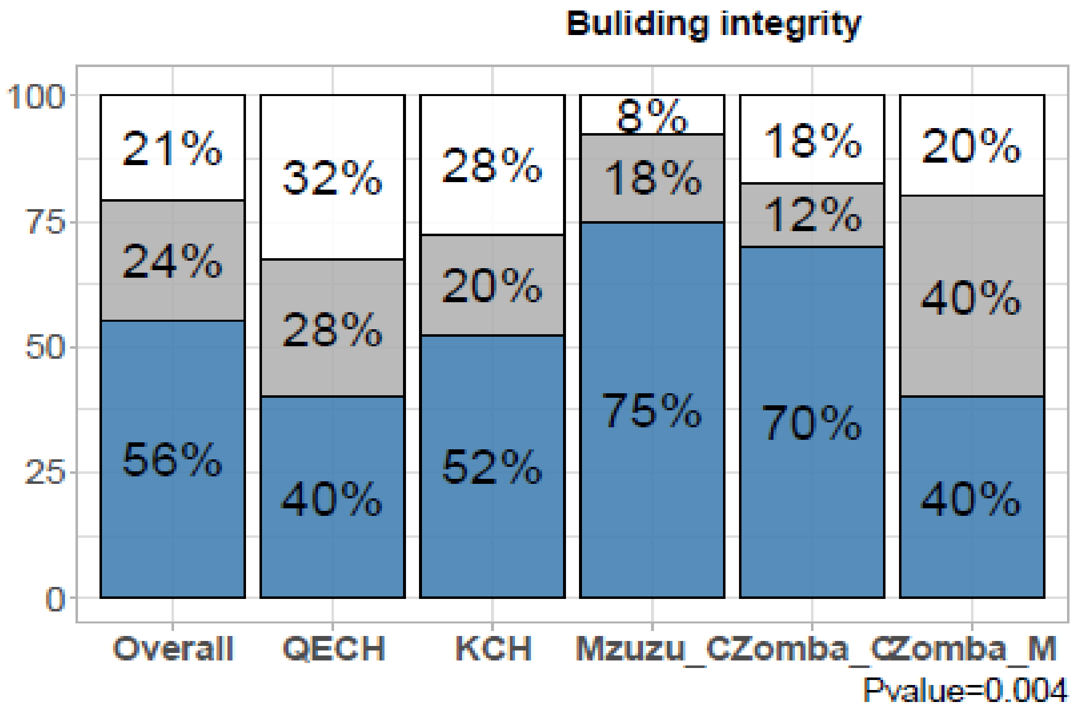

Figure 10: Building integrity quality satisfaction graph.

4. Discussion

The study is the first to be conducted in Central Hospitals in Malawi to comprehensively assess its quality and performance. The analysis has shown that the central Hospital infrastructures are not performing according to international standards which means the wards are not giving a good healing and working environment to our patients and health workers.

The higher acoustic results show that the patients, health workers, and guardians in Malawi's Central hospitals are exposed to hearing impairment, tinnitus, heart diseases, hypertension, annoyance, and birth defects (Rathnayake, Sridarran, & Abeynayake, 2020). Furthermore, high levels of noise lead to sleep deprivation, which is widely documented to impair immune function and healing in patients. Sleep deprivation can also result in an unregulated immune function with elevated inflammatory markers and decreased neuroendocrine regulation. People who are sleep-deprived are more depressed, likely to be Obese, hypertensive, dyslipidaemic, and diabetic (Oliveira, Gomes, Bacelar Nicolau, Ferreira, & Ferreira, 2015). The acoustic results are similar to other studies that have been conducted a study in a South African hospital found noise levels above WHO guidelines with participants thinking otherwise (Van Reenen, 2015), and in Pakistan's hospitals, noise levels were higher in public hospitals being higher (Baqar et al., 2018). University of Medical Schools in Iran found that the sound levels were higher with recordings of 60.24+/- 5.76dB on working hours and 58.1+/-5.44 (Mousavi & Sohrabi, 2018).

The higher thermal quality results also show that patients, guardians, and health workers are exposed to the effects of high temperatures in the wards. There is a high risk of bacteria spreading and compromising the safety of the patients because bacteria spreads when the temperature is not between 21°C and 24 ° and patients are subjected to the risk of damaging the antibacterial mucous layer of the respiratory because of accelerated breathing and sweating as the humidity is not within the range (Vijaykrishna & Balaji, 2023). The thermal results are similar to other studies conducted, a study in Nigeria's Hospital found a temperature range of 23.1 degrees to 33.1 degrees, and humidity the range of 41.2% to 68.2%, above (Alfa & Öztürk, 2019), another study in China found temperature ranges of 24.5 degrees to 26 degrees, and the range of humidity was 65% to 75%, with participants satisfied (Tang, Ding, Li, & Li, 2019a).

The results also show that the patients in the wards are subjected to high levels of $PM_{2.5}$. $PM_{2.5}$ induces cardiopulmonary disorders and impairments and has health effects that are, driving the initiation and progression of diabetes mellitus and eliciting adverse health effects its low levels within the standards still pose a public health hazard (Feng, Gao, Liao, Zhou, & Wang, 2016). The Air quality index is between 51 and 100, which is an acceptable standard, however, patients are sensitive, so there is a need for the air to be below 50 (Kumar & Yadav, 2021). The carbon dioxide in the central hospitals is within standards, like other studies conducted in hospitals. A study in Nigeria showed that the CO2 concentration levels that fall within acceptable limits ranged between 446.00 ppm and 608.00 ppm in April, 399 ppm and 442 ppm in May, and 393 ppm and 455 ppm in June (Ramli, N; Mohd Sobani, 2013). A study on an acute hospital revealed that carbon dioxide levels in hospitals were below 800 ppm (Ha et al., 2022).

The objective results for building integrity show that the hospital infrastructure is conforming to standards apart from wards whose defects identified include cracked floors, damaged windows, damaged ceilings, and damaged door locks. The results show that the health workers are satisfied with the building integrity quality in the ward and there is a correlation between the health workers' perception and the objective measurements.

The results are similar to other studies, for example, a study on Malaysian hospital buildings which assessed the building integrity of the hospitals found that the hospitals had defects (Jesumoroti, Olanrewaju, & Khor, 2022). The defects that were identified were cracked floors, floor tile failure, wall tile failure, blocked water closet, damaged windows, damaged ceilings, damaged door locks, faulty showers, and fans, however, the users of the central hospitals were satisfied with the quality of the hospitals.

With Illuminance quality not meeting standards the quality of healthcare is compromised as lighting quality in hospitals has a strong correlation with the quality of healthcare given to the patients (Leccese, Montagnani, Iaia, Rocca, & Salvadori, 2016), poor lighting will create a visual environment that does not allow people to see, move around safely, and perform visual tasks efficiently and accurately, and this can cause undue visual fatigue and discomfort. The results found are similar to other studies conducted on Hospitals, as a study in Iran on Hospitals found that the illumination levels in almost 56 percent of the wards did not conform to the standards (Dianat, Sedghi, Bagherzade, Jafarabadi, & Stedmon, 2013), in Nigeria, an assessment of infrastructure found that illuminance quality in the wards was above the standard recommended standards (Alfa & Öztürk, 2019) and another assessment of two hospitals in Nigeria recorded illuminance levels were below the minimum recommended levels for hospitals (Ramli, N; Mohd Sobani, 2013).

A study in a hospital in China found that the objectively measured illuminance levels in 60% of wards were below the illuminance standards of 300 Lux, but the satisfaction levels were high among the users which were above 80% (Tang, Ding, Li, & Li, 2019b).

With Spatial quality not meeting standards in Central Hospitals, it seriously impacts hospital functions, research has shown that it is the primary cause of admission and surgery cancellations, delays in emergency admissions, early patient transfers from intensive care units, delays in patient transfers between units and early patient discharges (Ravaghi, Alidoost, Mannion, & Bélorgeot, 2020).The results are similar to results from other studies, a study in a United Kingdom hospital found that the bed space areas were below recommendations with a bed space of 6.24 m^2 (Hignett & Lu, 2010), in a developing country of Nigeria found that the bed spaces were not sufficient for the patients to move around and for staff to treat patients (Alfa & Öztürk, 2019).

5. Limitations

The study has limitations, data was collected for only one month in all central hospitals. There is a need for a study to be conducted for a longer period to observe temporal variations due to weather. Secondly, the gadgets used were not enough, the gadgets were supposed to be collecting data in all the wards simultaneously, however, the collection was done in one ward per day. Thirdly the study was conducted only in the wards, there is a need for data to be collected in other rooms, for example, delivery rooms. Lastly, the study only collected perceptions from three groups of people, there is a need to collect from other users of the hospital.

6. Conclusion

The study has managed to use a concept called total building performance to assess the quality and performance of the central Hospital. This is the first study in Malawi and has provided much-needed data on the quality and performance of the central Hospitals in Malawi. The data will be used to improve the quality and performance of our central hospitals by informing policymakers on the gaps and coming up with policies that will ensure that there is continuous assessment of the hospital quality and performance and frameworks that will ensure that the hospitals are meeting the standards

7. Data and Software Availability

The sample size estimation and subjective and objective data analysis were conducted in R statistical software available at https: R-projec.org, version 4.04 using the power. prop.

8. Consent

The study was conducted according to the guidelines of the Declaration of Helsinki and the College of Medicine and Ethics Committee (COMREC) of Kamuzu University of Health Sciences approved the study protocol (P.10/22/3795). Informed consent was obtained from all participants involved in the study. To maintain the confidentiality of the participants, names were replaced with unique identification codes.

9. Author Contributions

Thokozani Mbewe: Conceptualization, data curation, formal analysis, writing- review and editing, formal analysis, funding acquisition, investigation, methodology, project administration, software, validation, visualization, writing-original draft, writing- review and editing

Kenneth Gondwe: Conceptualization, data curation, supervision, formal analysis, investigation, methodology, writing-original draft, writing- review and editing

Ignasio Ngoma: Conceptualization, data curation, supervision, formal analysis, investigation. Methodology, writing-original draft, writing- review and editing

James Jafali: Formal analysis, software, visualization, writing-original draft, writing- review and editing

Latif Ndeketa: Supervision, writing-original draft, writing- review and editing

Arthur M. Chiwaya: Writing- review and editing

10. Competing Interests

None

11. Grant Information

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Paper 25: Evaluating Potential Climate Change Impacts on Hydro-meteorological extremes of Shire River Basin in Malawi

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Abstract

The impacts of future climate change on the hydrological extremes of Shire River Basin (SRB) in Malawi was investigated. This was aimed at developing sustainable systems to address environmental degradation challenges and increase resilience to infrastructure in response to recurring natural disasters and climate adversities in line with the aspirations of Enabler number 7 of the Malawi 2063 vision. The SRB, which is very prone to hydro-meteorological disasters, was chosen as a case study due to its huge economic potential. The calibrated Hydrological Engineering Center's Hydrological Modelling System (HEC-HMS) hydrological model, driven by the downscaled Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCMs), derived the projected extreme streamflows for the basin. HEC-HMS model was chosen due to its simplicity, free availability and less demanding on input data. Evaluation of climate change impacts was done by comparing the future (2071-2100) and control (1961-1990) streamflows. Future streamflow was predicted to increase by 88.8% and decrease by 25%. These findings have potential to respectively bring about severe floods and droughts in some sections of the SRB in future. To mitigate against these anticipated negative impacts, a very strong policy statement is recommended. Water managers and policy makers must take keen interest on these research findings by reviewing the current practices regarding designs of hydraulic structures though modifications or reviews of design parameters and strongly investing in the acquisition of hydrometeorological data by relevant ministries so that future research should be based on empirical data as opposed to models.

Key Words: CMIP5, Extremes, GCMs, HEC-HMS and Hydrological

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1. Introduction

The increase in extreme precipitation has contributed to increase in severe flooding events in certain regions (Centers for Disease Control and Prevention, 2024). Floods are the second deadliest of all weather-related hazards around the globe, most due to drowning. Climate change is a possible cause of extreme hydrologic events such as floods, droughts, and heat waves (Bai et al., 2019). The influence of climate change on hydrological events is substantial and could further affect runoff and flow in river systems (Meenu et al., 2013). Climate change may result in increased variability in rainfall intensity in the future, leading to more frequent flooding and a substantial loss of lives (Bai et al., 2019). Better understanding of climate change and flood events nexus is needed to design proper flood control facilities to mitigate against the impact from flooding events. According to Bai et al., (2019), water resources projects are often intended to have long expected lifespan, and understanding the uncertainty and risks of floods associated with climate change provides a scientific basis to better design, construct, and operate these projects in the long run. Therefore, it is essential to evaluate the impact of climate change on hydrological extremes.

Recently, climate change impact studies have been given greater attention worldwide (Taye et al., 2011a). The Intergovernmental Panel on Climate Change, (2013c) observed that water resources ought to receive special attention since they are very vulnerable to change in climate. Liu et al., (2018) observed that when long-term hydrologic records are obtained, frequency analysis is employed to predict frequency and magnitude of floods. However, for ungauged basins where long-term hydrologic records are not available, hydrological models are often used to estimate flood frequency and magnitude. Hydrological models are also used to simulate floods for variable basins from changing climate (Huang et al., 2019). The use of hydrological models has gained momentum globally, owing to their ability to provide answers for water resources management, water system design, real-time forecasting and flood design, among others. Khadka & Bhaukajee (2018) noted that floods are possibly the most frequent, widespread and disastrous hazards of the world. The most affected are developing countries owing to their low levels of resilience due to poor socio-economic conditions and haphazard settlements. Accordingly, it becomes a challenge to predict and properly design flood control structures and develop mitigation measures. The situation is even worse if prediction for future behaviour is to be taken into account.

Enabler 7 of Malawi 2063 vision has put environmental sustainability as being central in ensuring sustainable development in Malawi (National Planning Commission, 2020). However, the advent of natural disasters and climate adversities, which often emanate from climate change induced extremes, often pose a challenge. Knowledge of magnitude of these extremes is crucial in developing strategies for disaster risk reduction. In addition, Sustainable Development Goal (SDG) number 13 urges all countries across the world to take urgent action to combat climate change and its impacts. This can be achieved by strengthening resilience and adaptive capacity to climate-related hazards and natural disasters and integrating climate change measures into national policies, strategies and planning. In order to achieve all these, knowledge of how climate will change the environment is very crucial.

Hydrological modeling is effective for analyzing and simulating hydrological processes. Kaspar, (2004) noted that a good performing hydrological model is very crucial in the estimation of the hydrological impacts of climate change. Taye et al., (2011) used Nedbør-Afstrømnings-Model (NAM) and Veralgemeend Conceptueel Hydrologisch (VHM) conceptual hydrologic models to investigate the potential impact of climate change on the hydrology and hydrological extremes of Nyando River and Lake Tana catchments, in Ethiopia. The hydrological impact of possible future climate change in Gilgel Abbay catchment (Ethiopia) was investigated by Shaka (2008) using the Hydrologiska Byråns Vattenbalansavdelning (HBV) hydrological model. Daba & Rao, (2016) used the Soil and Water Assessment Tool (SWAT) to assess the impact of climate change on the hydro climatology of Finchaa Sub-basin located in upper Blue Nile Basin of Ethiopia. Khadka & Bhaukajee, (2018) developed Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS) and Hydrologic Engineering Centre's River Analysis System (HEC-RAS) models for Kankai River basin of Nepal and Kävlinge river basin of Sweden to analyze the effects of rainfall on surface runoff and peak discharges of these rivers and ultimately produce flood inundation levels to assess the flood risks in both areas. In Malawi, SWAT was used to assess how climate and land use change affect the flow regime of Wamkurumadzi River, a key tributary of the major Shire River in southern Malawi (Nkhoma et al., 2021). Bui (2011) simulated streamflow for different climate change scenarios for the Rio Grande watershed above Elephant Butte Dam in New Mexico to estimate future average streamflow using the Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) model. Girma et al., (2009) inputted the downscaled meteorological variables corresponding to global emissions scenario (A2a) into HEC-HMS hydrological model calibrated and validated with observed station data to simulate the corresponding future streamflow changes in the Beles River, Ethiopia. Al-Safi & Sarukkalige, (2017) evaluated the impacts of future climate change on the hydrological response of the Richmond River Catchment in New South Wales (NSW), Australia, using the conceptual rainfall-runoff modeling approach (the Hydrologiska Byrans Vattenbalansavdelning (HBV) model).

The foregoing has clearly demonstrated that climate change impacts on the hydrology of different catchments has been extensively studied across the world including Malawi e.g. Nkhoma et al., (2021). Similar studies for Shire River Basin (SRB) in Malawi, which is very prone to many hydro-meteorological disasters, despite having huge economic potential, are lacking. This study proposed a framework to investigate the potential climate change-impacts on the hydro-meteorological extremes of SRB. It aimed at quantifying the possible effects of possible future climate change on the hydrological extremes of the basin based on the downscaled climate scenario data using the already calibrated and validated HEC-HMS model. The quantification of the impacts is expected to address environmental degradation challenges and increase resilience to infrastructure in response to recurring natural disasters and climate adversities in line with the aspirations of Enabler number 7 of the Malawi 2063 vision. This was achieved by developing an integrated model composed of the HEC-HMS hydrologic model and CMIP5 climate change model. The focus was on the projected peak discharges of this river and ultimately assessment of flood risks in the basin.

2. Data and methods

2.1. Study area

The study area is Shire River Basin (SRB) - Figure 1. The basin lies between 9° and 20° S; and 18° and 36° E, at the southern extreme of the East African Rift System (Banda et al., 2020). The SRB was chosen because its hydrological system represents Malawi's biggest and most important water resource system that supports significant socio-economic activities. The SRB drains much of Southern Malawi and receives the sole outflow of Lake Malawi whose catchment extends over much of Central and Northern Malawi (Tanzania and Mozambique) (Banda et al., 2020). The river flows approximately 400km from Mangochi on the southern extremity of Lake Malawi, to Ziu Ziu in Mozambique at the confluence with the Zambezi River (MoAIWD, 2016). The entire Shire river catchment area is 22,621km^2 and is divided into the upper, middle and lower sections. The area was delineated using ArcGIS ArcMap 10.8. The SRB faces a growing threat of environmental degradation stemming from developmental pressures such as rapid population growth (about 3% per annum), urbanization, and industrialization and increasing waste among others from both countries of Malawi and Mozambique. The area is vulnerable to climate change with frequent flood and drought extreme occurrences (Coulibaly et al., 2015). This situation leaves both the quantity and quality of water resources to be at risk.

The dominant climate in the basin is tropical savannah with distinct dry and wet seasons. Rainfall is influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ). Peak rainfall occurs between December and March, and may exceed 1000 mm/annum in the high escarpment. Temperatures in the basin vary with altitude. During the cold season from May to August, the temperatures go as low as 15ºC -18ºC. Mean annual temperature is approximately 24ºC. In hot seasons, temperatures go as high as 45ºC in the basin, especially in the lower sections.

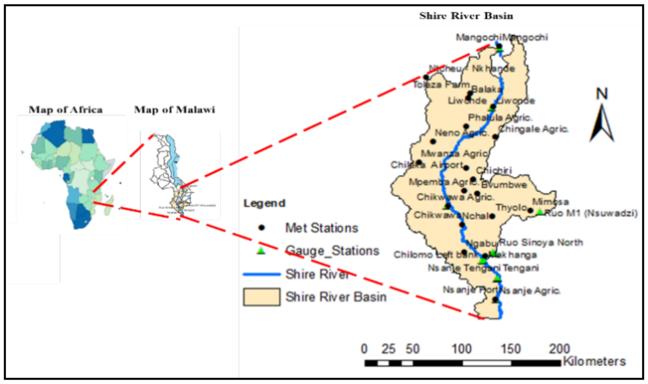


Figure 46: Shire River Basin showing meteorological stations and streamflow gauges used in the study

2.2. Data

Data for Hydrological modelling

The categorization of input data needed for rainfall-runoff modelling can be grouped into meteorological (rainfall and stream flow) and physiographic (Digital Elevation Model (DEM), land use/ cover and soil type). Essential data required to build the HEC-HMS model are elevation, land use/cover, percent impervious area, soil, and hydrograph information. These datasets were used to determine stream/sub-basin characteristics and hydrologic parameter estimations. The basic information on physiographic characteristics of the catchment (elevation and slope) was extracted from a 50m × 50m resolution Shuttle Radar Topography Mission (SRTM) DEM of the Shire River Basin, which was freely downloaded from the web. The Geographic Information System (ArcGIS ArcMap 10.8) interface of the HEC-GeoHMS model was used to further process the DEM data. Terrain pre-processing and basin processing tools were used to generate the characteristic parameters of the basin and input files for HEC-HMS.

Data for future streamflow prediction

Thirty years (2071-2100) of statistically downscaled climate model data of precipitation under RCP 4.5 emission scenario were used. This involved the dataset from CMIP5 scenarios called Representative Concentration Pathways (RCPs), which cover the period of 1850 to 2100. From the plethora of models available in CMIP5 GCMs, this study used five models namely ACCESS1-3_r1i1p1, BNU-ESM_r1i1p1, CSIRO-Mk3-6-0_r3i1p1, CSIRO-Mk3-6-0_r8i1p1 and GFDL-ESM2G_r1i1p1. The statistically downscaled daily precipitation data that was integrated in the models.

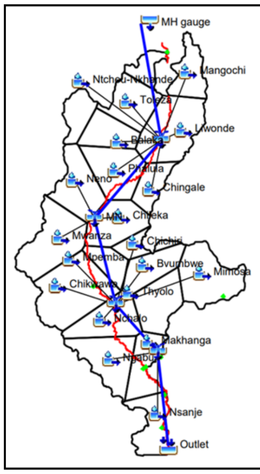
2.3. HEC-HMS Model

The HEC-HMS model is a hydrological model designed to simulate the rainfall-runoff processes of dendritic watershed systems (U.S. Army Corps of Engineers, 2016). To construct a watershed model, the hydrologic cycle is separated into manageable pieces and boundaries around the watershed of interest. HEC-HMS has since become a standard hydrologic model for drainage design and the evaluation of impacts of land use on flooding events in the USA (Singh & Woolhiser, 2002). In this study, HEC-HMS 4.8 was used owing to its simplicity and less demanding on input data hence appropriate for data scarce regions such as Malawi.

Model set up

The methodology used for carrying out rainfall-runoff modelling can be described by creating the basin model, developing hydrological parameters and carrying out the actual hydrological modelling. ArcMap 10.8 version of ArcGIS was used to create the model basin. Using the meteorological stations, the Thiessen Polygon toolkit in ArcMap was used to create polygons around each meteorological station and these polygons were eventually used as subbasins Figure 2. Since simulations in HEC-HMS only cares about the interconnectivity of basin elements, the schematic layout of the basin elements is also shown in Figure 2. In setting up the model, a total of nine different loss methods are provided in HEC-HMS both for events and continuous simulation. The physical representation of a watershed is accomplished with a basin model. Hydrologic elements such as subbasin, reach, junction, reservoir, diversion, source, and sink are connected in a dendritic network to simulate runoff processes. Computation proceeds from upstream elements in a downstream direction. Methods such as SCS curve number, exponential, Green Ampt, and Smith Parlange, deficit constant, soil moisture accounting, initial constant, Green Ampt, SCS curve number, and soil moisture accounting are used to simulate infiltration losses. Canopy and surface components can also be added when needed to represent interception and capture processes. Clark, Snyder, and SCS techniques are used to transform excess precipitation into surface runoff. In terms of baseflow, five methods are included for representing baseflow contributions to subbasin outflow. Channel flow is simulated using nine routing methods. Water impoundments and diversions can also be represented in the model. To account for the loss, transform and flow routing, the methods used in this study are Deficit and Constant, Clark Unit Hydrograph and Muskingum were respectively.

HEC-HMS has been applied to assess runoff, simulate hydrologic events and forecast flooding in many regions across the globe. Guduru et al., (2023) used HEC-HMS to model the streamflow and predict flood in the Meki watershed in Ethiopia. The assessment of the performance of HEC-HMS model in a data-scarce high-humidity tropical catchment in Tanzania yielded superior results (Tibangayuka et al., 2022). (HEC-HMS) model was applied to simulate runoff in the ten gauged and ungauged Upper Manyame sub-catchments in Zimbabwe (Gumindoga et al., 2017). The HEC-HMS simulation of surface runoff for the Gilgel-Abay Catchment (1609 km^2), Upper Blue Nile Basin, Ethiopia, showed the appropriateness of the model in simulating rainfall-runoff processes for the basin (Tassew et al., 2019). The calibration of HEC-HMS for the upper Blue Nile River Basin was satisfactory and acceptable for simulation of runoff for the catchment (Gebre, 2015). Derdour et al., (2017) used HEC-HMS to simulate rainfall RR in the semi-arid region of Ain Sefra watershed in Algeria, and results showed close reproduction of the observed values by the simulated peak discharge. Using HEC-HMS, a flood estimation model was developed for Wadi Ressoul in the El Berda watershed, north east of Algeria and the model performance evaluation indicated a close approximation between the observed and simulated floods (Skhakhfa & Ouerdachi, 2016). In order to develop a Flood Early Warning System (FEWS) that will alert downstream communities of imminent flooding for communities in the downstream region of the Manafwa River Basin in eastern Uganda, which have been experiencing floods caused by heavy precipitation upstream, HEC-HMS was developed to accurately predict the peak hydrograph caused by the precipitation event which had occurred in the upstream (Kaatz, 2014). In the Deduru Oya River basin in Sri Lanka, a continuous RR modeling was done to estimate runoff in the basin, using HEC-HMS (Sampath et al., 2015).



No	Name of subbasin	Shape Area (km^2)
1	Makhanga	937.690
2	Bvumbwe	888.332
3	Mpemba Agric.	562.112
4	Nchalo	1199.501
5	Nsanje Agric.	930.962
6	Ngabu	1313.977
7	Mimosa	1546.018
8	Chichiri	406.792
9	Thyolo	1126.857
10	Neno Agric.	1271.269
11	Mwanza Agric.	1709.792
12	Chikwawa Agric.	2133.295
13	Balaka	835.668
14	Mangochi	1220.548
15	Liwonde	1789.288
16	Toleza Farm	1045.660
17	Phalula Agric.	1285.616
18	Chilcka Airport	1152.160
19	Chingale Agric.	650.076
20	Ntcheu - Nkhande	615.913
Total		**22,621.53**

Figure 47: The Shire River Basin model showing the schematic layout of the basin elements

Model calibration and validation

A credible hydrological model can be achieved after being calibrated and validated against the observed streamflows. The simulated streamflow must be compared with the observed streamflow to evaluate the goodness of fit and conclude whether the model is able to predict and present credible results (Ouédraogo et al., 2018). Calibration is the process of adjusting the model parameters within reasonable ranges until the simulated results are close enough to the observed values (Zeckoski et al., 2015). Validation, on the other hand, is the process of ensuring that the calibrated model is capable of reproducing a set of observations or predicting future conditions without any further adjustment to the parameters (Zheng et al., 2012). Validation attempts to examine the ability of the calibrated model to mimic the observed but also to predict streamflow outside the calibration period. During model validation, a set of data, different from the one used for calibration, is used. The schematic representation of calibration process is shown in Figure 3.

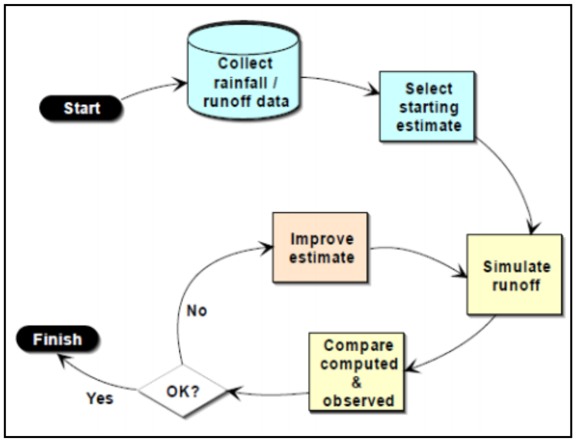


Figure 48: The schematic of calibration procedure. Source: (Feldman, 2000)

In this study, calibration was done to simulate streamflows at the outlet (Chiromo gauge stations indicated as Nsanje port). Values of different parameters were adjusted until a good calibrated model was obtained. This was aimed at making the simulated streamflow data match the observed streamflow data in terms of peak value, shape of the curve, and time of peak, while keeping changes of the parameters in a reasonable range. Optimization trials were implemented to improve calibration results. From literature, the mostly-used parameters for HEC-HMS simulation were identified. The process of validation followed that of calibration using the same input parameters as used by the calibration process but with different simulation period. Calibration was done for 20 years period (1961-1980) and 10 years period (1981 – 1990) for validation. To check the performance of the calibrated model, the Nash–Sutcliffe Efficiency (NSE) was used. If Q_{obs} is the observed streamflow, Q_{sim} the simulated streamflow and Q_{sim} bar the mean of observed streamflow, NSE is given by:

$$NSE = 1 - \frac{\sum (Q_{obs} - Q_{sim})^2}{\sum (Q_{obs} - \overline{Q_{0bs}})} * 100$$

Nash-Sutcliffe efficiencies can range from -∞ to 1. An efficiency of 1 corresponds to a perfect match of modelled streamflow to the observed data. An efficiency of 0 indicates that the model has the same predictive skill as the mean of the observed data in terms of the sum of the squared error, whereas an efficiency less than zero occurs when the observed mean is a better predictor than the model. The closer the model efficiency is to 1, the more accurate the model is (Nash & Sutcliffe, 1970). In addition, peak streamflow, peak time, and shape of the hydrograph were also examined visually to assess the model performance.

Climate change hydrological impact analysis

After successfully calibrating and validating the HEC-HMS model, with the historical record, the simulation of streamflows in the basin using the downscaled precipitation, as input to hydrological models, was done using the downscaled precipitation as input to calibrated HEC-HMS model for the 30 years of end century period, 2071-2100. The potential of using HEC-HMS in projecting climatic data to simulate future streamflows, has already been demonstrated in many catchments.

After calibrating and validating the HEC-HMS model, climate change impact on streamflows was evaluated by using the statistically-downscaled climate model data of precipitation, for the SRB as input to the calibrated/validated HEC-HMS model to examine the general catchment streamflow responses in the future years. The analysis was executed daily for streamflow. This was done using the downscaled precipitation data for each emission scenarios discussed in the previous sections. This approach was undertaken assuming that the watershed would behave similarly in future as it did during the calibration and validation period. This stage involved inputting the downscaled precipitation, resulting from given scenarios of future climate, into the calibrated and validated HEC-HMS model for hydrological impact assessments. All five models were used in the simulations thereby yielding five different outputs. The objective was to simulate streamflows for the future climate. The 30-year projected climate change scenarios were used. Figure 4 shows the simple conceptual framework illustrating the procedure that was used (especially the part circled RED).

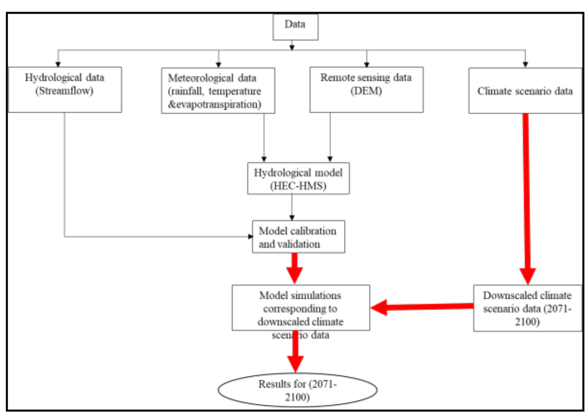


Figure 49: Simple conceptual modelling framework. Source: Shaka (2008)

From the constructed future precipitation scenarios, the perturbed series were then used to drive the calibrated and validated HEC-HMS model for the basin.

3. Results and discussions

This section summarizes results for streamflows induced by climate change.

3.1. Calibration

Table 1 gives a summary of the calibrated HEC-HMS model parameters and the simulated and observed streamflows are illustrated by hydrographs in Figure 5. There is a reasonably close agreement in terms of peak values and an acceptable agreement in terms of streamflow distribution, evidenced by the shape of the hydrographs (Figure 5). However, the model is observed to overestimate low flows in almost all the years. HEC-HMS modelling stringently simulates precipitation-runoff (USACE, 2016). Even though the model does not consider water withdrawal for irrigation, inputs from artificial tributary sources, it takes into account inflow from other sources nonetheless. Due to the foregoing, the modeled volume is higher than the observed volume. This is because the Shire River has a constant inflow, averaging 480m^3/s, outflowing from Lake Malawi, which is the source. This constant inflow was considered in the model. Water being abstracted from Shire River by Illovo at Nchalo, BWB at Walkers Ferry, SRWB in Liwonde and other irrigation activities spearheaded by the Greenbelt initiatives, was not accounted for in the model. Despite existence of an artificial control of water through the barrage at Liwonde, this too was not considered in the modelling because the barrage does not divert water; it only controls the timing of flow through the barrage, and eventually, all water finds its way to the outlet.

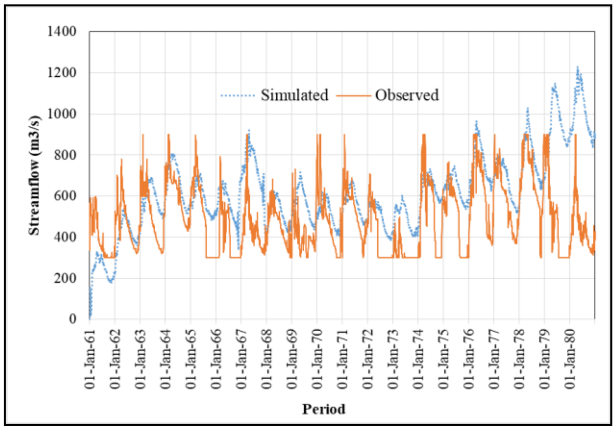


Figure 50: Observed and simulated hydrographs for calibration

Table 19 Calibrated model parameters

		Subbasin																				Reaches				
		Liwonde	Phalula	Mangochi	Toleza	Balaka	Chingale	Nkhande	Mwanza	Neno	Chileka	Mimosa	Chikwawa	Nchalo	Thyolo	Mpemba	Bvumbwe	Chichiri	Ngabu	Makhanga	Nsanje	Rch1	Rch2	Rch3	Rch4	Rch5
Model	**Parameter**																									
Canopy	Maximum storage (mm)	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6					
	Crop coefficient	1	1	1	1	1	1	1	1	1	1.5	1.5	1.5	1.5	1.5	1.5	1	1	1.5	1.5	1.5					
Surface	Initial storage (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
	Maximum storage (mm)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20					
Loss	Maximum deficit (mm)	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500					
	Constant Rate (mm/hr)	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6					
	Impervious (%)	18	18	18	8.5	13	8.5	4	8.5	4	18	18	4	4	13	13	13	27	3	3	3					
Transform	Time of concentration (hr)	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500					
	Storage coefficient (hr)	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150					
Baseflow	Initial Discharge (m^3/sec)	0.3	0.3	0.25	0.25	0.25	0.25	0.3	0.3	0.3	0.2	0.25	0.3	0.3	0.25	0.3	0.3	0.3	0.25	0.25	0.25					
	Recession constant	1	1	1	1	1	1	1	1	1	1	1	1	1	0.8	1	1	0.8	0.7	0.7	0.7					
	Ratio to peak of baseflow	0.25	0.2	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.2	0.5	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.3					
Routing	Initial Discharge (m^3/sec)																					0	233	0	0	0
	Muskingum K (hr)																					150	150	150	150	150
	Muskingum X																					0.5	0.5	0.5	0.5	0.5

These results have shown that the deficit and constant loss method, Clark Unit Hydrograph method and exponential recession method, are the best fit performed methods of the hydrological processes of infiltration loss, direct runoff transformation and baseflow part of the HEC-HMS model for the basin. The NSE of 72% also suggest that good performance of the HEC-HMS model was obtained according to model performance rating by Moriasi et al., (2007).

The deficit and constant and Clark Unit Hydrograph methods has been widely used in several studies. Gebre, (2015) indicated that deficit and constant loss method and exponential recession method was the best fit for the Upper Blue Nile River Basin. It was also noted by Straub et al., (2000) that the Clark unit hydrograph method is commonly applied for hydrologic designs. In addition, Banitt, (2010) used the HEC-HMS with the Clark unit hydrograph method to transform the rainfall into runoff to generate 100-year simulations of natural, existing and alternative operation plans for the Salt River watershed, in the Mississippi River basin. The results from the HEC-HMS model filled the actual stream gauge data gaps. All sub-catchments in Rio Rancho area in Central New Mexico were modelled by Schoener, (2010) using the HEC-HMS model that, performed using the Clark unit hydrograph method. With the low imperviousness, the peak flow rates were significantly higher. The Clark unit hydrograph method also could be used to estimate runoff in tropical watersheds as it provides reasonable output compared to other methods such as SCS-CN. In terms of the loss method, the deficit and constant method was tested in the application of the HEC-HMS model for runoff simulation in a tropical catchment such as the SRB and was found to be a better option than other methods such as the SCS CN method (Halwatura & Najim, 2013). Clark unit hydrograph transformation method, and recession base flow method of the HEC-HMS model were used in the flow estimation from tropical catchment of Deduru Oya River Basin, Sri Lanka and simulation results were found to be satisfactory (Sampath et al., 2015).

To appreciate the monthly variation of simulated flows during calibration period, the mean monthly flows for both the simulated and observed flows were plotted. These have been illustrated in Figure 6.

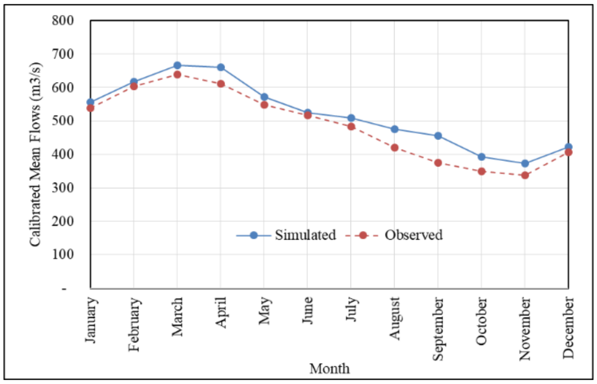


Figure 51: Simulated and Observed Mean monthly flows

From Figure 6, the mean monthly flows for both the simulated and observed flows again show a reasonably close agreement in terms of peak values and an acceptable agreement in terms of streamflow distribution. Evidently from the hydrographs, the simulated flows have somehow over-estimated the observed throughout the simulation horizon especially from April to December.

In order to assess the quantitative measures for the skill of simulations during calibration, the Nash–Sutcliffe Efficiency (NSE) was used. According to the results and based on the recommended performance evaluation rating by Moriasi et al., (2007), the NSE of 72% suggest good performance of the HEC-HMS model was obtained in simulating the peak flows with deficit and constant loss and transform methods. These findings demonstrate that the model is satisfactory and acceptable to simulate the basin runoff for future projections well. However, in order to increase the performance of the model in simulating the runoff with these combinations, it is better to develop the local and regional parameter values of the catchment instead of using the tabulated standardized values and to identify regional valid unit hydrographs.

3.2. Validation

The validation results are illustrated in Figure 7 and Table 2. There is relatively consistent flow pattern between the simulated flows at the outlet station with that during calibration. The timing of the simulated peak flows are also generally in agreement with those of the observed flows. Considering the Nash–Sutcliffe Efficiency (NSE) criteria, satisfactory results were obtained between the simulated and observed values, with a mean NSE value of 69%. Despite the above shortcomings, and based on the recommended performance evaluation rating by Moriasi et al., (2007), the NSE of 69% suggest good performance of the HEC-HMS model outside the calibration period. This also suggests that the calibrated model can be applied to catchments of similar physiographic qualities to the SRB. The general simulation results for validation has demonstrated the possibility of getting a good performance of the HEC-HMS model in predicting the peak flow in the SRB even outside the calibration period. Credible simulation results of the peak flow in the HEC-HMS model containing a combination of different loss and transform methods were also obtained by Majidi & Shahedi, (2012) and Yilma & Moges, (2007).

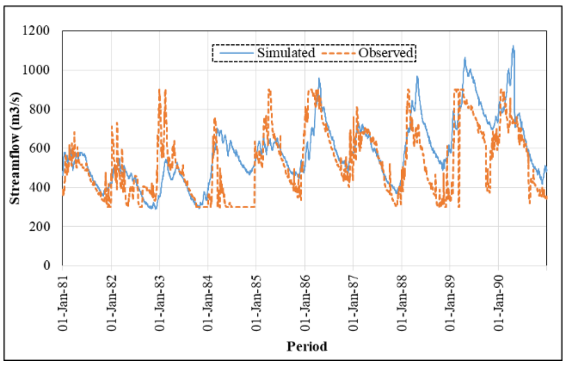


Figure 52: Observed and simulated hydrographs for validation

3.3. Future streamflow simulations

The calibrated HEC-HMS model was forced with the downscaled future climate signals to simulate the future daily streamflow at Chiromo gauging station for the late periods of the 21st century for the RCP4.5 climate scenarios. A time interval of 30 years period (2071-2100). Results of the simulated streamflows are illustrated in Table 2 and Figure 8.

Table 20: Climate Change-induced future streamflows

GCM Run	Peak Discharge (m^3/sec)	% Change in Peak Discharge (m^3/sec)
OBSERVED	900.00	
ACCESS1-3_r1i1p1	951	6
BNU-ESM_r1i1p1	673.4	-25
CSIRO-Mk3-6-0_r3i1p1	1699.2	89
CSIRO-Mk3-6-0-r8i1p1	1489.2	65
GFDL-ESM2G_r1i1p1	732.5	-19

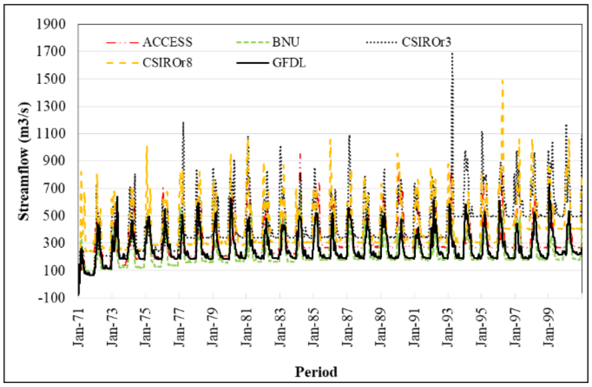


Figure 53: Future annual mean streamflows at Chiromo gauging station for RCP4.5 climate scenario

Figure 8 illustrates the simulation results of future streamflow at the Chiromo gauging station for the RCP4.5 climate scenarios. The annual mean streamflow is projected to increase by 6%, 89% and 65% for ACCESS1-3_r1i1p1, CSIRO-Mk3-6-0_r3i1p1 and CSIRO-Mk3-6-0_r8i1p1 scenarios respectively, compared to the observed streamflow while BNU-ESM_r1i1p1 and GFDL-ESM2G_r1i1p1 GCM scenarios have projected a decrease of 25.18% and 18.61% respectively. Table 2 and Figure 8 clearly show the response of the Shire River basin to the anticipated climate change impact through both an increase and decrease in peak discharge. Based on these results, the HEC-HMS conceptual hydrological model was successfully used to predict the impact of future climate changes on the hydrological behaviour of the Shire River basin. Findings of this study are consistent with previous studies that have been implemented in other basins in Africa. Reduction and increase in streamflows for the future have already been predicted in some studies e.g. Shaka, (2008) in the Gilgel Abbay catchment (Ethiopia). Flooding was predicted at 2, 10, 25, 50, and 100 years when Guduru et al., (2023) used HEC-HMS to model the streamflow and predict flood in the Meki watershed in Ethiopia. Increase in the simulated peak discharge was simulated when Derdour et al., (2017) used HEC-HMS to simulate rainfall RR in the semi-arid region of Ain Sefra watershed in Algeria.

4. Conclusions and recommendations

This study evaluated the potential impacts of future climate change on the hydrological extremes for Shire River Basin (SRB) in Malawi. The SRB, which is very prone to hydro-meteorological disasters, was chosen as a case study due to its huge economic potential. The calibrated and validated HEC-HMS model, driven by the downscaled CMIP5 future climate signals to simulate the future extreme streamflows for the SRB at Chiromo gauging station for the late periods of the 21st century for the RCP4.5 climate scenarios. HEC-HMS hydrological model was chosen for evaluation due to its simplicity, free availability and less demanding on input data hence appropriate for data scarce regions such as SRB in Malawi. Evaluation of climate change impacts was done by comparing the future and control streamflows. Future streamflow was projected to respectively increase by 6%, 89% and 65% for ACCESS1-3_r1i1p1, CSIRO-Mk3-6-0_r3i1p1 and CSIRO-Mk3-6-0_r8i1p1 scenarios, compared to the observed streamflow while BNU-ESM_r1i1p1 and GFDL-ESM2G_r1i1p1 GCM scenarios have projected a decrease of 25.18% and 18.61% respectively. These findings have potential to respectively bring about severe floods and droughts in the SRB in future. To mitigate against these anticipated negative impacts that will arise from the projected extreme streamflows, a strong policy statement is recommended. This study therefore recommends that water managers and policy makers must take profound interest on these research findings by reviewing the current design practices regarding designs of hydraulic structures through modifications or reviews of design parameters considering the information presented in this research and strongly investing in the acquisition of meteorological, hydrological and hydrographic data by relevant ministries so that future research should be based on empirical data as opposed to models. This will also address aspirations of Enabler number 7 of the Malawi 2063 vision, which targets environmental sustainability as being central in ensuring sustainable development in Malawi. It is also recommended that this kind of research should be extended to other river catchments, within the region to obtain a complete picture for the possible impacts of climate change on hydrological extremes. This study has therefore demonstrated that the tool that combines the HEC-HMS hydrologic model and downscaled CMIP5 models can proficiently evaluate the impact of climate change on hydrological extremes.

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Paper 26: Feasibility of Using Unmanned aerial vehicles in EstimatingTurbidity Levels: A case study of Mudi River

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Abstract

The study focuses on the use of unmanned aerial vehicles in estimating turbidity levels in open surface water sources. Following high water pollution, Turbidity as one of the physical water quality parameters need to be monitored regularly. Traditional methods are being used to measure this physical water quality parameter but these methods are expensive, time consuming, labor intensive and provide results which are limited to the sampled points. Since monitoring is a continuous process, an approach which is cost effective, time efficient, less tedious and which can provide a holistic picture of the study area is needed.

This study aims at validating the use of unmanned aerial vehicles in estimating turbidity levels.

The approach involves collecting RGB images of the study area from which an orthomosaic is formed. Then the NDTI values are calculated from the orthomosaic by extracting the bands from it which are used to estimate turbidity levels in water.

In this study, drone images were taken in three epochs on Mudi Dam and turbidity levels were calculated. The approach was also tested on a small waterbody with minimal water level, Mudi River. Data for in-situ measurements was also collected. Correlation analysis results showed that there is a strong relationship between the two datasets. A regression analysis was also run and a higher R Square value of 0.9985 was found. Finally, the variations in turbidity were determined both spatial and temporal in three epochs and it was revealed that the variations are significant.

Keywords: Remote sensing, RGB images, orthomosaic, in-situ, NDTI

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1. Introduction

Water quality is a measure of how suitable the water is for a certain purpose based on selected physical, chemical, and biological characteristics (shamaltani, 2021). Waste accumulation in water sources becomes dangerous to aquatic life, human health as well as the tourism industry sector of a nation which in turn can affect the economy of a country. Water resources are of major environmental, social and economic value (Simon et al., 2015). Quality water is therefore useful as it provides ecosystem habitats, farming, fishing and contributes to tourism and recreation. Turbidity is one of the physical parameters of water quality which is caused by particles or solids that are suspended in water and remain undissolved. Turbidity in water can have several indirect effects such as bacterial and viral contamination, reduced effectiveness of disinfection and highly turbid water is visually unappealing.

Mudi reservoir is one of the urban surface water sources in the southern part of Malawi particularly Blantyre city. The reservoir is built on Mudi river which carries various suspended particles into the reservoir. Mudi river is regarded as one of the most polluted rivers in the region. Efforts have been made to control water pollution in the river but the challenges keep on rising. There have been a lot of concerns from people on the current state of the river and other open surface water sources in urban areas. For example the Mudi River Clean Up initiative is an indication that people are really concerned with the current state of the river. According to Pensulo(2021), industries release pollutants into the river, contributing to environmental contamination. This is putting thousands of lives who depend on water from this river at health risks. Therefore, these open surface water sources need to be monitored regularly.

In Malawi and beyond, people are still using the in-situ methods only when it comes to turbidity measurements. These methods are labour intensive, costly, time consuming and the results are limited to the sampled points (Gholizadeh, 2016). Therefore, this study has been conducted with an aim of validating a model which uses remote sensing technique in estimating turbidity levels. Turbidity as an example of the physical water quality parameters has been widely studied in open surface water sources. It has been proven that the traditional methods are expensive, time consuming, prone to errors and the results are limited to the sampled points. Water quality management requires regular monitoring of water quality. With the in-situ methods, it is difficult to monitor water quality parameters regularly. Therefore, Remote Sensing techniques are best suited for this purpose as they are time efficient, cost effective, less tedious and provide a holistic picture of the study area. In addition to that, the previous authors including Murray (2022) and Hossain et. al., (2021) used satellite images in their studies. After reviewing literature and appreciating works of different researchers including Zamberletti (2023) and Sowit (2022), it has been proven that drone data has higher resolution as compared to satellite data. It is for this reason that this study has adopted the use of drone in collection of data for this study as opposed to the satellite data.

The approach employs remote sensing techniques to estimate turbidity levels on open surface water sources. It uses red band and green band of an RGB image to calculate turbidity. In this technique, turbidity is calculated by calculating reflectance from the image. It involves calculating how much light is reflected by the water surface at those specific wavelengths. Those areas which are high in turbidity reflect more in red while areas with low turbidity reflect more in green.

2. Materials and Methods

2.1 Study Area

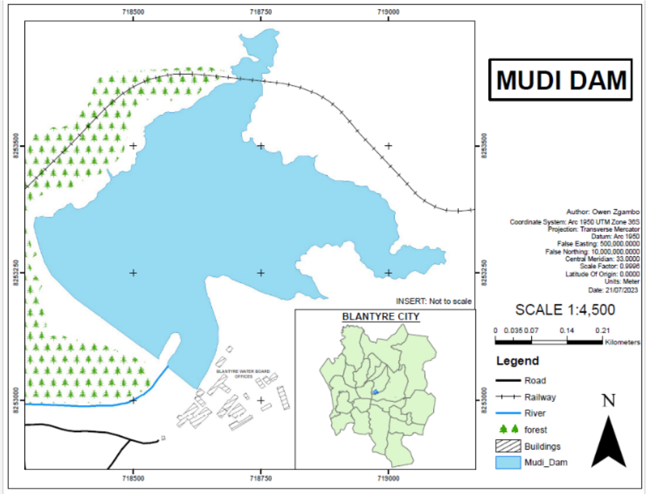

Figure 54: Location of study area

2.2 Data Acquisition

Unmanned Aerial Vehicle was utilised as a data collection tool for this study. A Mavic pro 2 drone was used to capture images of the dam and river. Secondary turbidity data were also collected from Blantyre water board.

2.2.1 Aerial Surveys

Aerial surveys were conducted with an end lap of 75% and side lap of 60% for three epochs on the dam and a single epoch on the river. The UAV was flown at a flight height of 100m.

2.2.2 Pointcloud / Othomaisaic / Digital Surface Model generation

Pix4d mapper was used with the aid of concepts from photogrammetry and structure from motion to generate pointclouds, orthomosaics and digital surface models.

2.2.3 Generation of NDTI values

The process started with preparation of bands in ArcGIS. Red band and green band were extracted to be used in the calculation of turbidity. The Normalized Difference Turbidity Index was generated in ERDAS Imagine software. The following equation by Lacaux. JP., et.al (1986) was adopted:

$$Turbidity = \frac{red\ band - green\ band}{red\ band + green\ band} \quad (1)$$

For visualization purpose, the files were put in ArcGIS.

5.1. 2.2.4 NDTI at an Abstraction Point

Each and every point on the NDTI Map has its own value. So, few random sample points were created around the abstraction point where water is pumped from the dam into the pipe. These points were the same in all the three epochs. In each epoch, an average turbidity value was found for the sample points. The calculated average value represented turbidity level at an abstraction point for that particular hour.

2.3 In situ measurements

These measurements were for raw water which are done before doing any water treatment. At the dam, water is pumped from the dam at every hour and tests also happen every hour. The dates and time for the collection of results were corresponding to the dates and time the remote sensing data were captured. The records were in Nephelometric Turbidity Units (NTU).

5.2. 2.4 Making the Two Datasets Comparable

The in-situ data and the remote sensing data were in different units; therefore, it was not possible to compare two datasets of different units. Since the remote sensing data had values ranging from negative one to positive one, a procedure was followed which converted the in-situ data values to a range of negative one to positive one making the two data sets comparable. Mean and standard deviation of in-situ data were computed. Then the mean was subtracted from each value of in situ data and then divided by the standard deviation. This procedure transformed the in-situ values to a desired range of negative one to positive one.

5.3. 2.5 Determining the Relationship Between Remote Sensing Data and In-Situ Data

Correlation analysis was run using Microsoft excel to find the relationship. This helped in determining how a particular NDTI value estimates the level of turbidity. Finally, regression analysis was conducted to check the validity or reliability of the analysis.

2.6 Determining the Spatial-Temporal Variations

The differences in turbidity were determined among sample points for the spatial variations and among the three epochs for temporal variations. The process involved adding a polygon defining the extent of the study area and the Normalized Difference Turbidity Index (NDTI) for each epoch in ArcMap. Then, random points were created using the polygon as a constraining feature class. Finally, turbidity values for the sample points were extracted in all the three epochs using the extraction tool (extract multi values to points). The tool was adopted as it extracts cell values at locations specified in a point feature class from one or more rasters and records the values to the attribute table of the point feature class.

2.7 Testing the Significance of Spatial-Temporal Variations in Turbidity

The process utilised turbidity values which were extracted in the previous process. Anova: Two-factor without replication data analysis tool of Microsoft excel was used to test the significance.

3. Results and Discussion

3.1 Pointcloud / Othomaisaic / Digital Surface Model generation

For each epoch, an orthomosaic was created. Below is a figure that shows orthomosaic generation results for Mudi Dam.

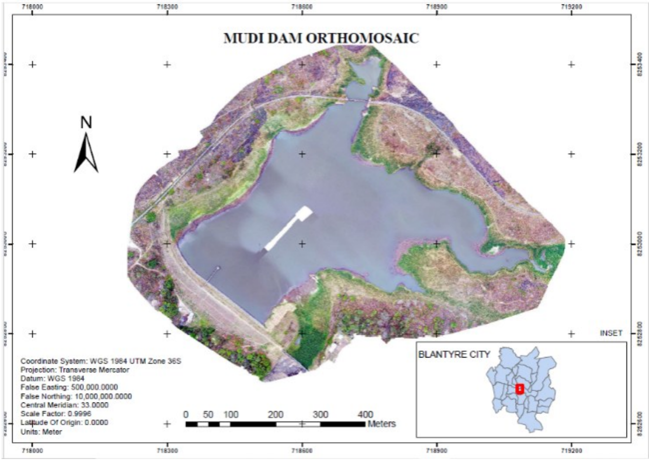

Figure 55: Orthomosaic of the study area

Large water bodies like any other features such as dense forests which tend to be too homogenous bring issues during image calibration when creating orthomosaics according to Buie, (2022). This happens in the early stage of orthomosaic generation, initial block adjustment. The results of the orthomosaics which were created for the dam were affected by that calibration issue. Some images failed to calibrate living a gap which looks like a patch on the orthomosaic. The patch was very small as compared to the rest of the area without calibration issues hence it did not affect the turbidity estimation process.

Another orthomosaic was created for a stretch of Mudi River. Figure 3 below shows an orthomosaic for Mudi River.

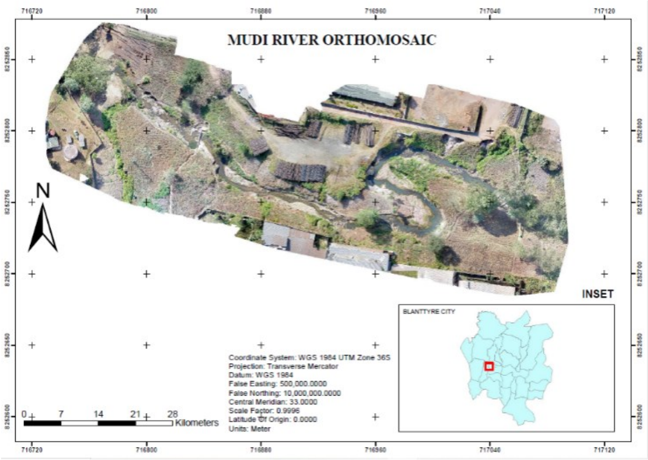

Figure 56: Orthomosaic for a Stretch of Mudi River

Unlike on the dam, the initial block adjustment did not encounter calibration issues in the generation of the orthomosaic for Mudi River. This is due to the small area of the water body hence a big portion of the area was land having features of different characteristics.

5.4. 3.2 The Normalized Difference Turbidity Index (NDTI) Maps

The outcomes of turbidity estimation were presented using maps. The maps below are illustrating turbidity levels in Mudi Dam and Mudi River.

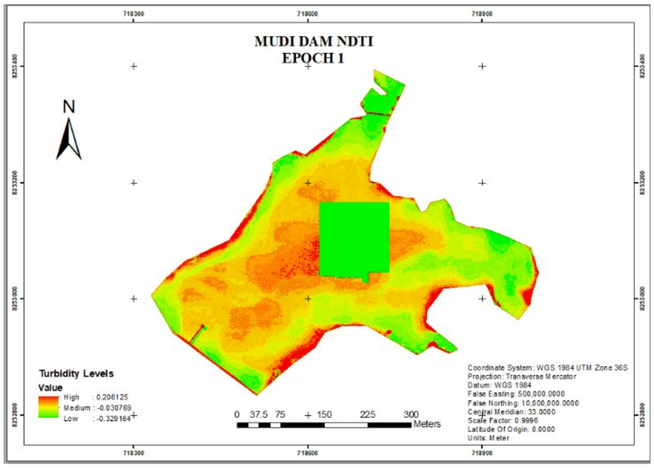

Figure 57: Turbidity for 2 September, 2023.

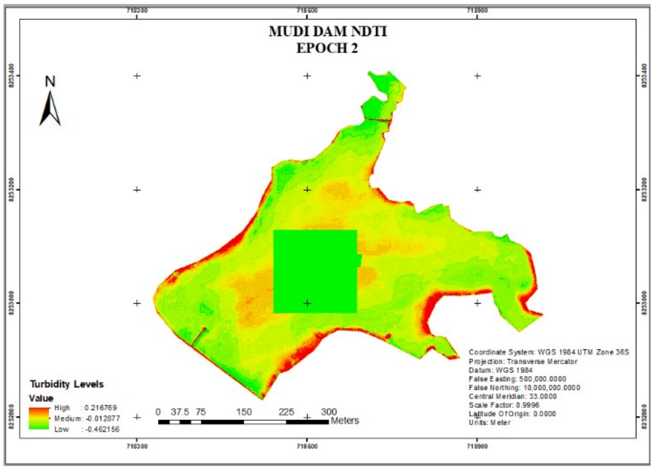

Figure 58: Turbidity for 7 September, 2023.

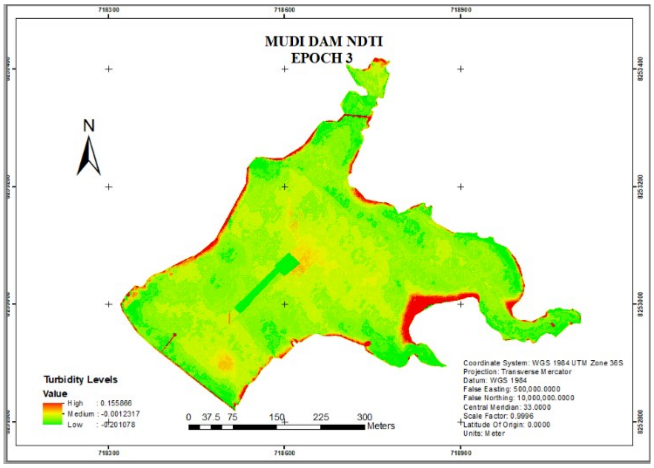

Figure 59: Turbidity for 14 September, 2023.

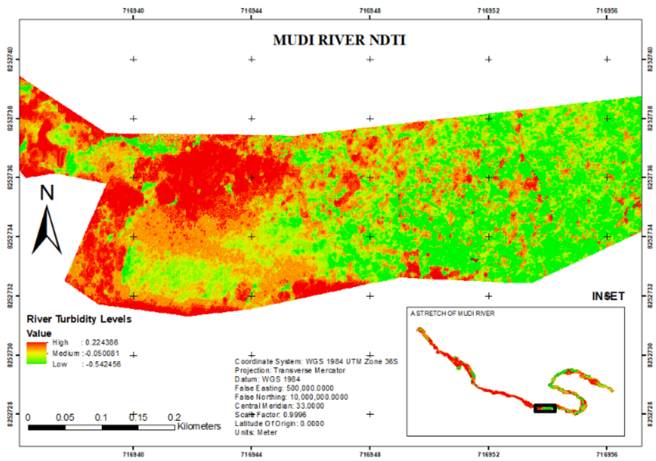

Figure 60: Turbidity for Mudi River

This has shown that this remote sensing technique can also be used to estimate turbidity levels for water bodies with minimal water.

The NDTI values obtained in this study provide valuable insights into the turbidity levels of the dam water as well as river. Higher NDTI values corresponded to elevated turbidity levels while lower NDTI values indicated clear water. For first epoch, turbidity values ranged from -0.329164 to 0.206125. The second epoch had its turbidity ranging from -0.462156 to 0.2 16769 while turbidity in the third epoch ranged from -0.201078 to 0.155866. For the river turbidity ranged from -0.542456 to 0.224336. These findings are most similar to what Subramaniam et al, (2011) found in their study upon using this technique.

Based on the colors which are on the turbidity maps, red areas correspond to highly turbid water. Turbidity decreases as the colors are turning to orange then yellow. Those green areas correspond to low turbidity.

3.3 Transformation of In-situ Values

The in-situ data were converted from nephelometric turbidity units to values which can be comparable with UAV data.

Table 21: In situ Data

Date	Original Value	Converted Value
02 September	13.5	0.602
07 September	9.58	-1.193
14 September	13.9	0.807

5.5. 3.4 Correlation Analysis

There was a positive correlation between the remote sensing data and the in-situ measurements. The found coefficient of 0.9 is close to 1, which signifies an extremely strong positive relationship between the two variables. This means that as one variable increases, the other tends to increase in a linear fashion. A correlation of 0.9 implies that changes in one variable have a substantial and predictable impact on the other. This suggests that the model used is performing well and is a reliable tool for gathering data or information.

5.6. 3.5 Regression Analysis

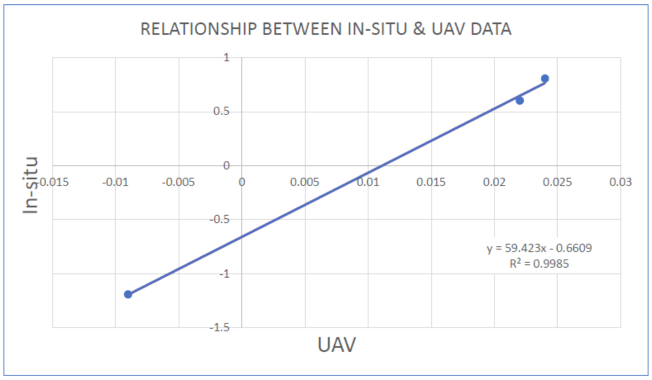

Figure 61: Relationship Between In-situ Measurements and UAV Estimates

An R squared value of 0.9985 suggests that approximately 90% of the variability in remote sensing data can be explained by the in-situ data. This indicates a strong statistical relationship between the sets of data. The model which has been used seems to be a good fit for the data.

5.7. 3.6 Spatial-Temporal Variations

Turbidity levels can vary among different points across the area of study. It can also vary between certain time intervals. A trend analysis was conducted to determine these variations on the dam in the three epochs. Figure below shows the trends in turbidity levels of Mudi dam:

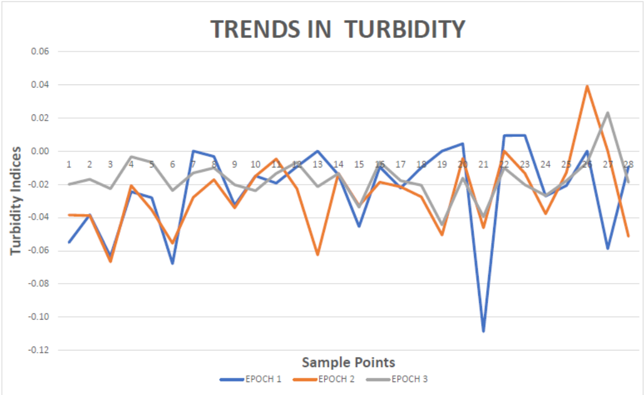

Figure 62: Trends in Turbidity

According to the trend analysis conducted, turbidity is not uniform across the studied area and is changing over time. This could be due to factors such as weather, (Khatri & Tyagi, 2014). Turbidity can change even within a short period of time due to weather conditions at that specific time.

5.8. 3.7 Significance of the Spatial-Temporal Variations

A P-value of 0.002505 which is less than 0.05 suggests that there are significant differences in the data across different spatial locations within the dam. This means the turbidity observations at various points within the dam are not the same.

Similarly, a P- value of 0.000377 for temporal variations indicate that there are significant differences in the data over time as it is also below 0.05. This suggests that turbidity in the dam changes significantly from one time period to another. This implies intra-seasonal variations.

4. Conclusions and Future Work

This study involved capturing drone images of the study area in three epochs and drone images of Mudi River for only one epoch. Orthomosaics were created for all the flights made from which turbidity estimations were calculated. In-situ turbidity measurements were obtained from water quality laboratory for Blantyre Water Board. A correlation analysis was made to determine the relationship between the results of unmanned aerial vehicle data and the traditional method data. This was followed by regression analysis which was conducted to test the goodness of the normalized difference turbidity index model which was employed in this study. The variations in turbidity were then determined both spatial and temporal variations. The last thing done was testing the significance of these variations.

The following conclusions were made from this study:

- It was shown that there is a strong positive relationship between the in-situ measurements and the remote sensing estimates. This was indicated by a correlation of 0.999231 which is very close to 1.
- Regression analysis showed R square results of 0.9985 indicating a better fit of the model. Therefore, it can be concluded that the normalized difference turbidity index model can generate reliable data which is very close to the actual data.
- It has also been noted that turbidity levels vary in different locations of the waterbody. Again, turbidity changes with respect to time. This was indicated by the three epochs having different turbidity. The variations were seen to be significant indicated by the P values of less than 0.5.

The following recommendations have been made based on the findings/ results of this study:

- To have a holistic picture of a study area when determining turbidity levels of a water body, authorities or individuals should consider using the remote sensing techniques. In so doing costs can be saved and the work can be done faster and easy.
- The Mudi River which is the main source of water in this Mudi dam and some other tributaries should be monitored regularly to avoid high levels of turbidity in this dam.
- Other researchers are encouraged to determine inter-seasonal variations in turbidity for open surface water sources as this study has only focused on intra-seasonal variations.
- Researchers are further encouraged to find other remote sensing techniques which can deal with other water quality parameters since this study has only focused on one parameter.

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