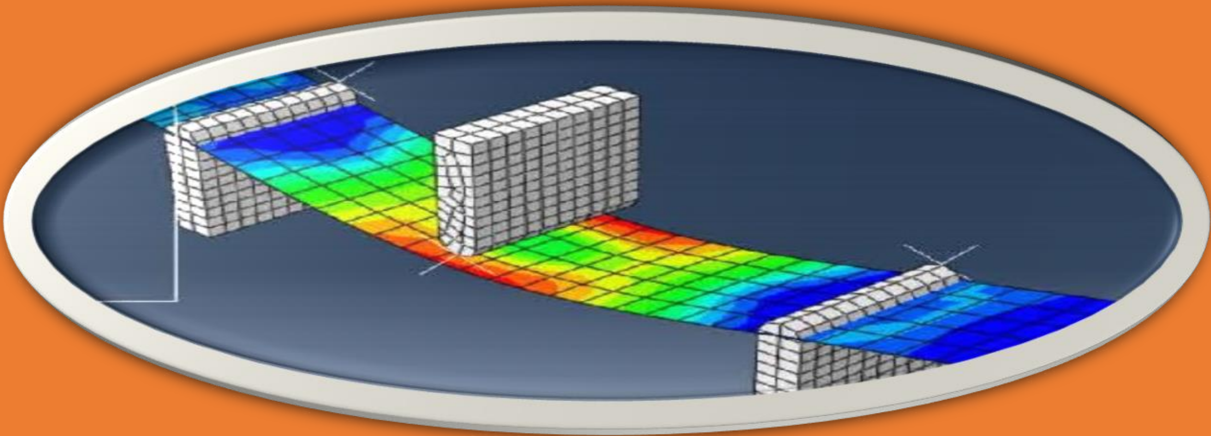
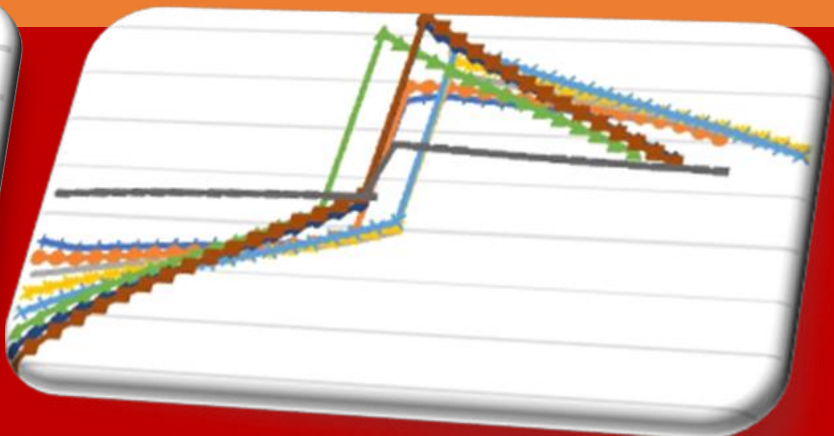
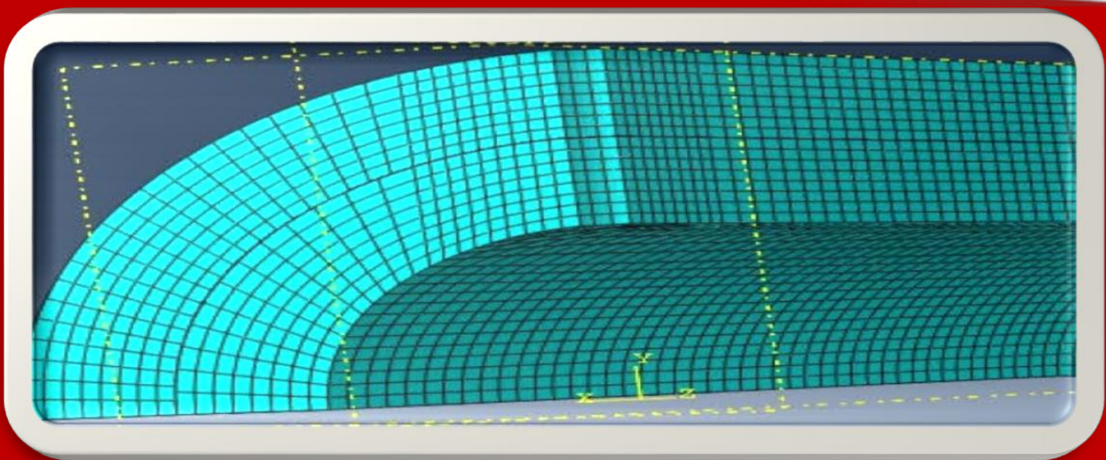
African Journal of Engineering Research and Innovation

AJERI Vol 3. No. 3. 2025







The Institution of Engineers of Kenya

ISSN: 2957- 7780

In partnership with

ENGINEERS BOARD OF KENYA

Enhancing Professionalism

ISSN: 2957- 7780

AJERI

African Journal of Engineering in Research and Innovation

ISSN: 2957- 7780 Volume 3. No 3. 2025

Published by:

The *Institution of Engineers of Kenya*

P.O Box 41346- 00100

Nairobi Kenya

Tel: +254 (20) 2729326, 0721 729363, (020) 2716922

Email: editor@iekenya.org

Website: www.iekenya.org

IEK

African Journal of Engineering Research and Innovation (AJERI), is published by **The *Institution of Engineers of Kenya,*** IEK, as an international forum for publication of high-quality papers in all areas of Engineering

ISSN: 2957- 7780

CONTENTS **Pages**

 ISSN: 2957- 7780

Enhancing Frequency Stability in Low-Inertia Power Grids Using Variable Generation for Fast Frequency Response

B.K. Wamukoya[1*], K. K. Kaberere[1], C. M. Muriithi[2]

[1]Department of Electrical and Electronic Engineering, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya

[2]Department of Electrical and Electronic Engineering, Murang'a, University of Technology, Murang'a, Kenya

*Corresponding author: brianwamukoya@gmail.com

Abstract

The modern power system is experiencing an unprecedented rise in the integration of renewable variable generation (VG) sources. Increased use of converter-based VG sources to replace conventional Synchronous Generators (SGs) presents new challenges to grid operators in terms of dynamic frequency stability and regulation. Reducing the number of SGs while increasing non-synchronous, inertia-less VG penetration reduces the grid's natural inertia, which is critical for frequency stability. Frequency regulation for low inertia power grids has largely been addressed in literature by recommending a minimum level of inertia to be maintained or by providing additional virtual inertia via energy storage systems. However, inertia fortification is not the only solution to addressing the low inertia problem. Since SGs provide essential ancillary services to the grid such as frequency support, it is imperative that researchers explore the viability of VG to provide these services. Investigating alternative frequency regulation strategies, beyond inertia-based solutions, is essential for ensuring the stability and resilience of future low-inertia power grids. In this regard, this paper investigates the viability of deployment of VG as a fast frequency response (FFR) source to better post contingency frequency dynamics for low inertia power grids. VG sources can be operated in deloaded mode to provide a reserve margin that can rapidly be deployed to meet power imbalances in case of a contingency leveraging on the agility of power electronic based converters. The proposed strategy was applied to a modified IEEE 39 bus system. The results demonstrate that deployment of FFR from VG sources improves power system frequency response and allows uptake of more VG sources without concerns on inertia levels. The best frequency response performance was at 30% VG penetration that improved frequency nadir and the rate of change of frequency (RoCoF) by 0.14% and 7.04% respectively. The output of this work provides insights into a frequency regulation strategy that is sensitive to the needs of the modern power system.

Keywords: Deloaded Mode, Fast Frequency Response, Frequency stability, Inertia, and Variable Generation.

 ISSN: 2957- 7780

1. Introduction

In the wake of escalating climate change impacts, globally, power grids are embracing the energy transition to renewable energy to reduce greenhouse gas emissions (GHG). The transition has been characterized by a fair share of renewable variable generation (VG) sources such as wind and solar photovoltaics technologies [1]. According to an International Renewable Energy Agency (IRENA) report on energy statistics, for the year 2020 alone, 111 GW of wind and 127 GW of solar installations were completed globally representing 50% of renewable energy capacity installed for that particular year [2]. As benign and sustainable generation technologies gain traction, it is expected that VG sources will make a significant contribution in future power grids [3].

However, increased uptake of VG sources into modern power grids presents new challenges for grid operators, particularly in managing dynamic post-contingency frequency response, which can potentially undermine frequency stability [4]. This is because higher penetration of VG into power grids reduces grid inertia, as VG sources are connected to the grid via power electronic converters that decouples them limiting their ability to contribute to inertia. Also, VG sources such as solar photovoltaic power plants (SPVPPs) lack any rotating parts in their inherent operation hence inertia-less in nature [5]. Grid inertia is predominantly provided by the rotating masses of conventional synchronous generators (SGs) and assists in resisting changes in system frequency. SGs typically provide an inertial response by naturally dissipating or absorbing the kinetic energy stored in their large rotating masses, assisting in frequency regulation in the event of a power imbalance for a short time before governor action kicks in to provide active power support [6], [7], [8]. Therefore, increased adoption of VG sources replacing SGs denies the power of this critical ancillary service resulting in a frequency control problem. Decreased inertia makes the power system more dynamic, less resilient and hence more susceptible to large frequency changes even with smaller disturbances [9]. Further, decreased inertia shortens the period allowable to respond to a power imbalance which drives the need for a fast-acting frequency response service for low inertia power grids to maintain frequency stability [10].

As power grids ramp-up the installed capacity of VG, it is critical that researchers investigate the ability of VG to provide ancillary energy balance services in the short term to improve frequency regulation in inertia-deficient grids. A plethora of solutions to address the frequency control

ISSN: 2957- 7780

problem caused by to low inertia have been presented in literature. For instance, power system purists in literature have argued on the need to maintain a certain critical level of inertia to ensure frequency stability which serves as a limiting factor to integrating more VG sources [11]- [13]. Other researchers in [14]- [16] have suggested alternative ways of providing additional inertia to fortify inertia deficient grids of this critical resource. This type of inertia has been christened as synthetic/virtual/emulated inertia provided through a virtual synchronous generator (VSG) using power electronic devices that mimics the natural inertial response from SGs. The VSG has primarily been powered by various energy storage system (ESS) technologies including batteries, super-capacitors or hybrids. Alternatively, VG sources can be operated below their maximum power point (deloaded mode) to have a reserve margin or in conjunction with ESS to provide a fast-acting frequency response service know as fast frequency response (FFR) [10], [17], [18]. FFR is the rapid increase in active power by a VG source operating in deloaded mode or an ESS, proportional to the RoCoF and frequency deviation after a contingency. It leverages its rapidness to respond to a power imbalance to the agility of power electronic devices [17].

From the reviewed literature, little effort has been made to quantify the absolute performance of FFR action from VG without assistance of other frequency regulation mechanisms such as loadshedding. This paper seeks to provide interpretation of the dynamic performance of FFR support in frequency regulation from SPVPP as a VG source which has largely been merely observed in existing literature without providing justification.

2. System Modelling

SPV systems are made up of photovoltaic modules that function similarly to p-n junctions when illuminated. When exposed to light, carriers are formed, producing a current proportional to the incident radiation. A single PV module is made up of several solar cells, which serve as the module's basic building blocks and have a voltage rating of 0.5V. PV modules were connected in series and parallel to increase voltage and current, respectively. The voltage of a photovoltaic system determines its output power. In the conventional SPV system operation at maximum power point tracking (MPPT) mode, the system generates a maximum power output P_{mpp} operating at a voltage V_{mpp} .The V_{mpp} is given by (1) [18]

 ISSN: 2957- 7780

$$V_{mpp} = V_{mpo} \times \frac{ln(G)}{ln(G_{STC})} \times \{1 + T_{CF\_V}(T - T_{STC})\} \quad (1)$$

Where (G) is the irradiance, V_{mppo} is the PV module value provided by the manufacturer, (T) is module temperature and T_{CF_v} is the voltage temperature correlation coefficient. In addition, G_{STC} and T_{STC} denote the standard testing conditions for irradiance and temperature respectively.

In contrast, the output current of an SPV module was determined by (2) [19].

$$I_{PV} = n_p I_{SC} - n_p I_s \left(e^{\frac{qV_{DC}}{kTAn_s}} - 1 \right) \quad (2)$$

where n_p- number of cells in parallel, n_s- number of cells arranged series. Furthermore, $I_{SC}, I_s, k, T, A\ and\ V_{DC}$ denote cell short circuit current (in A), cell saturation current (in A), Boltzmann's constant $[1.3806503 \times 10^{-23}\ J/K]$, Temperature (in K), Ideality factor and dc output voltage (in V) respectively. The cell short circuit-I_{SC} is given by (3).

$$I_{SC} = \frac{G \times I_{SC(STC)}}{G_{STC}} \{1 + T_{CF\_I}(T - T_{STC})\} \quad (3)$$

where $I_{SC(STC)}$ represents the short circuit current under standard test conditions. I_{SC} is mainly affected by temperature- T and irradiance- $G\ (W/m^2)$ and Current Temperature correlation factor- (T_{CF_I}) as expressed in (3)

The MPPT operation mode for SPVPPs ensures the generation of maximum low-cost power; however, it does not maintain any reserve capacity. However, SPVPPs can be configured to operate away from their optimal point, resulting in a reserve margin that can be quickly deployed with the help of auxiliary control strategy on the inverter side for frequency support much like legacy SGs. This operation mode of VG sources is referred to as Deloaded mode. In this mode, the SPVPP acts as a source of FFR because it can instantly surge active power to the grid in response to a frequency event to reduce the power imbalance [17].

DIgSILENT PowerFactory was used to develop a dynamic model for the SPVPP as well as carry out dynamic simulations to test and validate the model performance. The FFR action from SPVPP was modelled to mimic the primary frequency response from SGs with significantly reduced delay time, allowing the fast-acting frequency support to operate partially in the inertial response phase hence participate in reducing the initial RoCoF. To enable the deloaded operation mode in SPVPP, the inverter's control strategy must be modified. In the conventional operation of the SPVPP (MPPT mode), the converter generates maximum power- P_{mpp} when operating at a voltage- V_{mpp} as shown in figure 1.

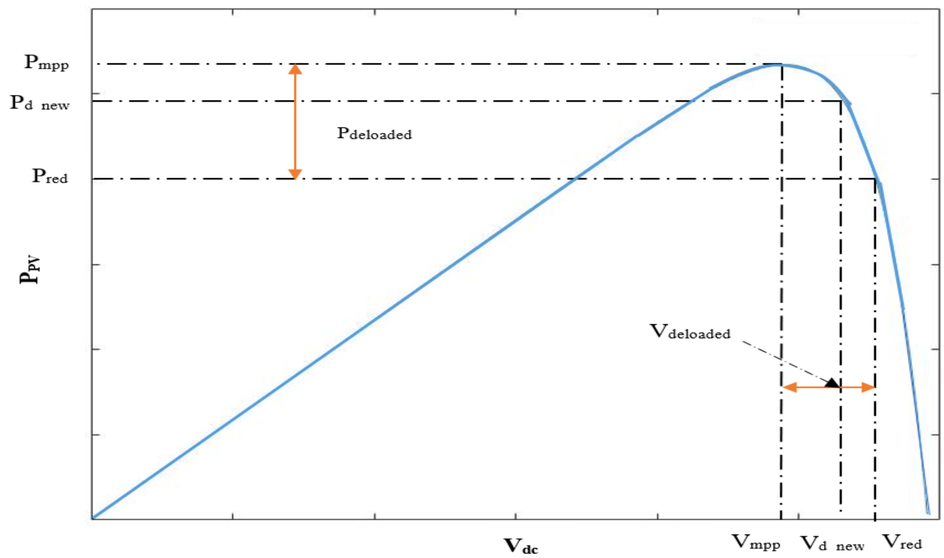


Figure 1: Deloaded SPVPP operation

The output power of the SPVPP is determined by the operating voltage selected on the DC side. Therefore, to achieve deloading operation and create a reserve margin- P_{deload} the converter is configured to operate at a higher voltage- V_{red} or $V_{mpp} + V_{deload}$ greater than V_{mpp} generating a corresponding reduced power output of -P_{red}. A greater voltage than V_{mpp} is preferred to operating at a lower voltage to ensure stability.

In case of a frequency contingency, a signal proportional to the frequency deviation (Δf) is used to reduce the operating voltage- V_{red} to a new voltage- V_{d_new} that is close to the maximum power operating voltage- V_{mpp} thereby ramping up the output power to a new value of- P_{d_new} to reduce the power imbalance. The new operating voltage after an underfrequency event- V_{d_new} is given by (4) [20].

$$V_{d\_new} = V_{red} - K_g \Delta f = V_{mpp} + V_{deload} - K_g \Delta f \quad (4)$$

Where K_g denotes the proportional gain constant.

ISSN: 2957- 7780

Figure 2 depicts the DIgSILENT Simulation Language (DSL)-based active power controller that implements this frequency regulation strategy. DSL is a highly specialised tool available in PowerFactory for accurately modelling dynamic behaviour of power system such as transient responses, oscillations and interactions between system components [21]. A decrease in system frequency due to power imbalance causes the converter operating voltage- V_{red} to fall towards V_{mpp}, rapidly increasing active power output of the SPVPP (with potential to reach P_{mpp}) in response to the frequency event. In this case, the SPVPP closely resembles the SG's primary frequency response without turbine delay.

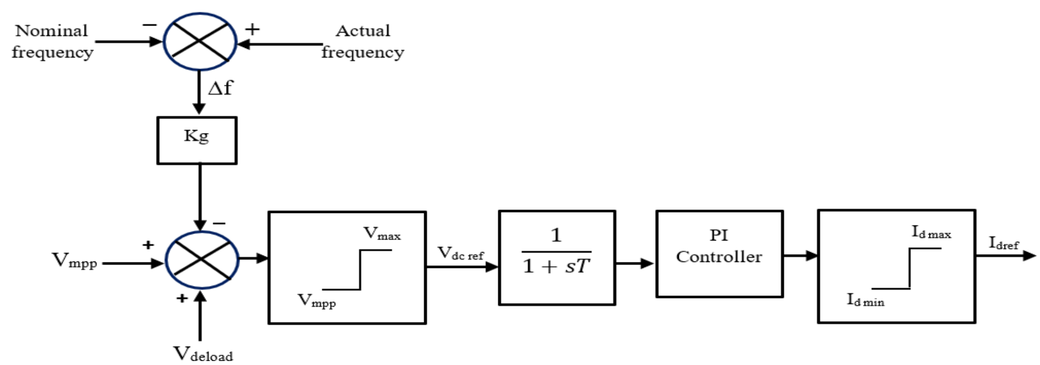


Figure 2: Active power controller for a deloaded SPVPP

According to the active power controller depicted in figure 2, the actual system frequency is measured using a frequency measuring available in PowerFactory (ElmPhi_pll) and compared to the nominal frequency which is the reference to determine the frequency deviation- Δf which is used to generate a signal that determines the operating voltage of the SPVPP array. After the summer, the limiter ensures the operating voltage is withing the prescribed limits $between\, V_{max}\, and\, V_{mpp}$ to guarantee stability where V_{max} is the maximum possible operating voltage of the DC side of the converter. The signal is then passed through a lowpass filter to eliminate high frequency noise signals. The PI controller is used to generate a signal (i_{dref}) to the converter that determines the active power output. The PI controller was chosen because of its ability to regulate DC signals without introducing steady-state error. RoCoF and f_{nadir} were the critical frequency stability metrics used to assess performance of FFR action from deloaded SPVPP after a frequency event.

ISSN: 2957- 7780

3. Case Study

3.1 Simulation setup

3.1.1 Test system model

The modified IEEE 39-bus New England System, shown in Figure 3, was used to test and validate the dynamic model of the SPVPP in deloaded mode as it is widely used in literature for this purpose [22]. The system was also used to investigate frequency stability analysis through time domain simulations that included SPVPP. This test system has a high inertia, making it ideal for investigating frequency stability in the short term. Also, it consists standard dynamic control models of SGs that have been iteratively validated and refined through previous studies ensuring accuracy of their dynamic response behaviour [23]. The test system inherently consists of 10 generators operating at a frequency of 60 Hz with a base MVA of 100 and 19 load buses with a cumulative demand of 6,097.1 MW. The performance of the modelled dynamic SPVPP was analysed by carryout time domain simulation in DIgSILENT PowerFactory considering outage of generator G 09 (largest and most loaded generator) as the worst disturbance. RoCoF and f_{nadir} were the critical frequency stability metrics used to assess performance of FFR action from deloaded SPVPP after a frequency event.

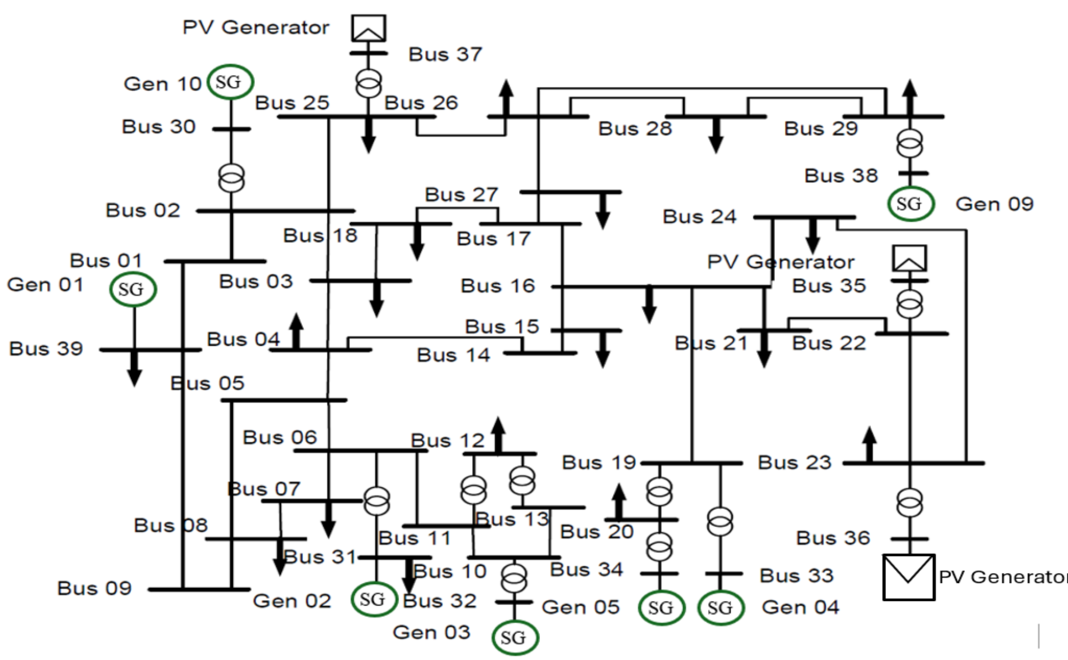


Figure 3: Single line diagram for the modified IEEE 39 bus system

ISSN: 2957- 7780

3.1.2 SPV Penetration

To achieve varying levels of SPV penetration, the SGs on buses 35, 36, and 37 were replaced sequentially with SPVPP with the same power output and rated capacity. As shown in Table 1, this accounted for approximately 10%, 20%, and 30% of SPV penetration.

Table 1: Total system Inertia constant with increasing SPV penetration

SPV Penetration (%)	SPV Generation (MW)	Conventional Generation (MW)	Total System inertia Constant- H (s)
0	0	6145.25	40.954
10	595	5550.25	37.183
20	1275	4870.25	32.833
30	1870	4275.25	29.362

3.1.3 Simulation Procedure

The steps taken in applying the proposed frequency regulation strategy to the IEEE 39 bus test system are summarised below:

1. The IEEE 39 bus test system model with controllers (governor, AVR) was activated in PowerFactory. Individual generator output limits are captured. Load flow was performed to verify the system was properly assembled. Dynamic simulation was executed without any event and the frequency monitored to verify generator controllers were soundly operational.
2. In step 2, with outage of Generator G 09 set as the disturbance (after 10 seconds) a dynamic simulation was executed for 120 seconds and a frequency response plot extracted. This scenario was at 0% SPV penetration.
3. After resetting the model to initial conditions, a dynamic model of SPVPP of the same capacity and operation limits replaced the SG at bus 36 (G 07) representing approximately 10% SPV penetration in the model. Dynamic simulation was executed for a period of 120 seconds considering the event described in step 2 above and a frequency plot extracted.

 ISSN: 2957- 7780

4. Furthermore, SGs at Bus 35 and 37 were replaced with deloaded SPVPPs of similar capacity and operational limits representing 20% and 30% SPV penetration scenario respectively. Step 3 was then repeated for these scenarios as well.

3.2 Simulation Results and Discussion

3.2.1 Frequency Response for Static SPV

Figure 4 depicts the power system frequency response to a generator outage with increased penetration of SPV lacking fast frequency response capability (static SPV).

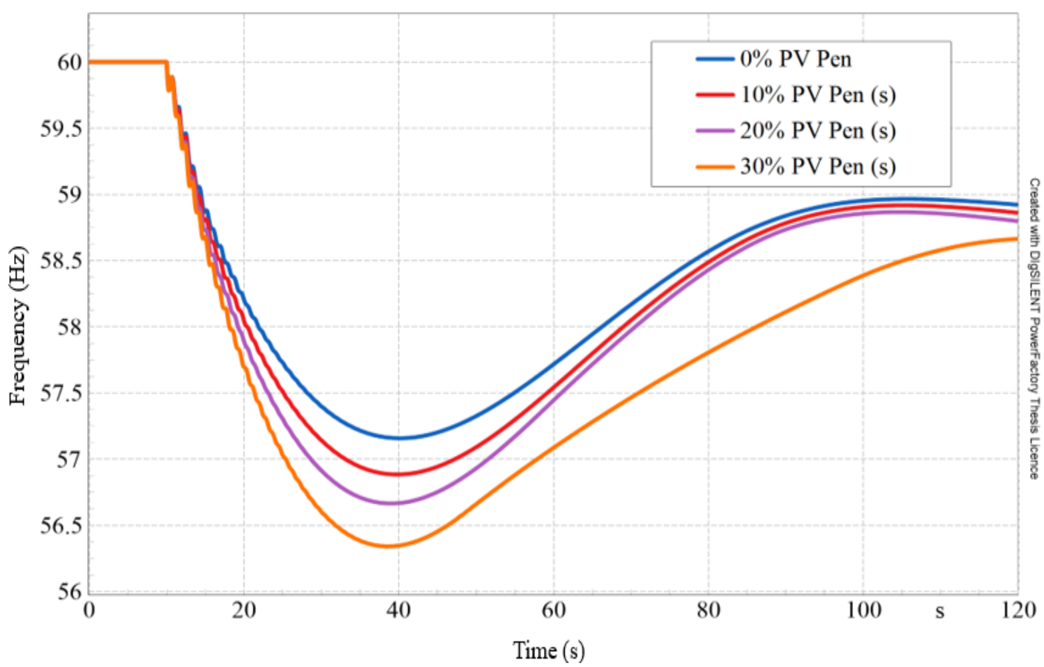


Figure 4: Frequency response with increased penetration of Static SPVPPs

According to the results in figure 4, the scenario without SPV penetration (0% SPV pen) posted the best frequency response performance. As the grid's adoption of static SPVPP increased, the frequency response performance of the power system deteriorated. The frequency stability indices for each study case were calculated and summarised in Table 2.

ISSN: 2957- 7780

Table 2: Frequency stability metrics with static SPVPP penetration

Static SPV penetration level	Total System Inertia Constant- H (s)	Frequency nadir-f_{nadir} (Hz)	RoCoF (Hz/s)
0%	40.954	57.16	0.09905
10%	37.183	56.88	0.1012
20%	32.833	56.67	0.1193
30%	29.362	56.34	0.1307

Table 2 shows that with 0% SPV penetration, the highest $f_{\_nadir}$ point and of 57.16 Hz and the slowest RoCoF of 0.09905 Hz/s were recorded. The rotating mass of SGs provides high levels of aggregate system average inertia, which accounts for the improved frequency response. At 30% SPV, the system has the poorest frequency response performance with the lowest $f_{\_nadir}$ of 56.34 Hz and the fastest RoCoF of 0.1307 Hz/s representing a 1.44% drop and 31.95% increased respectively taking 0% SPV penetration as the base case. Increased uptake of static SPVPPs (with a constant output) reduces grid inertia which is critical in initially resisting changes in frequency after an event hence, a poor power system frequency response as provided for in (5).

$$RoCoF = \frac{df}{dt} = \frac{f_0}{2} \times \frac{\Delta P}{H_{sys}} \quad (5)$$

Where f_0- denotes the nominal frequency, ΔP- denotes the magnitude of the power imbalance and H_{sys} represents the total system inertia constant.

Figure 5 and 6 depict SG governor action in ramping up turbine and active power respectively by all remaining committed generators to reduce the power imbalance and better post contingency frequency response with 0% SPV penetration scenario.

 ISSN: 2957- 7780

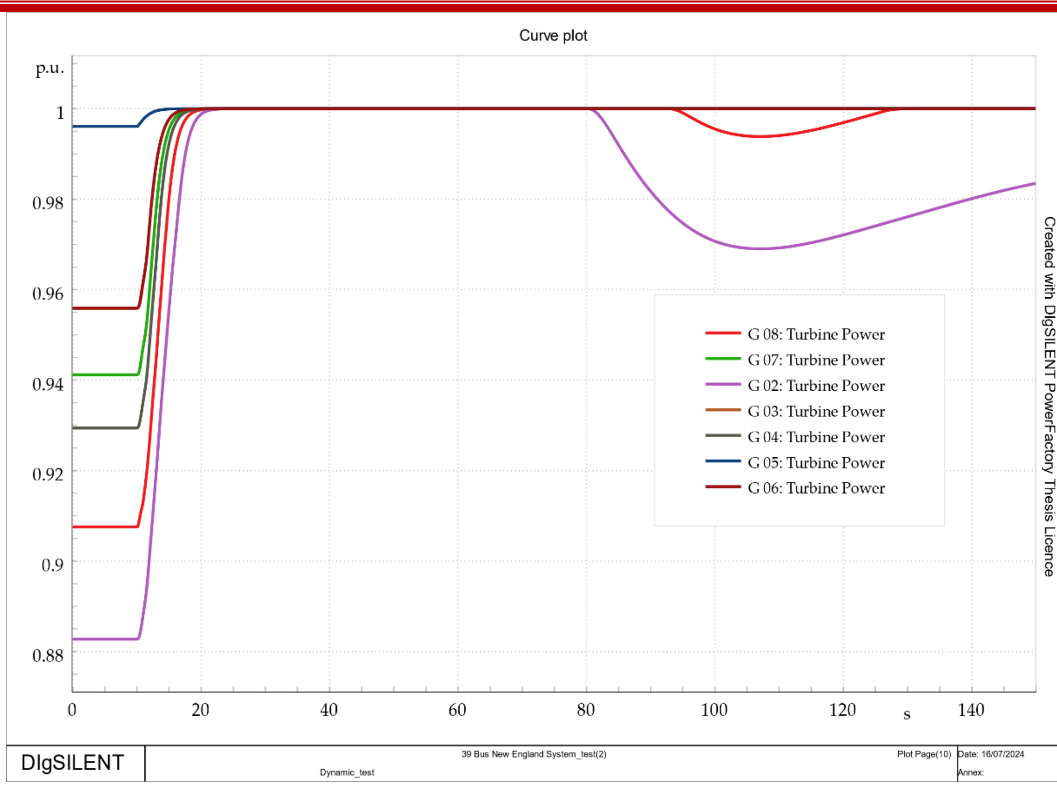


Figure 5: Turbine power dynamics with Gen 09 outage

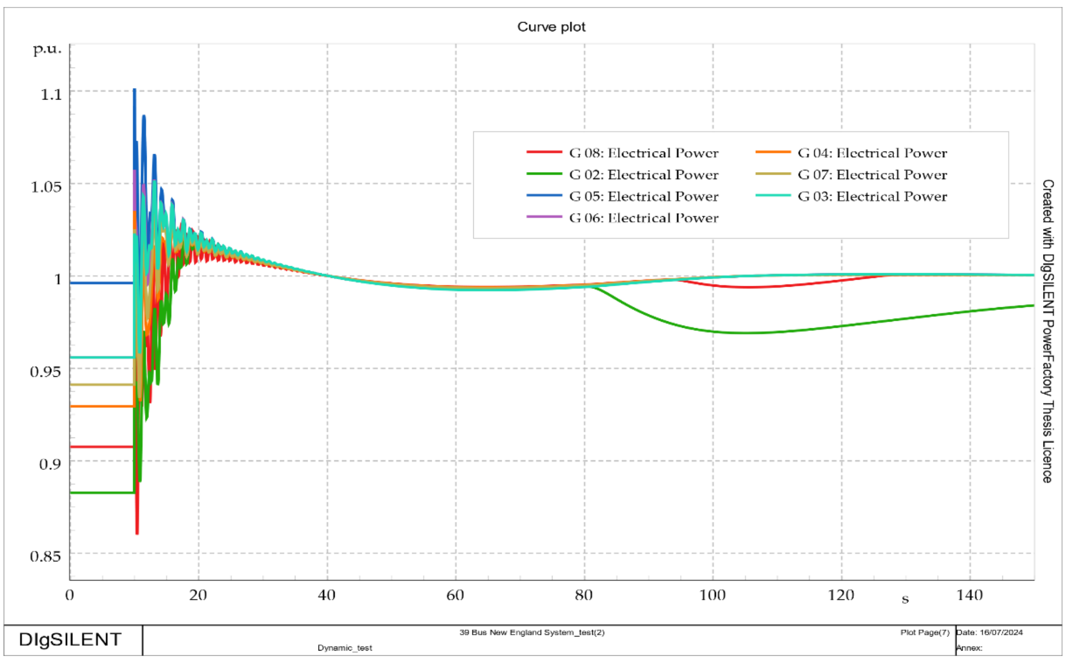


Fig. 6 Generator Electrical power dynamics with Gen 09 outage

ISSN: 2957- 7780

However increasing SPV penetration without FFR capability deteriorates frequency response since the power output from the SPVPP remains almost constant as depicted in figure 7 for 10% SPV penetration after an underfrequency event hence providing no active power support to improve the frequency response. The brief initial dip in the output of a SPVPP is attributed to its lack of inertia, the dynamics of its inverter control system and potentially a temporary activation of the protection mechanisms during transient disturbances. During grid disturbances, the MPPT algorithm may require a short period to adjust to the new operating conditions, leading to a temporary dip in power output. Once this adjustment is complete, the SPVPP stabilizes its output, resynchronizes with the grid and resumes normal operation. This behaviour underscores the fundamental differences between the responses of SGs and SPVPPs to grid disturbances.

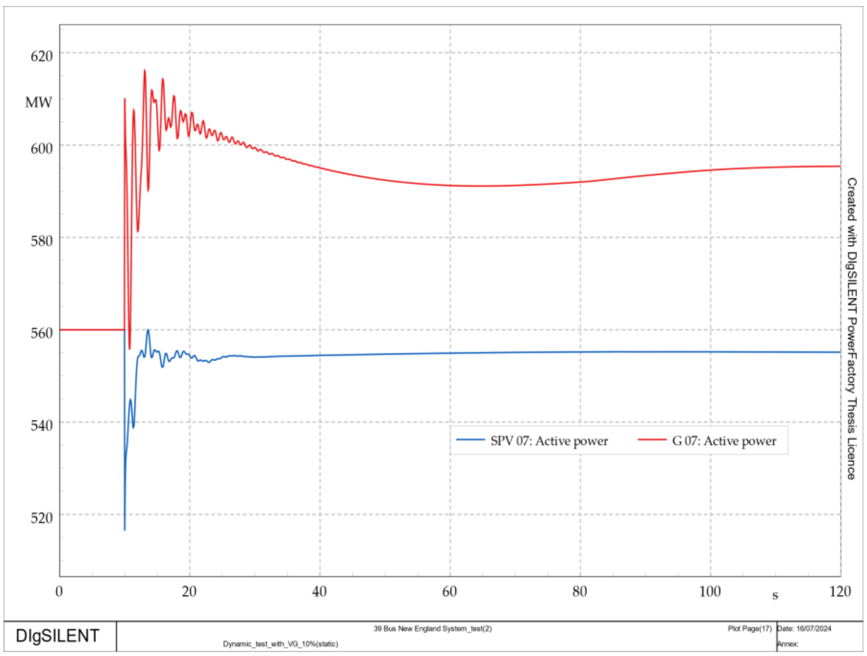


Fig. 7: Active power response of SPVPP vs SG

3.2.2 Frequency Response for SPV penetration with FFR capability

Figure 8 shows the power system frequency response to a generator Gen 09 outage with different penetration levels of deloaded SPVPP, which is dynamic and enabled respond to power imbalances during a frequency event hence provide frequency support. In this case, the operating point of the deloaded SPVPP was the same as that of the replaced SG, which determined its deloading level.

ISSN: 2957- 7780

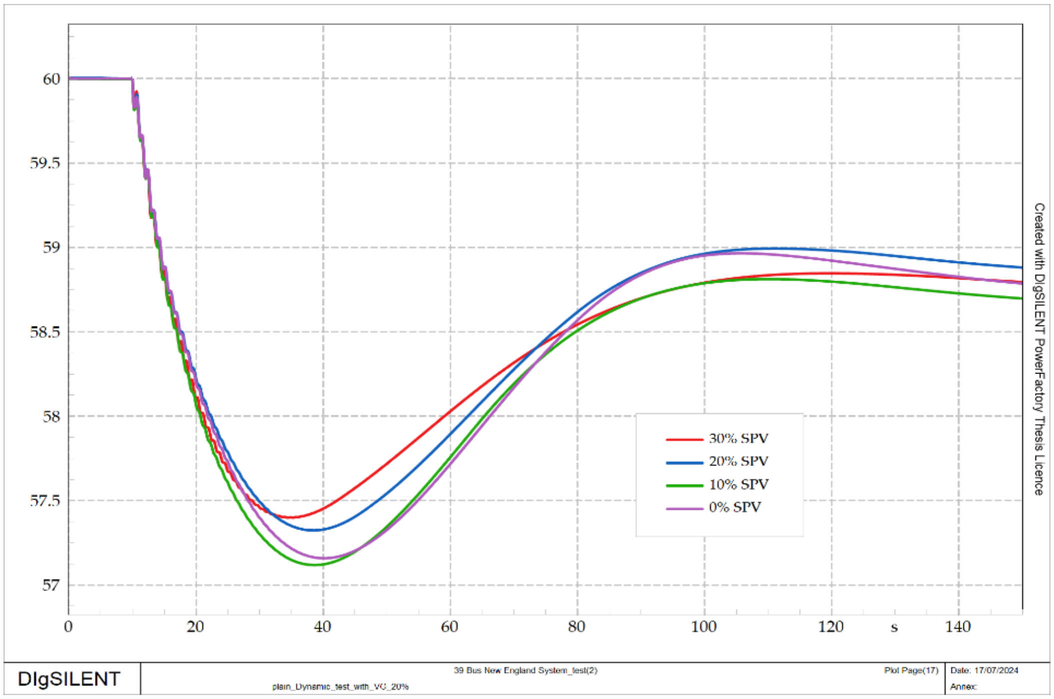


Fig. 8: Frequency Response with increased penetration of Deloaded SPVPP

As the percentage penetration of deloaded SPV increases, the power system frequency response dynamics decently improve as well. The best frequency response performance was recorded at 30% SPV penetration characterised by the highest f_{nadir} of 57.40 Hz and the slowest RoCoF of 0.0884 Hz/s representing a 0.41% increase and 7.04% reduction respectively taking 0% SPV as the base case. The is because at 30% SPV penetration had the largest magnitude of FFR capacity compared to other scenarios. The frequency stability indices for each study case shown in table 3.

Table 3: Frequency stability metrics with Deloaded SPVPP penetration

Deloaded SPV penetration level	Average Inertia Constant-H (s)	Frequency nadir (Hz)	RoCoF (Hz/s)	Deloading level (%)	Deloading capacity (MW)
0%	40.954	57.16	0.09509	-	-
10%	37.183	57.12	0.1001	5.88	35
20%	32.833	57.32	0.09469	5.46	65
30%	29.362	57.40	0.0884	6.42	120

ISSN: 2957- 7780

Deloaded SPVPPs can rapidly ramp up active power to respond to power imbalances faster compared to SGs leveraging on the agility of power electronic converters as depicted in figure 9 to arrest frequency decline. Figure 9 compares the active power response to the outage of generator G09 for SG-G07 at bus 36 (0% SPV penetration) and for a static and deloaded SPVPP of equivalent capacity representing 10% SPV penetration. Both the SG and deloaded SPVPP demonstrate the ability to increase active power output during a disturbance to support frequency, while the static SPVPP maintains a nearly constant output, showing no response to frequency changes.

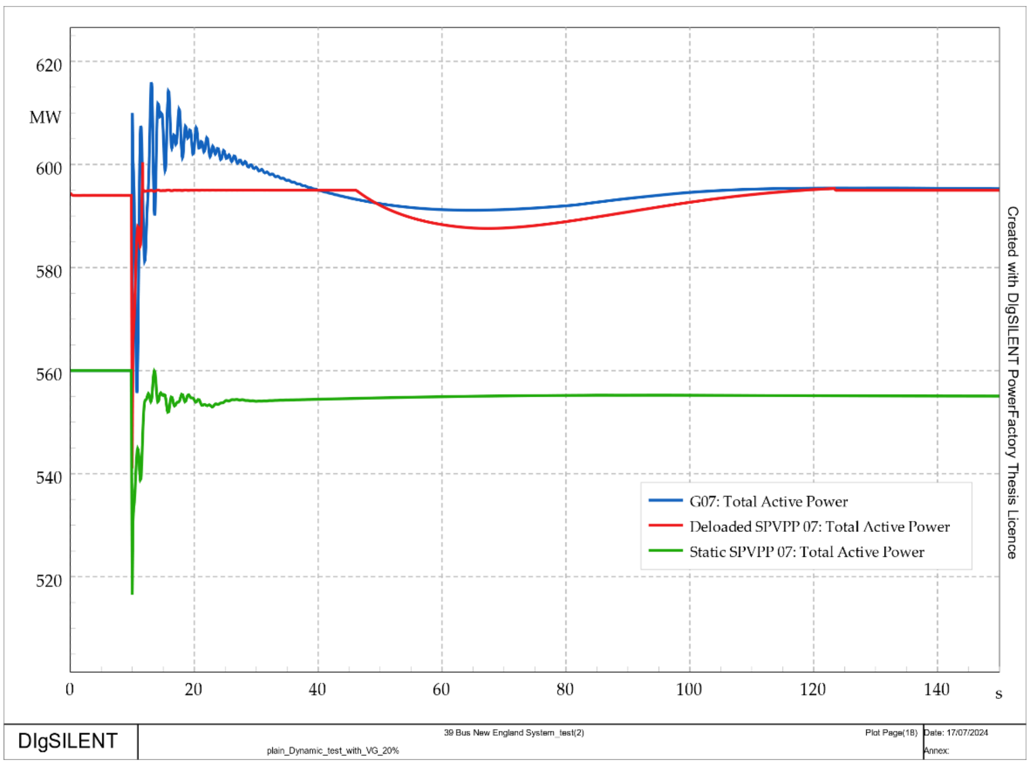


Fig. 9: Active Power response to a generator outage

The operating voltage (V_{dcin}) on the DC side of the converter reduces towards the maximum power point voltage- V_{dcref} to ramp up power of the deloaded SPVPP through the FFR action mechanism as shown in figure 10.

ISSN: 2957- 7780

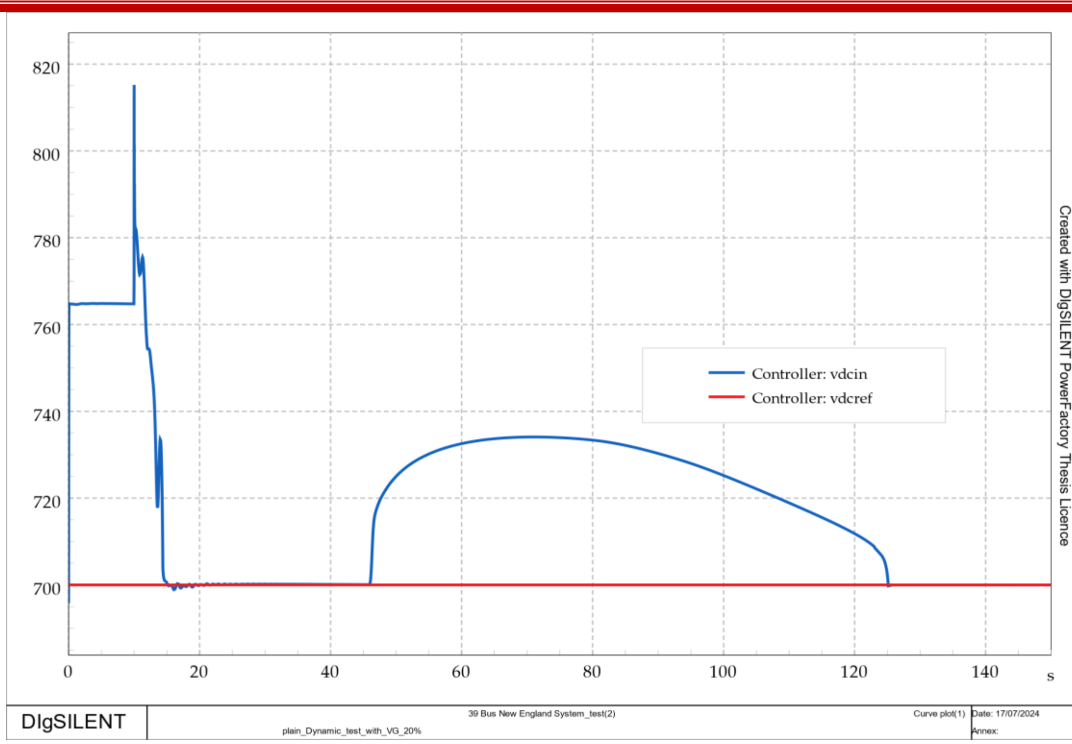


Fig. 10: Deloaded SPVPP operating voltage changes to a frequency event

The FFR action of deloaded SPVPPs enables power system operators to increase penetration levels without regard for the power system's average inertia. According to the findings, for FFR from deloaded SPVPPs to be effective in frequency control, it must be faster in response, larger in magnitude, and sustained over time.

4. Conclusion

This paper explores the technical viability of deploying SPVPPs as FFR sources to better post contingency frequency response for low inertia power grids for under-frequency disturbances such as major generator outage. This research established that, to better support frequency response, the FFR action from SPVPPs needed to be faster, larger with the possibility of being sustained for longer period. This frequency regulation strategy provides an avenue for enriching power grids with VG with little worry about inertia and frequency instability. Future work will investigate approaches to optimize the deloading level of SPVPP to avoid unnecessary power curtailment and ensure a minimum deloading level kept.

ISSN: 2957- 7780

REFERENCES

[1] B. K. Wamukoya, C. M. Muriithi, and K. K. Kaberere, "Improving frequency regulation for future low inertia power grids: a review," *Bulletin of Electrical Engineering and Informatics*, vol. 13, no. 1, pp. 76–87, Feb. 2024, doi: 10.11591/eei.v13i1.5873.

[2] IRENA, "Renewable capacity statistics 2021," 2021. Accessed: Jun. 06, 2022. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA_RE_Capacity_Statistics_2021.pdf

[3] S. C. Johnson, D. J. Papageorgiou, D. S. Mallapragada, T. A. Deetjen, J. D. Rhodes, and M. E. Webber, "Evaluating rotational inertia as a component of grid reliability with high penetrations of variable renewable energy," *Energy*, vol. 180, pp. 258–271, 2019, doi: 10.1016/j.energy.2019.04.216.

[4] B. Wamukoya, K. Kaberere, and C. Muriithi, "Improving Frequency Regulation for Future Low Inertia Power Grids with Increased Penetration of Variable Generation: A Review," in *IEEE AFRICON Conference*, Institute of Electrical and Electronics Engineers Inc., 2023. doi: 10.1109/AFRICON55910.2023.10293434.

[5] A. Fernández-Guillamón, E. Gómez-Lázaro, E. Muljadi, and Á. Molina-García, "Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time," *Renewable and Sustainable Energy Reviews*, vol. 115, no. January, p. 109369, 2019, doi: 10.1016/j.rser.2019.109369.

[6] G. Donnini *et al.*, "On the Estimation of Power System Inertia accounting for Renewable Generation Penetration," *12th AEIT International Annual Conference, AEIT 2020*, 2020, doi: 10.23919/AEIT50178.2020.9241204.

[7] B. Kroposki *et al.*, "Achieving a 100% Renewable Grid: Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," *IEEE Power and Energy Magazine*, vol. 15, no. 2, pp. 61–73, 2017, doi: 10.1109/MPE.2016.2637122.

[8] M. Dreidy, H. Mokhlis, and S. Mekhilef, "Inertia response and frequency control techniques for renewable energy sources: A review," *Renewable and Sustainable Energy Reviews*, vol. 69, no. November 2016, pp. 144–155, 2017, doi: 10.1016/j.rser.2016.11.170.

[9] A. Ulbig, T. S. Borsche, and G. Andersson, "Impact of low rotational inertia on power system stability and operation," *IFAC Proceedings Volumes (IFAC-PapersOnline)*, vol. 19, no. August 2014, pp. 7290–7297, 2014, doi: 10.3182/20140824-6-za-1003.02615.

[10] Q. Hong *et al.*, "Fast frequency response for effective frequency control in power systems with low inertia," *The Journal of Engineering*, vol. 2019, no. 16, pp. 1696–1702, 2019, doi: 10.1049/joe.2018.8599.

ISSN: 2957- 7780

[11] F. Zeng, J. Zhang, G. Chen, Z. Wu, S. Huang, and Y. Liang, "Online Estimation of Power System Inertia Constant under Normal Operating Conditions," *IEEE Access*, vol. 8, pp. 101426–101436, 2020, doi: 10.1109/ACCESS.2020.2997728.

[12] V. Baruzzi, M. Lodi, A. Oliveri, and M. Storace, "Analysis and improvement of an algorithm for the online inertia estimation in power grids with RES," *Proceedings - IEEE International Symposium on Circuits and Systems*, vol. 2021-May, no. 2, pp. 2–6, 2021, doi: 10.1109/ISCAS51556.2021.9401229.

[13] P. Makolo, I. Oladeji, R. Zamora, and T.-T. Lie, "Data-driven inertia estimation based on frequency gradient for power systems with high penetration of renewable energy sources," *Electric Power Systems Research*, vol. 195, p. 107171, Jun. 2021, doi: 10.1016/j.epsr.2021.107171.

[14] H. Golpira, A. Atarodi, S. Amini, A. R. Messina, B. Francois, and H. Bevrani, "Optimal Energy Storage System-Based Virtual Inertia Placement: A Frequency Stability Point of View," *IEEE Transactions on Power Systems*, vol. 35, no. 6, pp. 4824–4835, 2020, doi: 10.1109/TPWRS.2020.3000324.

[15] B. K. Poolla, S. Bolognani, and F. Dorfler, "Optimal Placement of Virtual Inertia in Power Grids," *IEEE Trans Automat Contr*, vol. 62, no. 12, pp. 6209–6220, 2017, doi: 10.1109/tac.2017.2703302.

[16] B. K. Poolla, D. Groß, and F. Dörfler, "Placement and Implementation of Grid-Forming and Grid-Following Virtual Inertia and Fast Frequency Response," *IEEE Transactions on Power Systems*, vol. 34, no. 4, pp. 3035–3046, 2019, doi: 10.1109/TPWRS.2019.2892290.

[17] C. Rahmann and A. Castillo, "Fast frequency response capability of photovoltaic power plants: The necessity of new grid requirements and definitions," *Energies (Basel)*, vol. 7, no. 10, pp. 6306–6322, 2014, doi: 10.3390/en7106306.

[18] A. Jawad and N. Al Masood, "A systematic approach to estimate the frequency support from large-scale PV plants in a renewable integrated grid," *Energy Reports*, vol. 8, pp. 940–954, 2022, doi: 10.1016/j.egyr.2021.12.017.

[19] G. Lammert, L. D. P. Ospina, P. Pourbeik, D. Fetzer, and M. Braun, "Implementation and validation of WECC generic photovoltaic system models in DIgSILENT PowerFactory," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, IEEE, Jul. 2016, pp. 1–5. doi: 10.1109/PESGM.2016.7741608.

[20] P. P. Zarina, S. Mishra, and P. C. Sekhar, "Exploring frequency control capability of a PV system in a hybrid PV-rotating machine-without storage system," *International Journal of Electrical Power and Energy Systems*, vol. 60, pp. 258–267, 2014, doi: 10.1016/j.ijepes.2014.02.033.

[21] P. Pachanapan, "Dynamic Modelling and Simulation of Power Electronic Converter in DIgSILENT Simulation Language (DSL): Islanding Operation of Microgrid System with Multi-energy Sources," 2021, pp. 67–93. doi: 10.1007/978-3-030-54124-8_3.

[22] G. Bhatt and S. Affljulla, “Analysis of large scale PV penetration impact on IEEE 39-Bus power system,” in *2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, IEEE, Oct. 2017, pp. 1–6. doi: 10.1109/RTUCON.2017.8124840.

[23] P. Demetriou, M. Asprou, J. Quiros-Tortos, and E. Kyriakides, “Dynamic IEEE Test Systems for Transient Analysis,” *IEEE Syst J*, vol. 11, no. 4, pp. 2108–2117, Jul. 2015, doi: 10.1109/jsyst.2015.2444893.

Characterization of Subgrade Soils in Prediction Modelling of Subgrade CBR using Falling Weight Deflectometer (FWD) for Pavement Evaluation in Kenya

C. Mugai[1*] K. Abongo [2], B. J. Odero [3]

1. Department of Civil, Construction & Environmental Engineering, Jomo Kenyatta University of Agriculture & Technology, P.O Box 62000-00200, Nairobi, Kenya

2.Department of Civil, Construction & Environmental Engineering, Jomo Kenyatta University of Agriculture & Technology, P.O Box 62000-00200, Nairobi, Kenya

3. Department of Civil, Construction & Environmental Engineering, Jomo Kenyatta University of Agriculture & Technology, P.O Box 62000-00200, Nairobi, Kenya

*Corresponding author: cwmugai@gmail.com

Abstract

The subgrade is the foundation upon which pavement structures are built. Its strength, as measured by parameters like CBR, directly influences the performance and durability of pavements. The California Bearing Ratio (CBR) is a key indicator of subgrade strength used in pavement design. Kenya's Road Design Manual Volume 3 classifies subgrades from S1 to S6, with median CBR values ranging from 3.5 to 45. However, traditional CBR testing is invasive and time-consuming, prompting interest in faster, non-destructive methods like the Falling Weight Deflectometer (FWD). FWD allows in-situ evaluation of pavement stiffness using surface deflections, making it suitable for large-scale assessments. Accurate CBR prediction from FWD data requires thorough subgrade characterization, including physical and mechanical properties. Poorly characterized subgrades can lead to early pavement failure, making proper evaluation essential for long-term performance. This paper seeks to first classify the soils in preparation for development of predictive models. 18 road sections, covering various regions in Kenya, were selected purposively from past pavement evaluation data base. Analysis was done on the samples from trench logs and laboratory test results. Soils from the selected road sections were characterized and classified using Unified Classification System (UCS). The average Plasticity Index for samples from all the road

 ISSN: 2957- 7780

section ranged from 7 to 23%, the OMC values were 12 to 27% and the MDD 1250 to 1821 Kg/m3. The average CBR for each road section ranged from 5% to 31%.

The study found that most road sections had multiple soil types with lean clay (CL) being the predominant soil class at 34% of the samples, followed by elastic silt (MH) at 33% and Silt with sand (ML) at 22%.

Keywords: Unified Classification System, Falling Weight Deflectometer, California Bearing Ratio, Sub-grade.

1. Introduction

The California Bearing Ratio (CBR) is a widely used measure of subgrade strength properties in pavement design and evaluation. The new Road Design Manual Volume 3 specifies the subgrade strength in terms of CBR and provides a range of subgrade classes from S1 to S6 with the median CBR ranging from 3.5 to 45 (G.O.K, 2025). However, due to the time-consuming and invasive nature of CBR tests, there has been growing interest in using non-destructive techniques, especially Falling Weight Deflectometer (FWD) testing, to predict CBR through empirical or machine learning models. Accurate prediction of CBR from FWD deflection data depends significantly on proper characterization of subgrade soils.

CBR remains a key input in empirical and mechanistic pavement design methods. However, laboratory CBR testing involves sample collection, soaking, compaction, and testing, making it unsuitable for rapid, large-scale field evaluations (George et al., 2010). In contrast, FWD testing allows for rapid in-situ assessment of pavement and subgrade stiffness through surface deflection measurements under dynamic loading.

Proper characterization of subgrade is essential for predicting its behavior under load and for designing appropriate improvement measures where necessary. Subgrade characterization typically involves the evaluation of physical, mechanical, and sometimes chemical properties of the in-situ soils. According to Rahman et al. (2011), poor subgrade conditions are among the leading causes of premature pavement failure. As such, understanding the properties of subgrade materials is crucial for ensuring structural adequacy and longevity of transportation infrastructure.

 ISSN: 2957- 7780

2. Study Sites

18 road sections, covering various regions in Kenya, were selected purposively from past pavement evaluation data base. Purposive sampling was preferred due to availability of data. The study site locations are indicated in Figure 1.

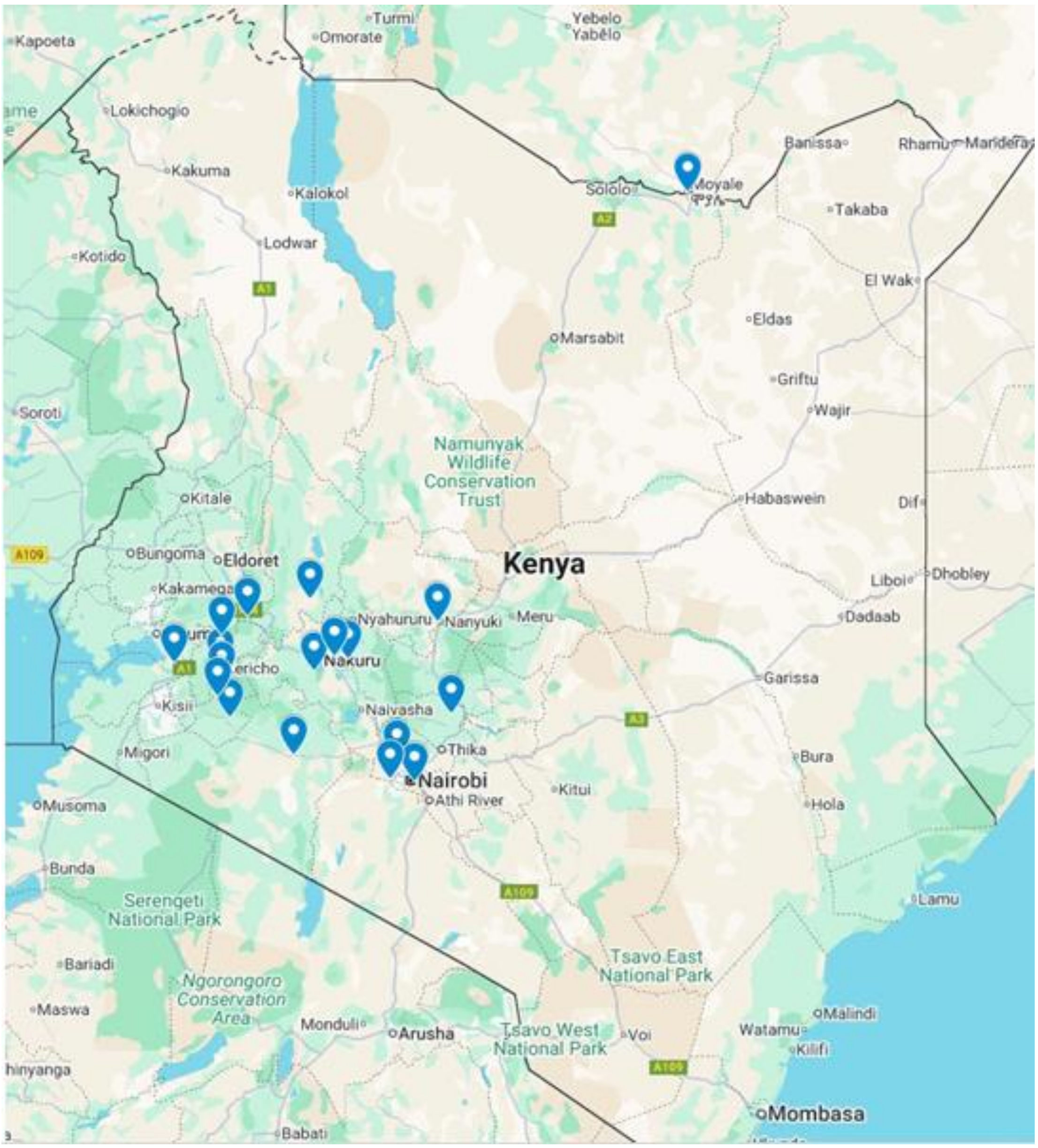


Figure 1: Map of Kenya showing the locations of the study sites

ISSN: 2957- 7780

3. Materials Used

The study utilized data from trenching logs, Laboratory results and Construction data. Subgrade materials had been extracted from 1m by 1m by approximately 1.5m deep trenches dug on the road shoulders and the samples were delivered in sealed sampling bags to the laboratory. CBR was then obtained by considering the maximum dry density and optimum moisture content determined from the Proctor test (Mugai et al., 2020). After the samples were extracted, the trenches were covered using nearby materials which were compacted in layers using a vibrating hammer. The top surface was protected using concrete.

4. Methodology

4.1. Sample Preparation

The soil samples were sufficiently dried to laboratory moisture conditions then sieved using a 5 mm sieve. To obtain a sample for sieve analysis, a riffle box was used where quartering of the sample was done.

4.2. Index Properties

Several parameters like grain size distribution, Atterberg limits, and moisture content were considered in identifying the soil type and its likely engineering behavior which is in accordance with Das (2016). These were important parameters in classifying soils under Unified Soil Classification System (USCS).

Soil was classified using Unified Soil Classification as follows:

i. Compilation of all data in one spreadsheet with the following information being captured: Road Name and location, Trial pit number, Depth of sample, chainage, density, moisture, CBR, Atterberg limits, Particle Size Distribution (PSD);
ii. Values passing 5mm (No. 4) and 0.075mm (No.200) BS sieves were highlighted;
iii. Where more than 50% was retained on No.200, the soil was grouped under “Coarse grained soils”. Where 50% or more passes No.200, the soil was grouped under “Fine-grained soils”. In this study, 167 samples were “fine-grained soils” while 8 were “coarse grained”;

ISSN: 2957- 7780

iv. Based on the Casagrande plasticity chart, a distinction was made between soils with LL less or greater than 50 (symbol L for Low and H for High), and between inorganic soil above the A-line;

v. Using the plasticity chart, the point where values of PI and LL intersect was located and the general group symbol recorded eg MH/OH; and,

vi. Computation was done to obtain gravel fraction, total course fraction and sand fraction as follows:

a) Gravel fraction = 100-%passing 5mm sieve

b) Total coarse fraction = 100 - %passing 0.075mm sieve

c) Sand fraction = (Total coarse fraction – Gravel fraction)/Total coarse fraction X 100

4.3. California Bearing Ratio (CBR)

This is a widely used empirical test that estimates the strength of subgrade soils. CBR is sensitive to soil type, moisture condition, and compaction level, as studied by George et al. (2010), making it a practical yet variable indicator of subgrade performance.

Figure 2: CBR Test

ISSN: 2957- 7780

CBR of the materials was obtained as follows:

i. The mass of soil to be used in the CBR test was first determined using proctor compaction test. This was done by considering the maximum dry density (MDD) and optimum moisture content (OMC) as determined from the Proctor test;
ii. From the mass obtained in (i) the wet mass to use for 3 layers was determined;
iii. The actual mass of wet material per mould with an addition of 500 g was determined;
iv. The dry mass per mould which considered the total wet mass and the present moisture content was determined;
v. The water to be added when mixing was then determined which is the product of the total dry mass and difference of optimum moisture content (OMC) and present moisture content (PMC);
vi. The measured-out sample was mixed with water determined in (v);
vii. The soil was placed in the mould in three layers. A filter paper was placed at the bottom of the mould and top of the sample;
viii. The mould with the compacted soil was then placed in a soaking tank for 4 days;
ix. On the 4th day, the sample was removed and allowed to drain water for about 15 minutes; and,
x. The sample in the mould was then assembled in the loading machine and penetration carried out on both sides of the mould.

5. Results and Discussion

5.1. Results on Classification

The study sought to first find out the soil classification for the samples from the various road sections and the CBR values. This information would be instrumental in developing predictive models using FWD data obtained from the road section studied.

The average Plasticity Index for samples from all the road section ranged from 7 to 23%, the OMC values were 12 to 27% and the MDD 1250 to 1821 Kg/m3. The average CBR for each road section ranged from 5% to 31%. The study found that most road sections had multiple soil types with lean

ISSN: 2957- 7780

clay (CL) being the predominant soil class at 34% of the samples, followed by elastic silt (MH) which was 33% of the samples.

Table 1 shows a summary of the soil classification and the CBR obtained on each road section. The numbers on the soil class signify the number of trenches with a specific soil class eg Road No. 1 had 4MH, CH and CL meaning there were four trenches with soil classified as MH, one trench with soil classified as CH and one trench with soil classified as CL.

Table 1: Summary of Soil classification and Average CBR per road section

Road No.	Location	Road Length (Km)	No of Trenches	Avg CBR	Avg PI	Avg LL	Avg OMC	Avg MDD	Avg % Passing No.4	Avg. % Passing No. 200	Soil Class (UCS)
1	Nakuru/Nyandarua	30	6	13	23	55	24	1382	91	54	4MH, CH,CL
2	Rift Valley/Kisumu	87	10	31	13	40	14	1761	63	22	7ML, 3CL
3	Marsabit	25	5	16	23	55	16	1699	66	26	2MH,CL,GM,GH
4	Kericho, Bomet	45	7	8	22	52	23	1371	91	70	3MH, 2CH, CL &ML
5	Nakuru, Baringo	85	6	9	12	40	21	1428	94	56	4ML & 2CL
6	Nakuru, Narok	50	6	9	16	42	25	1305	95	52	4CL &2ML
7	Narok	32	11	8	16	42	25	1250	92	58	5ML, 4CL, MH & CH
8	Nakuru, Nyandarua, Laikipia	53	7	16	21	56	22	1354	91	68	5MH, CH, ML
9	Laikipia	10	6	8	20	48	21	1401	95	66	4MH, ML,CL
10	Baringo, Elgeyo Marakwet	70	5	10	22	49	21	1305	96	84	3CL, 2MH
11	Nairobi	3.5	9	8	27	55	30	1332	92	78	5CH, 3MH, CL
12	Nairobi	3	4	21	18	50	17	1559	76	56	2CL, MH, ML
13	Homa Bay	45	5	22	14	41	13	1801	87	30	3CL, MH, ML
14	Bomet, Kericho	44	5	21	16	50	19	1533	90	59	3MH, CL &ML
15	Kisumu	15	3	12	16	40	22	1563	83	42	2CL,ML
16	Kericho,Kericho	38	8	31	21	47	19	1779	64	32	3CL, 3ML, CH, MH
17	Murang'a	11	21	12	23	52	25	1419	86	52	9MH, 5CH, 7CL,
18	Kikuyu	17	6	5	23	47	27	1396	100	77	4CL,CH,MH

Where MH represents Elastic Silt; CH is Fat Clay; CL is Lean Clay; ML is Silt with sand; GM is Silty Gravel.

Figure 3 outlines the various soil types found in all the road sections.

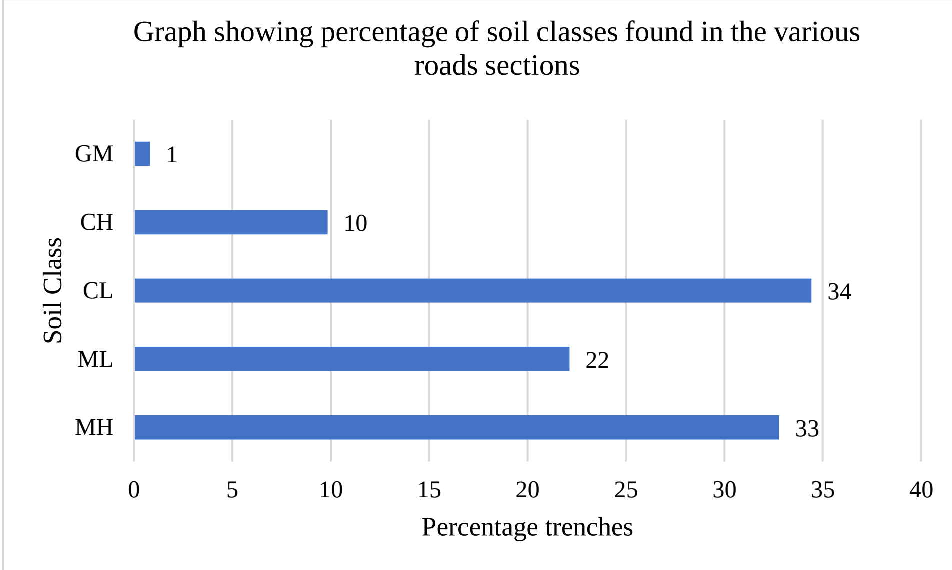


Figure 3: Soil types

5.2. Discussion

i. Most road sections had multiple soil types as shown on the results for the trial pits;

ii. Lean clay (CL) was the predominant soil class at 34% followed by Elastic silt (MH) at 33%. All road sections had a trial pit with soil classified as lean clay (CL) except Road No.11. These findings were in agreement with findings by Vasudeva Rao et al., 2019 who sought to characterize and map subgrade soils for future expansion of roads in Ethiopia. They used AASHTO classification system and found that the soils were mostly silt and clay type of materials.

iii. Chai et al (2013) sought to predict subgrade CBR using FWD for thin bituminous pavements. The model they developed was for sites with predominantly silty sand, clayey sand and clayey soil with AASHTO soil classification types A-2-4, A-2-7 and A-7-5. They further recommended that validation of their model be carried out when FWD deflection data are collected on pavements with different subgrade soils;

iv. The average Plasticity Index for samples from all the road section ranged from 7 to 23%, the OMC values were 12 to 27% and the MDD 1250 to 1821 Kg/m^3 and the CBR ranged from 5% to 31%;

ISSN: 2957- 7780

v. From the findings reported, the 4 major soil types ie Elastic silt (MH), Silt with sand (ML), Lean clay (CL) and Fat clay (CH) will be considered during development of models. Development of a model that can be applied on multiple soil classes as done by Chai et al will be considered.

6. Conclusion

This paper sought to characterize subgrade soils to enable development of models for predicting CBR from FWD deflections. From the results obtained, there were 3 major soil types ie Lean Clay (CL), Silt with sand (ML) and Elastic silt (MH). The influence of index properties on the predictive models will be investigated. Development of a model that can be applied on multiple soil classes as done by Chai et al will also be considered.

References

Chai, G. W., Argadiba, S., Stephenson, G., Condric, I., Oh, E. Y., & Manoharan, S. P. (2013). Prediction of subgrade CBR using FWD for thin bituminous pavements. *International Journal of Pavement Research and Technology*, *6*(4), 280–286. https://doi.org/10.6135/ijprt.org.tw/2013.6(4).280

Das, B. M. (2016). Principles of Geotechnical Engineering (9th ed.). Cengage Learning.

George, K. P., Uddin, W., & Luo, R. (2010). Subgrade characterization for highway design. Journal of Transportation Engineering, 136(12), 1237-1245.

G.O.K. (2025). *RDM 3.3 Road Design Manual Volume 3: Materials and Pavement Design for New Roads*.

Mugai, C., Sabuni, B., Neyole, E. & Mugai, F. (2020). Influence of Rice Husk Ash on Sub-grade Bearing Strength in Stabilization of Expansive Soils for Low Volume Roads in Kenya. *Civil and Environmental Research*

Rahman, M. A., Shukla, S. K., & Islam, M. M. (2011). Effectiveness of subgrade soil improvement using cement and fly ash. International Journal of Geotechnical Engineering, 5(3), 267-277.

Vasudeva Rao, P., Milkiase, L., & Lole, A. (2019). Characterization and Mapping of Subgrade Soils on Future Expansion Roads Between Kulfo and Hare Rivers. *International Journal of Engineering Development and Research*, *7*. www.ijedr.org

Performance of Park-and-Ride Stations in Nairobi Metropolis: A Case Study of Athi River and Syokimau Railway Stations

P.M. Mutua*, A. Ralwala & C. Mutali

Department of Architecture, Faculty of Built Environment & Design, University of Nairobi, Kenya

*Corresponding author: engpmutua@gmail.com

Abstract

Park-and-Ride stations are Intermodal Transfer Facilities (ITF) associated with Mass Transit Systems (MTS) in urban centres. They help to reduce traffic congestion and air pollution normally associated with increased automobile usage. However, successful performance of Park-and-Ride stations in terms of ridership numbers and parking utilization is dependent on some factors, which if not well investigated during planning and design of the facility can lead to failure or under-performance. This study on Performance of Park-and-Ride Railway Stations was carried out in Nairobi Metropolis. It employed quantitative and qualitative methods with primary data collected via questionnaires administered to commuters and the railway staff. Secondary data was obtained through documentary search and field surveys. The findings indicated that land use plan and character in the station influence area, operating train speed and schedules, availability of other socio-economic facilities like convenience stores, eateries and recreational facilities have a direct bearing on a station's performance. The study findings informed on improvement strategies recommended for the stations like introducing faster trains with condensed schedules, provision of connector transport to the stations, review and reconfiguration of the stations land area to create additional socio-economic facilities and collaboration among key stakeholders in re-planning the stations surroundings. The study also provided insights into other areas of further research, like impacts of land use and new transport development undertakings (e.g. the Nairobi Expressway) on existing transport facilities, among others.

Keywords: Park and Ride, Intermodal Transfer Facility, Mass Transit System, Ridership, Land Use Plan.

ISSN: 2957- 7780

1. Introduction

The key functions of an effective transport system are mainly mobility and accessibility. These functions also influence land use patterns and affect the lives of many people. A successful modern community in an urban set up require moving people, goods and services from one point to another which are critical components for its survival in an economic set up.

The urban managers in an urban set up should anticipate challenges and opportunities associated with an existing transportation system. Performance aspects are critical to the transportation system effectiveness which impacts on economic and social well-being of the dependent communities. An evaluation of performance of a transportation system begins with review of available data to identify where problems shall originate in the present time or in the future. Developing analysis tools or models to manipulate data and predict future behaviour of a system is therefore crucial (Banister, 1999).

The Nairobi Metropolitan Area (NMA) has been expanding significantly due to population growth and continues to experience worsening traffic congestion, urban sprawl and environmental degradation and deterioration among others urbanization problems. NIUPlan (2015) notes that urban developments have occurred without due regard to limitations associated with the existing transport infrastructure and utilities to support increasing developments especially in the urban fringes.

In the recent past, there has been minor extensions to the urban railway in NMA with relatively new stations developed with parking facilities to enable users of personal cars to park at the stations and ride the commuter train, in what is popularly known as Park-and-Ride (P&R) concept.

While the introduction of P&R stations in the NMA may be considered as one way to reduce cars in the main highways to the Central Business District (CBD) and consequently alleviate traffic congestion, under-utilization of a parking facility tends to be considered as a waste of public resources. This is more so when it fails to ameliorate increased car use along the highways to ease traffic congestion. The parking development in the station may therefore not measure up as an effective infrastructural investment for public gain.

ISSN: 2957- 7780

A parking lot may be perceived to be efficiently used when its occupancy threshold is generally in the range of 85% to 95% (Meyer, 2016). Individual lots of P&R facilities lacking successful demand characteristics depict an exaggerated transit system that is not efficient and therefore a classical waste of public funds (Spillar, 1997). This observation justifies the need to assess performance and therefore the study subject, i.e. performance comparison of Athi River and Syokimau Railway Stations.

1.1. Study Objectives

The objectives of the study were:

i. To investigate the best practices in planning and development of P&R stations.
ii. To establish the influence areas and their significance in contributing to ridership numbers to ACRS and SCRS.
iii. To find out the utilization levels of the P&R service at ACRS and SCRS and reasons behind such levels.
iv. To determine the suitability of ACRS and SCRS as P&R stations and make appropriate recommendations towards their improvement.

2. Literature Review and Situational Analysis

The most important factor for a successful and well-functioning sub-urban P&R facility is its ability to attract cars users to park their cars and transfer to a public transport system to continue with their journey and vice versa for the return trip (Spillar, 1997). In this regard, two key factors can gauge how well the P&R facility is performing, which are the parking utilization levels, and the ridership numbers generated ((Hamsa et al., 2021, p. 982).

2.1. The Inter-modal Transfer Facility Concept

Kaneko (2014) concisely makes a case for the following to be put into consideration in deciding the conceptual nature of an Inter-modal Transfer Facility (ITF) such as P&R facility:

a) As a transport hub for ensuring smooth transfer from one mode to another mode. Facilities associated with smooth transfer include bus terminal, bus berth, waiting space, riding/dropping space for private car and taxi, private car parking space for P&R, motorcycle and bicycle parking space, pedestrian deck, resting spaces, and sidewalks.

ISSN: 2957- 7780

b) As a place to revitalize the urban location or district where the facility is situated thereby promoting community interaction. In this regard, some commercial and recreational facilities need to be given consideration depending on the neighbourhood character.

Figure 2.1: A Station Plaza with Green Spaces and Rest Benches (Source: Kaneko, 2014).

2.2.Conceptual Framework for the Study

A conceptual framework has been devised for this study theme based on Miles & Huberman (1994) view that it is a graphical or narrative explanation of the ideas studied with the key variables brought out and highlighted with presumed relationship among them. Rukwaro (2016) further expounds that a conceptual framework when clearly articulated becomes a potential and useful tool to aid in deciding which data and information to collect and drawing meaning from the study findings.

The analysis of factors influencing performance of P&R facility while incorporating the intervening or mitigating variables through their interaction in the whole chain is visualised in Figure 2.2 below.

ISSN: 2957- 7780

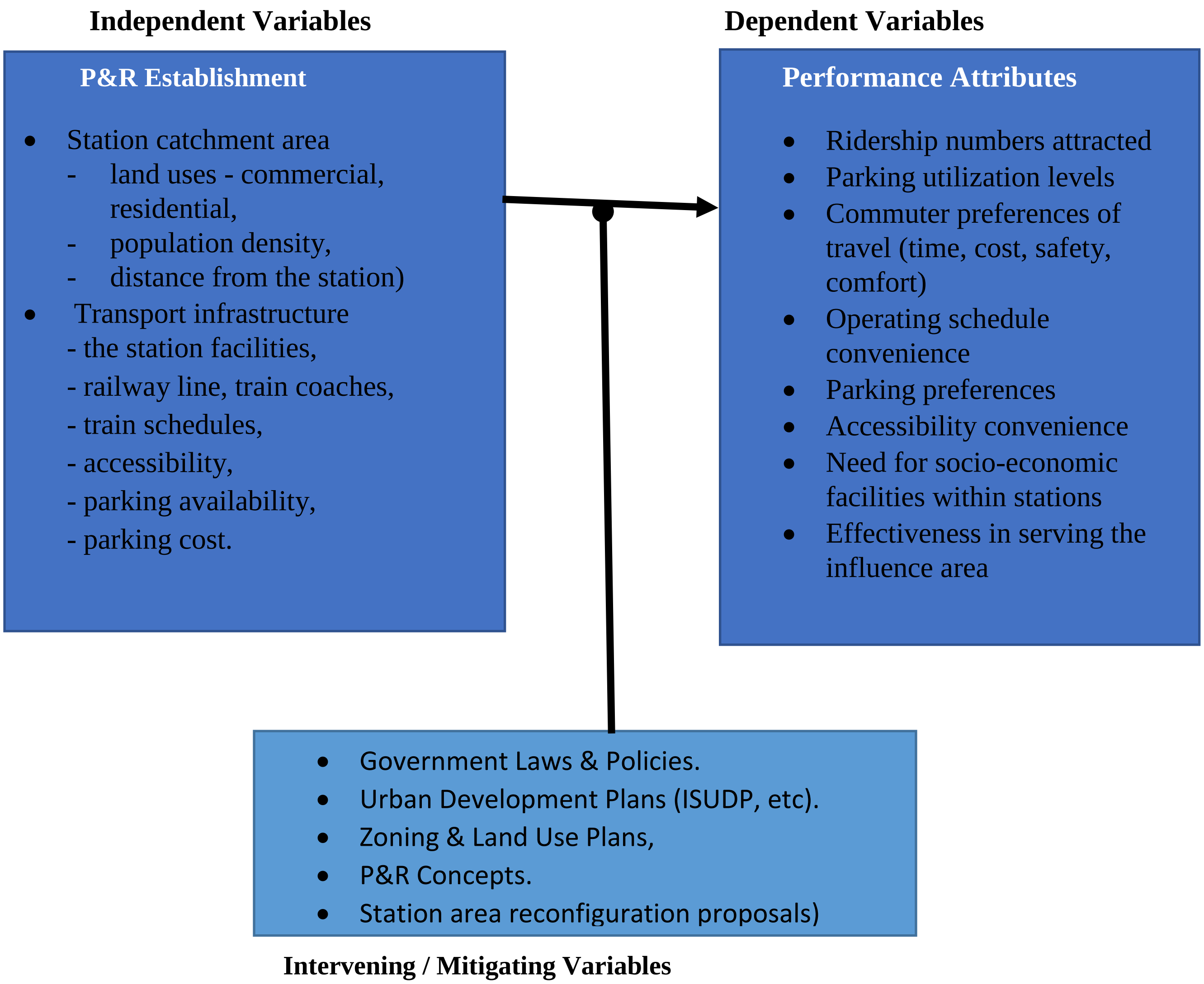


Figure 2.2: Conceptual Framework (Source: Author, 2023).

2.3.Criteria for Performance Assessment of the P&R Stations

The study variables were identified based on the overall objectives of this research and the researcher devised a weighted criteria to assess operational performance of the stations in meeting the needs desirable from a P&R environment.

Seven (7) criterion items were identified and applied by the researcher in performance assessment. Percentage weights were assigned depending on their significance on the P&R concept. The assessment was carried out from the quantitative study data and findings in Chapter 5. The selected criterion items from the dependent variables were as follows:

ISSN: 2957- 7780

i. Attraction and attainment of the expected train ridership numbers.
ii. Utilization levels of the provided parking facilities.
iii. Whether the P&R service meets the key commuter preferences of travel in a transport system which include avoidance of traffic jams, savings on travel cost and time, safety and comfort.
iv. Convenience of the train operating schedules to commuters.
v. Convenience of the parking facility to commuting car users.
vi. How commuters rated the need for developing socio-economic facilities for shopping or recreation, which are absent from the stations.
vii. Effectiveness of the stations in serving the influence area.

In arriving at the overall performance rating score for each station, percentage scores were categorised into five (5) bands using a commonly applied performance rating system in GoK institutions (Kenya Roads Board, 2023) as shown below.

- Below 50%: Unsatisfactory (signifies performance below expectations).
- 50% - 69%: Fair
- 70% - 79%: Good
- 80% - 89%: Very Good
- 90% - 100%: Excellent (this is the desired highest level of efficient performance).

2.4.Urban Development Plans for the Stations Location

Machakos County prepared an Integrated Strategic Urban Development Plan (ISUDP) covering the period 2020 to 2030 for one of its major Sub-counties, Mavoko. Mavoko Sub-county is also the main source of commuters to the two stations.The ISUDP proposes adoption of a Transit Oriented Development (TOD) in Mavoko which should be applied to help develop a compact city with the following aspects:

- Public transport hubs: These hubs could be established around the railway stations in Athi River town with mixed residential and commercial uses among other locations.
- Public space and infrastructure: the development of compact mixed-use communities around the transport hubs accompanied by structured public spaces, parks and supporting utilities.

ISSN: 2957- 7780

2.5. Influence Area and Demand Estimation

The influence area for P&R facility is critical to establish as this will be the source of users of the facility. If a feeder bus network is required, estimation of the coverage area has to be determined (Kaneko, 2014). The station influence area can range from 1km to 5km radius or even more, depending on the intensity of developments, available transport options and inherent needs connected to use of the station in the surrounding.

The Stations' influence area is critical in determining the success of the station of the stations in terms of the expected performance metrics mentioned here above. The characteristics of the influence area and land use activities are summarised in Table 2.1 below.

Table 2.1: Stations Influence Area Character (Source: Field surveys by Author, Google Earth Map)

Item Description	Influence Area	Land Use Activities
Station Area	Area directly adjoining the station or within the defined station property boundaries	• Station buildings / structures; parking area and open space; • Access road
Station Coverage	Area directly surrounding ITF or area within 100m radius of the railway station	• Commercial premises (mini-shop, bar, eateries points); Businesses and offices (post office, bank, Water & Sanitation Company) • Immediate supporting road and utilities infrastructure
	Area within 500m to 1Km radius of the railway station or within walking distance	• Commercial premises (shop, bar, eateries points); Residential dwellings; Industrial and warehouse activities; fuelling Stations; • Community facilities like markets, schools, hospitals, churches, mosques; • Steel and cement manufacture; • Open ground / undeveloped land; • Vegetables farming; River and flood plains; • Feeder roads network and PSV Stations
Station Catchment Area	Area that can be connected to the stations by feeder services (extends up to 5Km radius)	• GoK and County administrative offices • Technical training institutions; Police station • Public transport vehicle terminal; Shopping malls; Meat production; SGR station; • Export Processing Zone (EPZ) • Hotels and resorts • Livestock keeping and crop farming • Stone quarry and ballast production • All other urban activities in the 1km radius zone

ISSN: 2957- 7780

2.6.Research Gaps

The rationale for early P&R schemes was not grounded in research but rather on local experiments based upon supposition about the nature of traffic and congestion. In Kenya, the advent of P&R stations took place a decade ago in the NMA. However, their operational performance and economic impact to urban transport in the greater metropolitan scene is yet to be assessed properly. Table 2.2 below summarises the gaps identified.

Table 2.2: Knowledge Gaps Identified from Previous Studies (Source: Author, 2023)

Nature of the study area	**Knowledge gap identified**
A study in 2009 on the application of P&R and TOD concepts to develop a framework that can be used to maximize public transport patronage by S. Ginn.	• The study did not reveal the catchment area characteristics and distances to the stations which can influence the success of P&R facility. • The study did not examine other attributes like operating schedule convenience to commuters which can increase patronage.
A study in 2003 on factors that influence the choice of travel mode selection in major urban areas: "*The attractiveness of Park and Ride"* by L. Olson	The study did not reveal how users rate safety and security of the provided service among other key preferences of commuter travel.
A study in 2006 on the prices and quality of rail passenger services by Steer Davies Gleave Company, UK	The study was confined to fare pricing and the service itself but did not cover other measures that need to be taken by the railway operators to increase patronage like adjusting the train schedules or running faster trains for reliability and time saving.
A study in 2018 on factors that influence utilization of rail transport by private motorists at railway stations in Nairobi County, Kenya by J. Maina	The study did not investigate whether introduction of other facilities within or near the stations, e.g., shopping or recreation, could influence usage by the private motorist. Best practises in planning and development of P&R stations were also not researched or recommended.

3. Methodology

3.1.Introduction

A mixed research design was adopted for the study whereby both quantitative and qualitative research elements were applied in a complementary manner. Literature review (Chapter 2) on

ISSN: 2957- 7780

available work and materials also formed part of the research methods to answer the first objective on best practice to actualise functional P&R stations.

Additionally, a spatial analysis of the urban land use plans and activities within the stations' coverage area was carried out to understand local and regional planning and development issues to do with land optimization for ideal locations of land users and the supporting transport route networks.

Table 3.1 below gives the Kenya Railway Corporation (KRC) commuter statistics from both Athi River and Syokimau Stations. The average commuter numbers were given by the station masters for each station and used to compare with the computed train capacities.

Table 3.1: Commuter Railway One-Way Trip Statistics

Station Name	Capacity of One (1) Coach	No. of Coaches	No. of Trips	Passenger Statistics		
				Computed Capacity	Average Recorded Daily	% Ridership
Athi River Original Train	**62**	**5**	**1**	**310**	**190**	**61%**
Syokimau Original Train	62	7	1	434	270	65%
Syokimau DMU	98	2	2	392	330	82%
Syokimau Total				**826**	**600**	**73%**

(Source: KRC, February 2023)

From Table 3.1 above, it is noted that the average daily turn out of commuters is less than the computed train capacities for the two stations. For purposes of sampling, the target number of commuters was based on the computed train capacities which is the higher figure in both the stations.

3.2.Sample Size and Sampling Procedure

The research adopted the Nachmias & Nachmias (1992) formula in determining the sample size for commuters from the population of respondents given in table 4.2 above, while assuming 95% confidence level;

n = {(z*z) (p*q) N} / {e*e(N-1) +(z*z) (p*q)} where:

n = sample size;

ISSN: 2957- 7780

z = standard deviation at 95% confidence level (in this case 1.96 worked from tables showing areas under normal curve);
p = % of target population assumed to have similar characteristics (taken as 95% for this study);
q = 1-p
N = population size
e = margin of error at 95% confidence level
= 1-0.95; =0.05.

By substituting accordingly in the above equation,

$$n = 0.182N / (0.0025N + 0.1795)$$

From Table 3.1 above N for ACRS = 310 and N for SCRS = 826. Substituting N in the equation above, then:

- n (for ACRS) = 59.11; Say 60 and
- n (for SCRS) = 66.97; say 67.

To compensate for non-response during data collection, a 30% upward adjustment was made to the calculated sample as postulated by Israel (2012).

Adjusting the sample size for non-response, new sample size, n (new) = 130% * n. The final sample size are thus obtained as follows:

(i) ACRS sample size = 60 * 1.3 = 78 No. commuters;
(ii) SCRS sample size = 67 * 1.3 = 87 No. commuters.

The table below gives the final sample population for the target respondents in the study.

Table 3.2 Breakdown of Target Respondents (Source: Author, 2023)

Category	**Target Number**
a) Questionnaires	
Commuters to Athi River Station	78
Commuters to Syokimau Station	87
b) Interviews	
KRC Station Officers	2 Station Masters (1 at each station)
KRC Head Quarters Officer	1 officer

ISSN: 2957- 7780

3.3.Research Operationalization Matrix

Finally, a matrix for making the research operational was crafted by the researcher, based on the research objectives of the study. The matrix contained investigative questions to yield some responses for decision making. The type of variable and indicator, data source, collection, and analysis methods, what to measure and how to measure them were also captured in the matrix given in the succeeding Table 3.3 below.

ISSN: 2957- 7780

Table 3.3 Research Operationalization Matrix (Source: Author, 2023)

Investigative Question	**Name of Variable**	**Type of Variable**	**Indicator**	**Data Source**	**Data Collection method**	**Data Analysis Technique**	**Statistical Measure/Output**
Which place is source of the largest commuter numbers?	Source of commuters	Independent	Place names	Commuters	Questionnaire	Descriptive Analysis	Table; Frequencies. Percentages
What is the predominant land use within 5km radius of the Station?	Land use	Independent	Predominant land use activity	Field Observations, Maps	Field data & Maps review	Spatial Analysis	Spatial area description
How significant is the 5Km radius area in contributing to commuter numbers?	Influence area	Independent	Commuter numbers	Commuters	Questionnaire	Descriptive Analysis	Percentages; Bar Graphs
Which is the commonly used means of access to the station?	Transport means	Independent	Transport mode	Commuters	Questionnaire	Descriptive Analysis	Percentages; Pie charts
What is the capacity of the provided transport system	Transport facility	Independent	No. of coaches; No. of train trips	KRC Staff	Questionnaire	Quantitative Analysis	Tables; numbers
What is the average number of commuters using the station daily?	Ridership numbers	Dependent	Commuter numbers	Commuters	Questionnaire	Descriptive Analysis	Tables; Averages
What is the utilization level of the parking facility?	Level of utilization	Dependent	Utilised parking slots	KRC Staff; Author	Questionnaire; Field survey	Descriptive Analysis	Tables; Numbers; Percentages
How convenient is the provided P&R service to commuters?	P&R Service;	Dependent	Convenience level; Commuter opinion	Commuters	Questionnaire	Quantitative & Qualitative Analysis	Table, Percentages; Inferences (from qualitative analysis)

ISSN: 2957- 7780

Investigative Question	**Name of Variable**	**Type of Variable**	**Indicator**	**Data Source**	**Data Collection method**	**Data Analysis Technique**	**Statistical Measure/Output**
What are some of the appropriate practises to actualise functional P&R schemes?	Concept	Intervening	Applicable methods	Secondary Data	Literature Review	Deductive Reasoning	Applicable concepts
Would you recommend development of shopping premises and recreational facilities within or near the station to liven commuter experience?	Station area re-development	Mitigating / Intervening	Re-development proposals	Commuters. KRC Staff	Questionnaire	Descriptive Analysis	Table, Percentages,
What else could be done to attract more users to the park and ride service?	Attraction factors	Mitigating / Intervening	Actionable areas	Commuters KRC Staff	Questionnaire	Qualitative Analysis	Inferences

ISSN: 2957- 7780

4. Results and Discussion

4.1. Introduction

This chapter presents the findings from the field data collection exercise to investigate the situation at the stations. A discussion of the findings made and analysis was further undertaken to support the study objectives, as well as to validate the study proposition. Any challenges encountered in the field survey were also outlined.

It is pointed out that all the data and information in tables and figures given under this chapter were all from the field survey conducted in the month of February 2023 and are therefore purely of the author's construct.

4.2. Survey Response Rate

Questionnaires were prepared as discussed in Chapter 4 and administered randomly through physical distribution to commuters of the P&R service at the stations, as given Table 4.1 below. The overall response from each of the stations is also shown.

Table 4.1 Questionnaires Response Rate

Station	No. Issued	No. Returned	% Response
Athi River	78	57	73%
Syokimau	87	62	71%

Mugenda and Mugenda (2003) opines that a response rate of 70% and above is an excellent representative of the study sample. Thus, the two stations produced adequate responses for further analysis. The non-response by other commuters was attributed to circumstances surrounding their travel inside the train like their comfort levels to allow filling of the questionnaire freely.

4.3. General Information

Demographic information was gathered from the respondents like gender, age, and the timespan the commuter has been using the commuter train. This kind of information is of vital implication in travellers' choice of P&R transport service as argued by Clayton et al. (2014).

ISSN: 2957- 7780

4.3.1. Gender of the Respondent

The sample population in Athi River Station (ACRS) registered more male respondents which were double the size of female respondents while at Syokimau Station (SCRS), the female respondents were slightly more than men at 54% as shown in Figures 4.1(a) and 4.1(b) below.

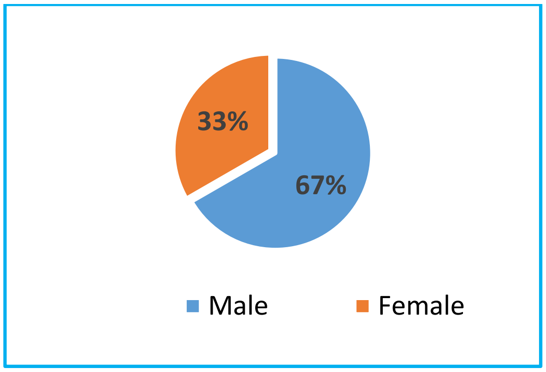


Figure 4.1(a): Gender Distribution – ACRS

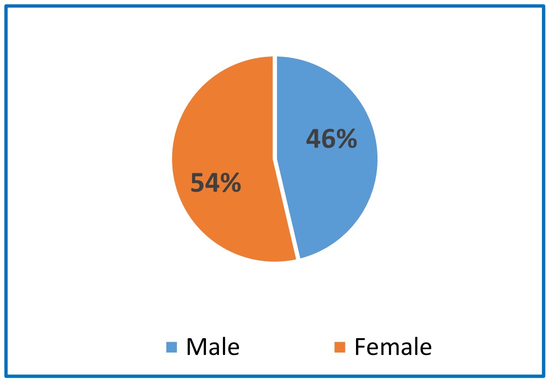


Figure 4.1(b): Gender Distribution - SCRS

From the findings above, it is possible to link the high number of car users parking and riding the train at Syokimau Station with female car owners who are assumed to want to avoid the strains and stresses associated with driving to the town centre along congested roads and streets. Conversely, this same gender at Athi River Station where car use was lower (see Section 5.4.4) was also less than the male gender.

4.3.2. Age of the Respondent

There is a strong correlation between age and travel behaviour. This can as well influence opinions arising from the survey. The figures below illustrate the age range for respondents in the study.

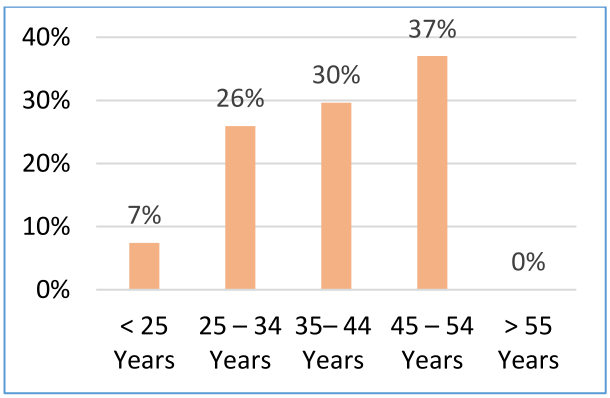


Figure 4.2(a): Age of Respondents – ACRS

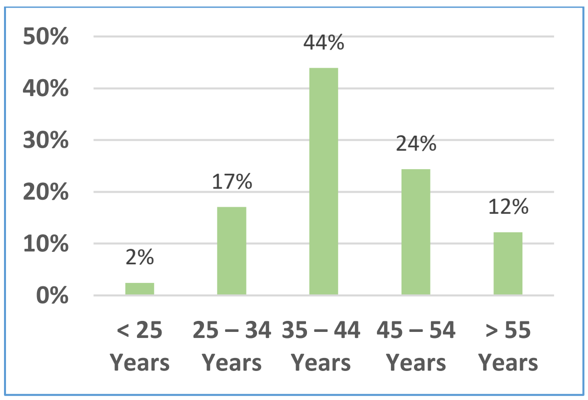


Figure 4.2(b): Age of Respondents - SCRS

ISSN: 2957- 7780

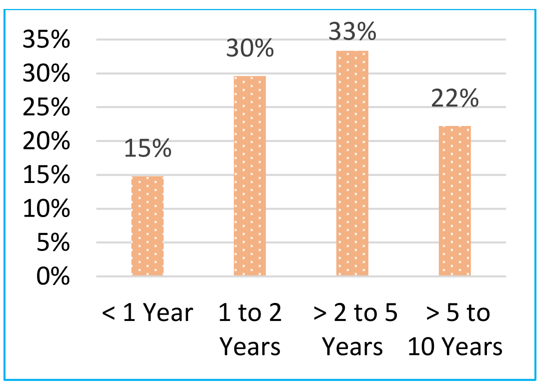
The dominant age for respondents in Athi River Station was in the range of 45 to 54 years at 37%. However, it was also observed that the age bracket of 25 to 54 years produced the largest proportion of travellers at 93%. In many cases, this is the working population in the Kenyan labour market, which captures the start of working life after college or university studies and early retirement age at 50 years.

The dominant age for respondents in Syokimau Station was in the range of 34 to 44 years at 44%. Similarly, and like for Athi River, the station had the working age bracket of 25 to 54 years producing the largest proportion of travellers at 85%.

It may easily be concluded that most of the travellers in the two stations were workers in various companies or institutions in the private or public sector.

4.3.3. Timespan for Usage of the Commuter Train

The timespan that respondents had used the commuter train was surveyed. The aim of this data was to judge whether the respondents could speak with certainty on issues of concern that touch on the commuter train based on their experience on a day-to-day basis in using the commuter train. The results of this survey are given in the bar charts here below.



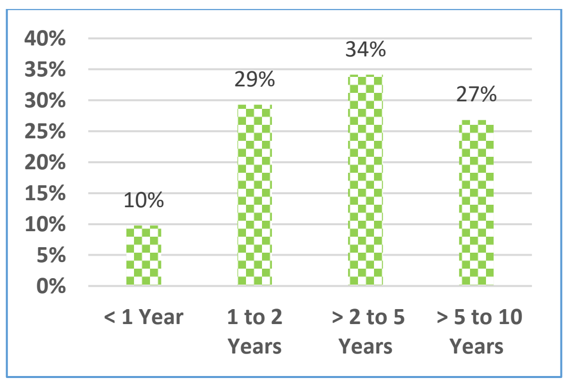


Figure 4.3(a): Years of Train Use – ACRS ***Figure 4.3(b): Years of Train Use - SCRS***

Both stations recorded 2 to 5 years as the most prevalent timespan users had used the commuter train. By combination of the age ranges, a sizeable number of respondents had used the trains for over a year at 85% for ACRS and 90% for SCRS and were therefore considered to be well informed on issues of concern that have affected commuters on a day to day.

 ISSN: 2957- 7780

4.4. Station Influence Area, Transport and Commuter Preferences

This section was designed to establish the location where most of the commuters were coming from, their transport means to the stations, and their reasons for preferring to use the train.

4.4.1. Residence of Respondents

The source of commuters to the station was established through this tool and statistics on various sources are represented graphically in the pie chart here below.

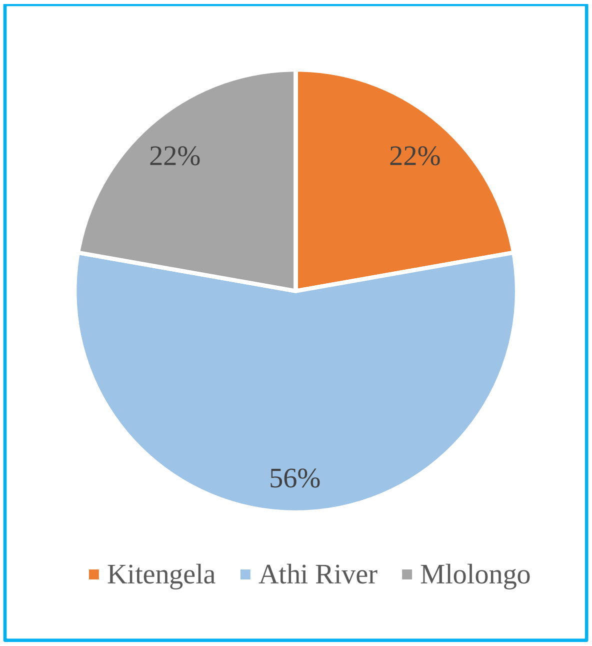


Figure 4.4(a): Residential Area – ACRS

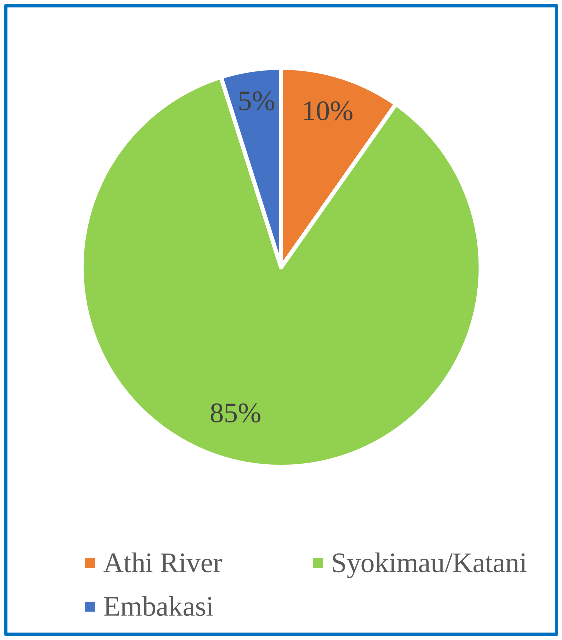


Figure 4.4(b): Residential Area - SCRS

From the pie chart above, it was observed that more than half of the commuter railway users in Athi River Station were from Athi River Town. The survey also revealed that there were users of the train service from Mlolongo Area (mostly expected to use Syokimau Station) which was the same number as that from Kitengela. It is noted that most of the commuter railway users in Syokimau Station were from the Syokimau / Katani Residential Area.

4.4.2. Locational Distance of Residences for Respondents

Locational distances of residences for the respondents in terms of varying distances to the train station were assessed with a view to establishing the distance covered by most of the commuters and ultimately the station influence area, which is the second objective of the study.

ISSN: 2957- 7780

The data below shows the results obtained from this analysis.

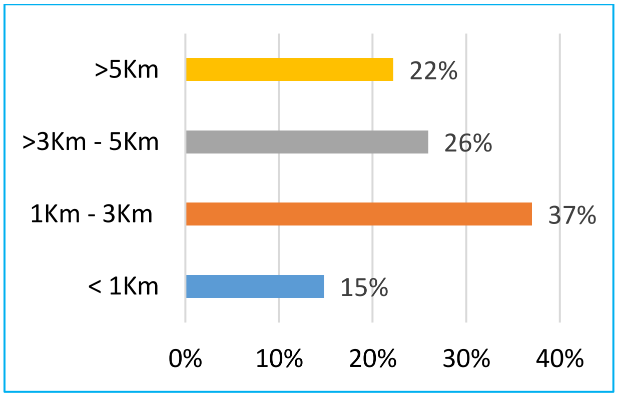


Figure 4.5(a) Residential Distances – ACRS

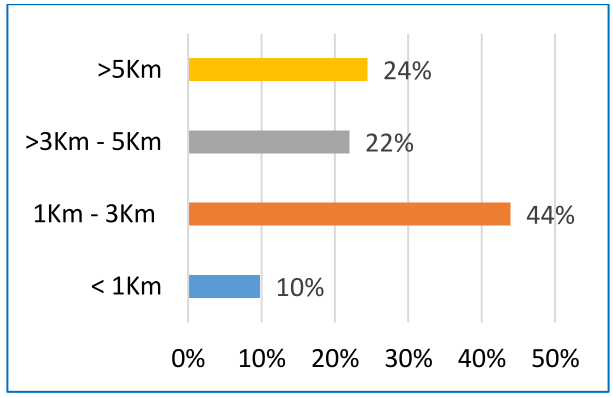


Figure 4.5(b): Residential Distances - SCRS

In both cases, it was notable that over 75% of the commuters in both stations were from a 5Km radius with Athi River Station at 78% and Syokimau Station at 76%. These distances were also commensurate with the recommended locational influence areas as given in Table 2.1.

4.4.3. Reasons for Preferring the Commuter Train

The survey sought to establish on some pre-determined reasons why the commuters preferred to use the P&R service. The objective was to identify the most popular reasons which would then require appropriate measures to best address it to improve utilization of the P&R service. This would aid in answering the third and fourth objectives of the study. The five-point Likert Scale rating was applied in this survey with parameters defined as follows:

1 = Strongly Disagree (SD); **2** =Disagree (D); **3** =Neutral (N); **4** = Agree (A) and 5 = Strongly Agree (SA).

To analyse the most popular reason in using the P&R service, there was aggregation of measures 4 = Agree and 5 = Strongly Agree. Similarly, to analyse the least popular reason in using the P&R service, measures 1 = Strongly Disagree and 2 = Disagree were combined for a unified score. The analysis then excluded parameter 3-Neutral since it was interpreted as indecision by the respondents. The outcome of the survey for the two stations is given in the tables here below. A similar approach was used for all the subsequent Likert scale cases undertaken in the study.

ISSN: 2957- 7780

Table 4.2(a) Reasons for Commuter Train Preference – Athi River Station

S/No.	Description	Least Popular (1 & 2)	1 (SD)	2 (D)	3 (N)	4 (A)	5 (SA)	Most Popular (4 & 5)
1	To avoid traffic jams	**8.3%**	8.3%	0.0%	8.3%	37.5%	45.8%	**83.3%**
2	To save on travel cost and time	**20.8%**	12.5%	8.3%	12.5%	20.8%	45.8%	**66.7%**
3	The station parking cost is less than the parking fee in Nairobi CBD	**9.5%**	4.8%	4.8%	23.8%	28.6%	38.1%	**66.7%**
4	The train service is safe and secure	**4.3%**	4.3%	0.0%	4.3%	34.8%	56.5%	**91.3%**
	Average Percentage	**10.8%**	**7.5%**	**3.3%**	**12.2%**	**30.4%**	**46.6%**	**77.0%**

From the analysis illustrated in Table 4.2(a) above for Athi River Station, safety and security of the train emerged the most popular and agreed reason for preferring the train at 91.3%. This finding may have a correlation with age of the train users as established at Athi River station most of whom were falling in the 45 to 54 years age bracket. This age group may want to take the secure and safe options of transport to avoid accidents. Avoidance of traffic jams followed at 83.3% while savings on travel cost and time tied with the station parking cost being less than that at Nairobi CBD, the destination point, at 66.7%.

Generally, 10.8% of the respondents conveyed their disagreement with the statements as factors influencing commuter train preference with only 12.2% of them indicating their neutrality in the reasons. A total of 77% of respondents agreed with the reasons thus validating their relevance and significance in usage of the commuter train.

ISSN: 2957- 7780

Table 4.2(b) Reasons for Commuter Train Preference – Syokimau Station

S/No.	Description	Least Popular (1 & 2)	1 (SD)	2 (D)	3 (N)	4 (A)	5 (SA)	Most Popular (4 & 5)
1	To avoid traffic jams	**7.9%**	5.3%	2.6%	5.3%	21.1%	65.8%	**86.8%**
2	To save on travel cost and time	**10.3%**	0.0%	10.3%	10.3%	17.9%	61.5%	**79.5%**
3	The station parking cost is less than the parking fee in Nairobi CBD	**14.3%**	5.7%	8.6%	14.3%	14.3%	57.1%	**71.4%**
4	The train service is safe and secure	**13.9%**	2.8%	11.1%	8.3%	19.4%	58.3%	**77.8%**
	Average Percentage	**11.5%**	3.4%	8.1%	9.5%	18.2%	60.7%	**78.9%**

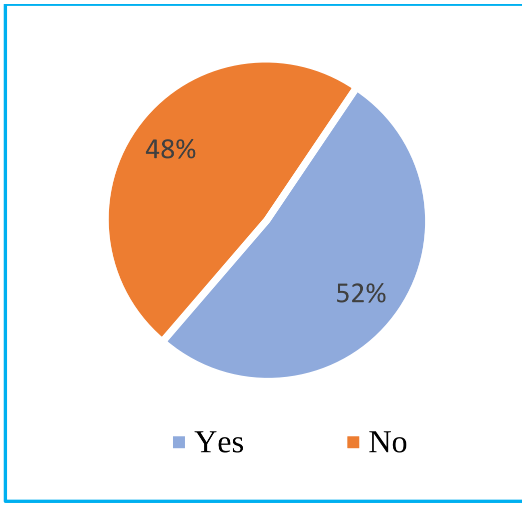
From the analysis in Table 4.2(b) above for Syokimau Station, avoidance of traffic jams emerged the most popular and agreed reason for preferring the train at 86.8% followed by savings on travel cost and time at 79.5% while safety and security followed closely at 77.8% with the station parking cost being less than that at CBD coming last at 71.4%.

Overall, 11.5% of the respondents voiced their disagreement with the statements as reasons influencing commuter train preference with only 9.5% of the respondents indicating their neutrality in the reasons. A total of 78.9% of respondents agreed with the reasons thus validating their relevance and significance in usage of the commuter train.

4.4.4. Car Ownership Statistics for Commuters

A key variable that this research sought to investigate is the number of car-owning commuters for each of the study station. The pie charts below represent the percentage ownership of cars among the train commuters.

ISSN: 2957- 7780



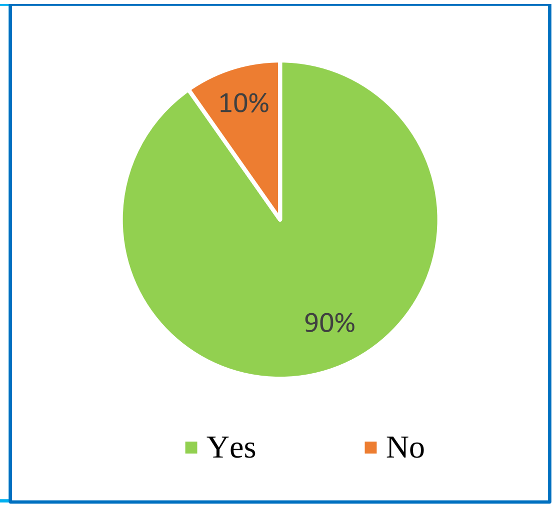


Figure 4.6(a): Car Ownership at ACRS Figure 4.6(b): Car Ownership at SCRS

As may be seen from the pie charts above, use of personal car to access the stations was dominant at Syokimau Station at 90% as compared to Athi River Station at 48% (nearly half the number at Syokimau). A further investigation of alternative means of access to the station revealed that 71% of respondents at Athi River Station relied on walking against 41% in Syokimau Station. This was a clear indication that car use in accessing Athi River Station was low. This finding would have significance in proffering recommendations for sustainability of the station as P&R facility as envisaged under the fourth objective of the study.

4.4.5. Convenience of the Park-and-Ride Service

The P&R service was further evaluated in terms of satisfaction of the commuters to the facilities offered by KRC. The five-point Likert scale was applied in this evaluation for defined areas of facility provision. The following key areas were explored:

a) Parking for commuters.
b) Prevailing train departure and arrival schedule; and
c) The available public transport means (matatu or connector bus) to take passengers to the stations.

Parking for Commuters

The Parking for each station was evaluated separately as given in the tables below.

ISSN: 2957- 7780

Table 4.3(a) Parking Convenience at Athi River Station

S/No.	Statement	Least Convenient (1 & 2)	1 (SD)	2 (D)	3 (N)	4 (A)	5 (SA)	Most Convenient (4 & 5)
1	Parking fee is affordable	**15.4%**	0.0%	15.4%	7.7%	46.2%	30.8%	**76.9%**
2	Payment mode is convenient	**30.8%**	7.7%	23.1%	23.1%	30.8%	15.4%	**46.2%**
3	Parking facility is accessible	**7.7%**	0.0%	7.7%	7.7%	53.8%	30.8%	**84.6%**
4	Cars are secure in the parking	**0.0%**	0.0%	0.0%	7.7%	38.5%	53.8%	**92.3%**
5	Persons with disability can use it conveniently	**8.3%**	0.0%	8.3%	16.7%	58.3%	16.7%	**75.0%**
	Average Percentage	**12.4%**	**1.5%**	**10.9%**	**12.6%**	**45.5%**	**29.5%**	**75.0%**

From the analysis illustrated in Table 4.3(a) above for Athi River Station, parking convenience ranked as follows:

a) Security of cars at the parking was highest ranked at 92.3%.
b) Accessibility of the parking followed at 84.6%.
c) Affordability of parking fee and usability of the P&R service by persons with disability ranked closely at third and fourth with 76.9% and 75% respectively.
d) Convenience of the payment mode for parking scored lowest at 46.2%.

12.4% of the respondents disagreed with the statements on parking facility provided and influencing utilization of the facility with 12.6% of the respondents indicating their neutrality in the reasons. A total of 75% of respondents agreed with the reasons thus validating the status quo of the parking facility and usage as a P&R facility.

However, the survey took a keen attention on the payment mode used at the station being the lowest ranked in importance and which also elicited an appreciably high proportion of negative responses compared to the rest with 30.8% disagreeing with the statement. In this regard, various respondents suggested adoption of other convenient methods of payment which were:

 ISSN: 2957- 7780

(i) Fully automate car park payment system.

(ii) Introduce MPesa payments for parking.

Here below are the results for Syokimau Station on the same aspects of parking.

Table 4.3(b) Parking Convenience at Syokimau Station

S/No.	Statement	Least Convenient (1 & 2)	1 (SD)	2 (D)	3 (N)	4 (A)	5 (SA)	Most Convenient (4 & 5)
1	Parking fee is affordable	**13.9%**	11.1%	2.8%	11.1%	22.2%	52.8%	**75.0%**
2	Payment mode is convenient	**11.4%**	5.7%	5.7%	14.3%	28.6%	45.7%	**74.3%**
3	Parking facility is accessible	**5.6%**	5.6%	0.0%	11.1%	27.8%	55.6%	**83.3%**
4	Cars are secure in the parking	**8.3%**	5.6%	2.8%	8.3%	19.4%	63.9%	**83.3%**
5	Persons with disability can use it conveniently	**6.1%**	3.0%	3.0%	27.3%	15.2%	51.5%	**66.7%**
	Average Percentage	**9.1%**	**6.2%**	**2.9%**	**14.4%**	**22.6%**	**53.9%**	**76.5%**

From the analysis above for Syokimau Station, parking convenience ranked as follows:

a) Parking accessibility and security of cars at the parking were highest ranked and tied at 83.3%.

b) Affordability of the parking fee and convenience of the parking payment method ranked closely at second and third with 75% and 74.3% respectively.

c) Usability of the P&R service by persons with disability scored lowest at 66.7%.

9.1% of the respondents conveyed their disagreement with the statements with only 14.4% of the respondents deciding to be neutral. A total of 76.5% of respondents agreed with the reasons thus validating the parking facility and its significance in usage as a P&R facility.

Trains Schedule and Means of Access to the Stations

The convenience of the stations was again evaluated against three statements tailored on the available means of access and the commuter train timetable as scheduled by KRC. These two aspects were evaluated together as the prevailing departure/arrival schedule may influence a

ISSN: 2957- 7780

traveller's choice of the means to use to access station. The results on the statements assessed on a Likert scale and pie charts on suitability of the train schedules are given here below. This assessment aided in answering the third and fourth objective of the study.

a) Athi River Station

Table 4.4(a) Athi River Station Train Schedule and Station Access

S/No.	Statement	Least Preferred (1 & 2)	1 (SD)	2 (D)	3 (N)	4 (A)	5 (SA)	Most Preferred (4 & 5)
1	The train departure/arrival schedule time is convenient	**29.6%**	14.8%	14.8%	22.2%	25.9%	22.2%	**48.1%**
2	My residential area has no available public transport means (matatu, bus) to take passengers to the station	**19.2%**	15.4%	3.8%	15.4%	15.4%	50.0%	**65.4%**
3	Introducing a Railway Connector Bus or PSV in my area can increase the number passengers to the train station	**12.5%**	4.2%	8.3%	20.8%	20.8%	45.8%	**66.7%**
	Average Percentage	**20.5%**	**11.5%**	**9.0%**	**19.5%**	**20.7%**	**39.4%**	**60.1%**

The ranking on the three statements for Athi River Station above was as follows:

a) Introduction of a railway connector bus was highest at 66.7%
b) Response on areas without public transport for access to the stations followed with 65.4% (needs connector bus)
c) Train schedule was last at 48.1%.

The convenience of the train schedule was further investigated by requesting the respondents to indicate their preferred train departure and arrival timings. Kenya Railways operates only one train trip to and from the Athi River Station each day from Monday to Friday. The findings of this running schedule against any other preferred timings by respondents are capture in the pie charts below.

i) Athi River Morning Train

 ISSN: 2957- 7780

The outcome of the survey on the Athi River Commuter train schedule, morning departure at 6.20am and arrival at CBD central station at 7.46am (takes 1hr and 26 minutes) revealed that the current departure and arrival times (37% and 29.6%) is not convenient for commuters. The outcome of this survey is shown in the pie charts Figure 4.7(a) and Figure 4.7(b) here below.

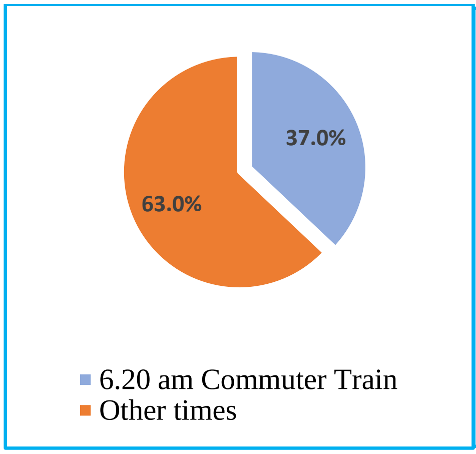


Figure 4.7(a): Preferred ACRS Departure Time

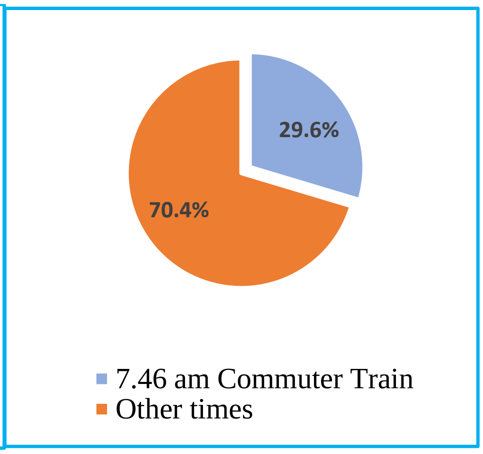


Figure 4.7(b): Preferred CBD Arrival Time

ii) Athi River Evening Train

From the pie charts on evening departure time here below, it was of interest to learn that the evening departure time of 5.50 pm from Nairobi Central Station was preferred by most of the respondents at 66.7% while the arrival time of 7.13 pm at Athi River was not convenient for many, scoring lowly at 22%. The resultant train journey was 1hr and 23minutes nearly the same as the morning journey.

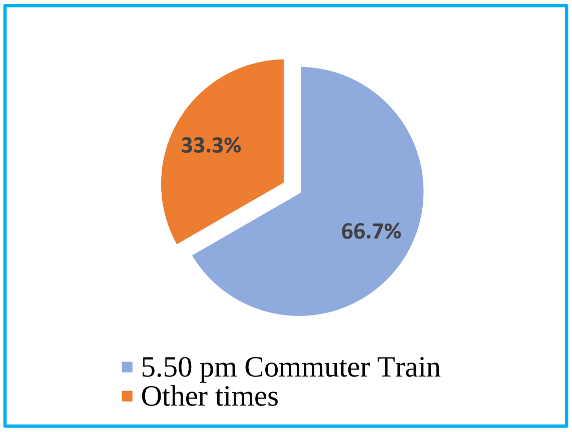


Figure 4.7(c): Preferred CBD Departure Time

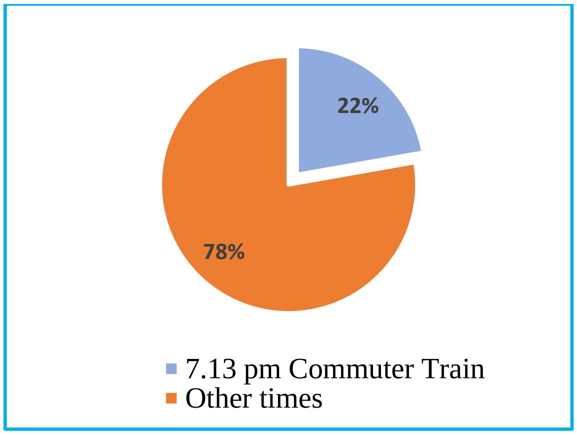


Figure 4.7(d): Preferred ACRS Arrival Time

ISSN: 2957- 7780

Thus, from the analysis above, ***only the evening departure time from Nairobi CBD Central Station*** was found to be okay with most of the commuters at ACRS.

(a) Syokimau Station

Table 4.4(b) Syokimau Station Train Schedule and Station Access

S/N	Statement	Least Preferred (1 & 2)	1 (SD)	2 (D)	3 (N)	4 (A)	5 (SA)	Most Preferred (4 & 5)
1	The train departure/arrival schedule time is convenient	**10.8%**	0.0%	10.8%	18.9%	45.9%	24.3%	**70.3%**
2	My residential area has no available public transport means (matatu, bus) to take passengers to the station	**26.5%**	20.6 %	5.9%	17.6%	23.5%	32.4%	**55.9%**
3	Introducing a Railway Connector Bus or PSV in my area can increase the number passengers to the train station	**8.1%**	5.4%	2.7%	10.8%	16.2%	64.9%	**81.1%**
	Average Percentage	**15.1%**	**8.7%**	**6.5%**	**15.8 %**	**28.6 %**	**40.5 %**	**69.1%**

The ranking on the three statements for Syokimau Station above was as follows:

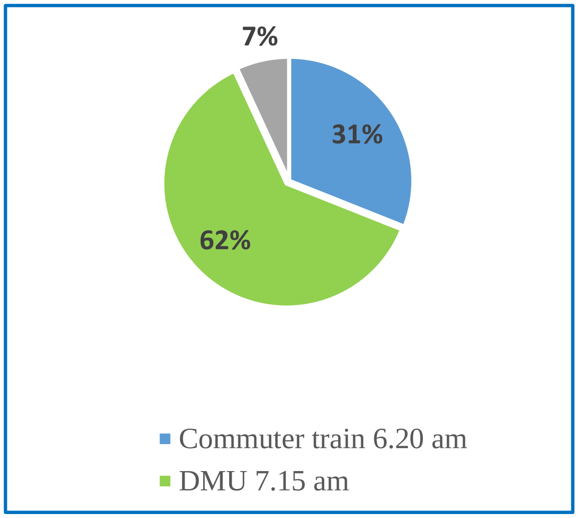
a) Introduction of a railway connector bus was highest at 81.1%
b) Train schedule was second at 70.3%
c) Areas without public transport for access to the stations ranked lowest at 55.9%.

The convenience was further investigated by requesting the respondents to indicate their preferred train departure and arrival timings based on the various train trips that Kenya Railways runs to and from the Syokimau Station. In the morning, KRC operated three (3) train trips while in the evening, the train trips were reduced to two (2). The findings of this survey on the prevailing train schedules operated at Syokimau Station are capture in the pie charts below.

(i) Syokimau Morning Trains

As can be seen from the pie charts 5.5(a) and (b) below, the DMU schedule option introduced by Kenya Railways at Syokimau Station emerged the most preferred at 62% for departure at 7.15 am and 63% arrival at CBD at 7.50 am respectively.

ISSN: 2957- 7780



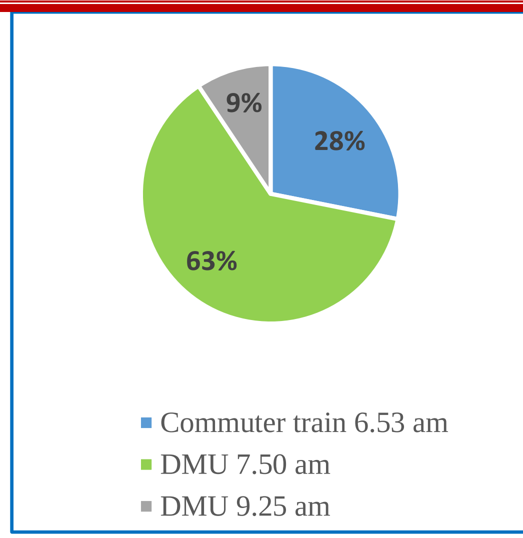
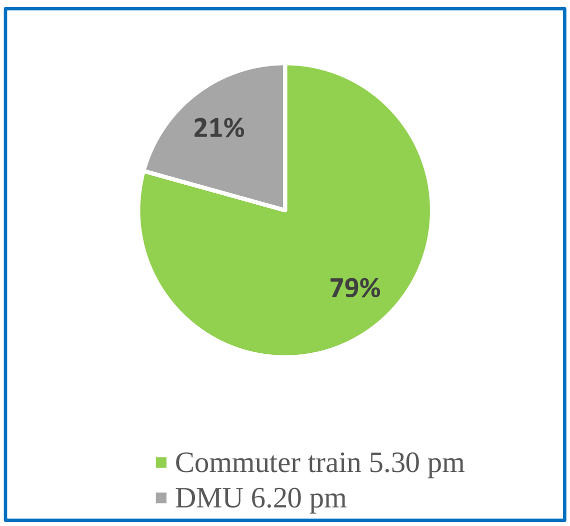


Figure 4.8(a): Preferred SCRS Departure Time Figure 4.8(b): Preferred CBD Arrival Time

(ii) Syokimau Evening Trains

From the analysis by pie charts here below, the ordinary evening commuter train with a schedule of 5.30 pm departure from CBD Central Station and 6.13 pm arrival at Syokimau Station emerged the most preferred at 79% and 76% respectively. Apparently, the type of train operated didn't matter as DMU was unpopular in the evening return trip while it was popular in the morning trip, which is implies the running schedule is more critical in terms of departure and arrival timings.



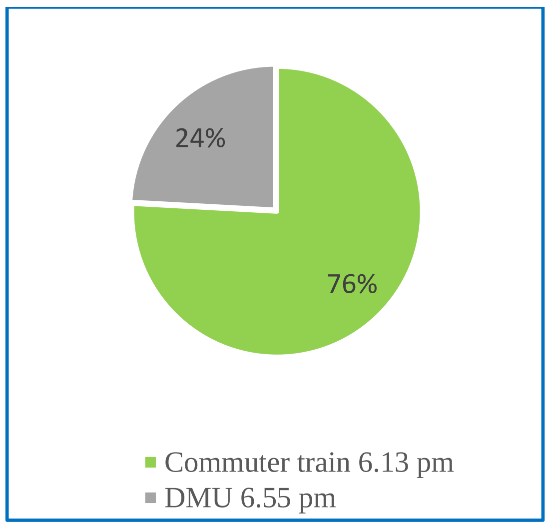


Figure 4.8(c): Preferred CBD Departure Time Figure 4.8(d): Preferred SCRS Arrival Time

 ISSN: 2957- 7780

Suggestions on Ways to Improve on the Park-and-Ride Service

Respondents were further required to give suggestions on what they thought KRC should do to improve the convenience of the P&R service. The varied suggestions given were extracted from the questionnaires as itemised here below.

a) Suggestions by Commuters

- Put up more infrastructure on the stations such as commuting videos, security lights, car sheds, car wash facilities etc.
- Adhere to time schedule and avoid stop overs (express train).
- Undertake media campaigns to enlighten the public on existence of the P&R service.
- Introduce new or modern trains to attract more users to the P&R service.
- Make the parking fees and fare rates affordable to many commuters.
- Fully automate car park payment system.
- Introduce MPesa payments for parking.
- Avail pre-loaded cards for payment at the entry gates to the riding platform.
- Allow 24hrs access to the station for commuters to pick their cars.
- Introduce much faster train or a DMU to depart from ACRS at 7.30am.
- Reduce the journey time taken by the train to and from ACRS to maximum 40 minutes.
- Run more than three train trips in a day to Athi River for more options to the public.
- Introduce another rail line from Imara Daima to Central Station to avoid wasting time waiting for the other trains from Embakasi, Ruiru, etc to pass.
- Introduce a P&R service at Kitengela Station.
- Repair the road serving ACRS from the Athi river - Namanga Highway. The rail-road junction crossing is very rough for cars.

b) Suggestions by Station Managers

Similarly, the station managers for the two stations were requested for feedback from customer perspective point of view based on their experience derived from handling commuters. The consolidated feedback cutting across both stations as received is as given below: -

- Advertise or market the P&R service to increase awareness by urban dwellers.

ISSN: 2957- 7780

- Introduce DMUs which are faster to the routes.
- Introduce overnight parking in case one is delayed in town to pick the car before 9pm (cars parked beyond this time attracts a fine).
- Develop and introduce differentiated fares for DMUs considering peak and off-peak hours for increased patronage of the service.
- Introduce amenities like car wash and electric vehicle charging points at the advent of electric driven vehicles.

As may be seen from the feedback by both commuters and the station managers, the following suggestions featured prominently and may comprise the quick wins that KRC could take to improve the P&R service:

(i) Introduce faster trains like DMUs to the Athi River Route.
(ii) Carry out Media campaigns on the use of commuter rails to enlighten the urbanites.
(iii) Allow 24hrs access to the station by commuters to collect cars.
(iv) Develop and introduce differentiated affordable fares for various train trips (DMUs) considering peak and off-peak hours for increased patronage of the service.
(v) Introduce amenities like car washing facilities, car shed, security lights commuting videos and even electric vehicle charging points at the advent of electric driven vehicles.

4.5. Land Use Factors and Station Area Re-configuration

This is the last and final section of the questionnaires which aimed at establishing whether the station users or commuters would prefer other essential investments of residential, commercial, or recreational nature within and around the stations. This could be achieved by way of land use changes that can be occasioned to transform the stations and their environs. KRC might consider developing or facilitating the investments through other entities. By reconfiguring the area based on the ascertained needs, this could make them more attractive and even increase the ridership numbers in future and goes a long way in answering the fourth objective of the study. The survey was based on statements measured on a 5-point Likert Scale as shown below.

Table 4.5(a) Athi River Station Area Land Use Changes and Transformation

S/No.	Statement	Least Accepted (1 & 2)	1 (SD)	2 (D)	3 (N)	4 (A)	5 (SA)	Most Accepted (4 & 5)
1	Preference for affordable houses near the station for access convenience	**30.8%**	19.2%	11.5%	19.2%	11.5%	38.5%	**50.0%**
2	KRC should develop shopping premises/mini malls within the station area to allow commuter shopping on their way home in the evening	**25.9%**	14.8%	11.1%	3.7%	29.6%	40.7%	**70.4%**
3	Recreational facilities, e.g. mini parks with benches or a fitness gym are necessary to liven or energize the commuter experience	**17.2%**	10.3%	6.9%	13.8%	34.5%	34.5%	**69.0%**
	Average Percentage	**24.6%**	**14.8%**	**9.8%**	**12.2%**	**25.2%**	**37.9%**	**63.1%**

Table 4.5(b) Syokimau Station Area Land Use Changes and Transformation

S/ No.	Statement	Least Accepted (1 & 2)	1 (SD)	2 (D)	3 (N)	4 (A)	5 (SA)	Most Accepted (4 & 5)
1	If there were affordable houses near the station, I would prefer them for my access convenience	**24.3%**	13.5%	10.8%	24.3%	16.2%	35.1%	**51.4%**
2	KRC should develop shopping premises/mini malls within the station area to allow commuters to shop for basic items on their way home in the evening	**18.9%**	5.4%	13.5%	13.5%	18.9%	48.6%	**67.6%**
3	Recreational facilities like landscaped mini parks with benches or a fitness gym are necessary to liven or energize the commuter experience at the station	**16.2%**	8.1%	8.1%	18.9%	8.1%	56.8%	**64.9%**
	Average Percentage	**19.8%**	**9.0%**	**10.8%**	**18.9%**	**14.4%**	**46.8%**	**61.3%**

ISSN: 2957- 7780

From Tables 4.5 (a) and (b) above, it can be observed that development of shopping premises or mini malls within the station area for shopping by commuters emerged the most accepted or popular change that can be introduced at both stations with ACRS at 70.4% and SCRS at 67.6%. The introduction of recreational facilities like landscaped mini parks or fitness gyms came close at second place with 69% for ACRS and 64.9% for SCRS respectively. Affordable housing near the stations scored averagely at 50% and 51.4% for ACRS and SCRS respectively.

However, it is not sensible to assume that all users of P&R stations will be car users as there will still be the walking population or the proportion of users using connector PSV for transport.

4.6. Research Proposition

The research proposition advanced by the researcher was that the car parking provided at Athi River Station has low utilization. The data below aids in making deductions on this proposition.

Table 4.6: Available versus Utilized Parking in both Stations (Source: Author, 2023)

Station	Available Parking Slots	No. of Cars Parked per day (Average)	Unutilized Car Park Slots	% Utilized
Athi River	200	20	180	10%
Syokimau	360	120	240	33%

From Table 4.6 above, the study established that the utilisation level of parking at Athi River Station was at 10% while that at Syokimau Station was at 33%. This study finding therefore fully supported the proposition that the car parking at Athi River Station has low utilization. However, the utilized parking at Syokimau Station was also quite low at 33%, with a decreasing trend in current times. The station master for Syokimau Station indicated that before the opening of the Nairobi Expressway, the station had quite a good turnout of car users as the parking would nearly be full to capacity. The development of the Nairobi Expressway is deemed to have contributed to the drop in commuter numbers probably due to the reduction of congestion along the traversed corridor, thus making car users to choose to travel all the way to Nairobi CBD and environs.

4.7. Performance Assessment for the Stations

As discussed in Sub-chapter 2.7.1, the performance of the stations was assessed on the basis of seven (7) key criterion items that influence the functioning and success of a P&R Station. Each of the criterion item was assigned a percentage weight to enable a rational evaluation (Manns, 2010)

ISSN: 2957- 7780

on a rule of thumb basis and depending on its significance in the whole P&R ecosystem. This was carried out as follows:

- the most significant determinants on the success of P&R (attaining expected ridership and utilizing the parking effectively) were each assigned more than a quarter of the total percentage weight, each at 30% thus taking 60% of the total percentage weight of 100%.
- moderately significant determinants (commuters' preferences of travel and the operating schedule convenience) were assigned percentage weights in the range of 10% to 25%.
- Other less significant determinants received less than 10% each from the total percentage weight.

Table 4.7 below gives a summary of the performance assessment. The table contains the criterion description, remarks on importance of each criterion, assigned percentage weight for each criterion, the results obtained for each criterion per station and its final weighted score (obtained by multiplication of the assigned % weight by the results obtained from the survey). The overall performance index per station was obtained by summation of all the criterion weighted scores. The reference source of the input data (results) was also included. For clarity, it is further noted that the results applied to weight the criterion for developing socio-economic facilities like shopping premises/mini malls within the station area as obtained in Table 4.5(a) and (b) was based on the negative response obtained which indicates that the status quo of the stations is to be maintained. In that way, its performance before the development of the facilities will have been gauged.

ISSN: 2957- 7780

Table 4.7: Performance Assessment Results for ACRS & SCRS (Source: Author, 2023)

S/No.	Criterion Description	Remarks on Importance of the Criterion	Assigned % Weight	ACRS Results (%)	SCRS Results (%)	Weighted Criterion Score for ACRS	Weighted Criterion Score for SCRS	Results Source & Reference
1	Attraction and attainment of the expected train ridership numbers	This is main priority for the P&R service	30.0	61.0	73.0	18.3	21.9	*KRC (Table 3.1)*
2	Utilization levels of the provided parking facilities	Utilised parking signifies relevance of the facility to the P&R concept	30.0	10.0	33.0	3.0	9.9	*Researcher (Table 4.6)*
3	Meeting the key commuter preferences of travel by commuters in a transport system	Includes saving on time and cost, safety, security and comfort	15.0	77.0	78.9	11.6	11.8	*Respondents (Tables 4.2(a) & 4.2(b)*
4	Convenience of the operating train schedules	A commuter preference parameter that covers both car users and non-car users	10.0	48.1	70.3	4.8	7.0	*Respondents (Tables 4.4(a) & 4.4(b)*
5	Convenience of the parking	Affects car users accessing the parking facility	6.0	75.0	76.5	4.5	4.6	*Respondents (Tables 4.3(a) & 4.3(b)*

ISSN: 2957- 7780

S/No.	Criterion Description	Remarks on Importance of the Criterion	Assigned % Weight	ACRS Results (%)	SCRS Results (%)	Weighted Criterion Score for ACRS	Weighted Criterion Score for SCRS	Results Source & Reference
6	No need for socio-economic facilities in or near the station (shopping, eateries, etc). These are not provided at the moment.	Not the main focus for the developing P&R facility but may influence usage and replanning of the station	5.0	25.9	18.9	1.3	0.9	*Respondents (Tables 4.5(a) & 4.5(b)*
7	Station is serving the effectively influence area and locational distance of commuter residences up to 5Km radius	Instrumental to future forward planning by authorities but not of immediate importance to commuters transport	4.0	78.0	76.0	3.1	3.0	*Respondents (Figures 4.5(a) & 4.5(b)*
	Overall		**100.0**			**46.6**	**59.2**	

As can be seen from Table 4.7 above, ACRS (Athi River Station) attained an overall performance score of 46.6% which is categorised as unsatisfactory performance while SCRS (Syokimau Station) achieved 59.2%, which is fair performance as per performance rating ranges given.

ISSN: 2957- 7780

4.8. Challenges Encountered in the Field Investigation

The main challenge that the researcher had to contend with was how to administer the questionnaires. This was envisaged at the start of the survey considering that commuters are always in a rush and may not afford time to fill a lengthy questionnaire. However, with the help of KRC staff, it was agreed that commuters would be issued with the questionnaire during boarding of the train and also given pencils for filling for those who didn't carry any pen. The questionnaires would then be collected during disembarking from the station on the exit end. This would require coordination at the departure and arrival station and could only be handled authoritatively by the KRC officers and it was effective for the survey. Some commuters however requested to go with the questionnaires at their workplace or home depending on the trip direction to fill and drop them back either in the evening or the following day for those in the evening trip from town. This group of commuters may have contributed to the percentage of unreturned questionnaires.

5. Conclusion and Recommendations

5.1. Introduction

This study aimed at evaluating the performance of P&R stations in NMA with a focus on Athi River and Syokimau Railway Stations and giving proposals to improve the performance and utilization of the P&R service. This chapter presents the research summary from study findings analysed and discussed in the previous chapter. Conclusions are drawn from these findings in with appropriate recommendations made to address the research objectives. Finally, some proposed areas of further research are proffered based on some of the study findings.

5.2. Summary of Main Findings

The objectives of the study are further explored in terms of how the study managed to actualise each. These are distinctly discussed in the succeeding sub-topics.

5.2.1. Regarding the first objective: To investigate best practice in planning and development of P&R stations, the study described best practices in development of P&R schemes from experiences across the world in Chapter 2. The approaches were identified, discussed, and illustrated in diagrams. The content is proposed in laying out strategies for developing new P&R stations not only for the Nairobi Metropolitan Area but also across other emerging cities and towns in the republic of Kenya. In particular, the following is emphasised:

a) *Land Use and Urban Transport Integration* - Good land use practise keeps common activities like housing and food market close while placing higher-density development closer to transportation lines and hubs. Poor land use on the other hand concentrates activities like jobs far from other vital destinations like residential housing zones. In brief, land use and transportation systems are closely intertwined, and models that are used in supporting transportation planning need integration with land use models for best results.

b) *Conceptualisation, planning, design and development of a P&R station* - this requires a structured process right from city planning to ensure the facility is in harmony with city development masterplans or blueprints that have focus on land use. Key considerations are:
   - As a transport hub for ensuring smooth transfer from one mode to another mode.
   - As an open space to revitalize the urban location or district where the facility is situated thereby promoting community interaction.

   The flow diagram in Figure 2.1 summarised the whole process ranging from planning concepts through facility design and subsequent construction.

c) *Facility location* - a checklist of site selection criteria was proposed for application in making location decisions and pegged upon: -
   (i) Assurance of strong patronage demand – the following rules of thumb can be used to decide the location of applicable site alternatives for evaluation among other patronage factors:
      - Geographic affinity to activity centres served.
      - Minimizing auto access time.
      - Maximizing the facility's visibility in the urban space.

   (ii) Provision for integration with the community - choosing P&R site alternatives that provide for improved integration of the facility with the surrounding community enhances the economic benefit that the lot can bring to area businesses, and the ability of such facilities to develop a transit-oriented suburban market.
   (iii) Reduction of the financial impact and risk to the implementing agency - Trade-offs between the expected life-cycle operating costs and capital costs of site acquisition and construction should be evaluated through a NPV analysis. Of significance is designing P&R schemes to complement the local service rather than compete them.

d) *Influence Area and Demand Estimation* - The station influence area is critical to establish as this will be the source of users of the facility. This includes getting the current daytime and night-time population and the future development potential. The economically acceptable station influence area is in the range of up to 5km radius. This zone is also expected to be characterised by intense residential developments which ultimately generate the commuter numbers. If a feeder connector bus network is required, an evaluation of the characteristics of the coverage area must be done including considerations for improvement of the transport routes linking the station to various neighbourhoods.

5.2.2. Regarding the second objective: ***To establish the influence areas and their significance in contributing to ridership numbers to ACRS and SCRS,*** the study found out that the significant sources of commuters for ACRS and SCRS were Athi River and Syokimau Residential areas at 56% and 85% respectively. Additionally, more than three quarters of respondents for both stations were found to be from within the 5Km radius as required of effective P&R stations with ACRS at 78% and SCRS at 76%. The distances covered by most of the commuters were therefore within the acceptable range as recommended for both stations.

The importance of this objective was to confirm where the stations were suitably serving the desired spatial areas in terms of facility location as discussed under sub-chapter 2.4.3.2. Ascertaining the influence area sets the stage for development of abutting undeveloped land with residential housing in mind in what may be a transit-oriented approach to beef up the source of commuters and boost the ridership numbers for these stations. This observation is also in tandem with the aspirations of the Mavoko Integrated Strategic Urban Development Plan which proposes adoption of a Transit Oriented Development approach in Mavoko Sub-county and as expounded in section 3.4.1.2 of this report. The sub-county is also the host for the two research stations.

5.2.3. Regarding the third objective: ***To find out the utilization levels of the P&R service at ACRS and SCRS and reasons behind such levels,*** the survey established some facts about the station as follows:

a) The reasons for preferring the P&R service fronted by the researcher which were avoidance of traffic jams, saving on time and cost, safety and security were all validated by the respondents at 77% by ACRS users and 79% by SCRS users. However, at ACRS, saving on time and cost was most unpopular reason for using the service among all the reasons, registering 21% while the other reasons registered less than 10% response. This finding on saving on time further justified suggestions given by respondents on improving the service on the time and cost aspects, like introduction of faster trains and reduction of parking and fare rates.
b) Assessment of car ownership statistics for the commuters revealed that ACRS did not have many users of personal cars accessing the Station as compared to the SCRS with both stations at 52% and 90% respectively in car use. The spatial review of the neighbouring residential area characteristics undertaken by the researcher showed that ACRS is surrounded by the low-income residential class, except for

the new middle class residential developments currently emerging on the left side of the Mombasa bound highway in Mavoko area. The older Athi River estate within the 3Km radius of ACRS is characterised by low-income earners who are unlikely to afford cars. This area was also the dominant in source of commuters to ACRS. Thus, ACRS doesn't compare favourably with SCRS which is in the middle-income residential bracket. The residential area characteristics have a direct bearing on car ownership and use and ultimately on success of a P&R facility.

c) A further investigation of alternative means of access to the station by respondents revealed that 71% of respondents at ACRS often relied on walking against 41% in SCRS. Thus, walking was more prevalent in ACRS than in SCRS and therefore low utilization of the parking at ACRS. However, the station manager at SCRS also reported a reduction in number of car users accessing the station after commissioning of the Nairobi Expressway.

d) Generally, convenience of the parking facilities in terms of affordability, payment mode, accessibility, security of cars and use by Persons with Disabilities (PWDs) were all validated by the respondents for the two stations with ACRS at 75% and SCRS at 76% respectively. This means that the car parking facilities as designed were suitable for use under the investigated aspects. However, suggestion on improvements were made by respondents like automation of parking payments, facility enhancement by provision of car sheds, car washing areas and security lights.

e) In terms of train schedule convenience, only the evening train departing Nairobi CBD to ACRS at 5.50 pm was found to be convenient by commuters from Athi River with suggestions on a later morning departure time at ACRS and shortened journey times. This finding has negative bearing on usage of the P&R service at ACRS. On the contrary, SCRS which is served by various train trips in the morning and evening had respondents preferring some of the available train schedules. The 7.15am DMU train which only takes 35 minutes to arrive at the CBD at 7.50am was most preferred in the morning with departure and arrival at 62% and 63% respectively. The most preferred evening schedule was for the commuter train departing from Nairobi CBD at 5.30pm and arriving at SCRS at 6.13pm with departure and arrival registering 79% and 76% preference by commuters respectively.

f) In ACRS, the largest portion of respondents in terms of age range was the 45 - 54 years of age at 37% while SCRS had the 35 - 44 years age bracket dominant at

44%. The older generation of commuters at ACRS may be attributed to low reliance on personal cars unlike the younger generation at SCRS which may fancy cars than their older folks.

5.2.4. Regarding the fourth objective: ***To determine the suitability of ACRS and SCRS as P&R stations and make appropriate recommendations towards their improvement***, several findings were made based on convenience of the P&R service to commuters as well as their preferences. These are summarised as follows:

1. Most commuters for ACRS accessed the station by walking as shown in Section 6.2.3 above. Thus, provision of parking space at ACRS should have been minimal with the station adopting a simplistic pick-and-drop concept in the station development.
2. Over 65% of respondents in ACRS preferred to have a PSV or railway connector bus in their residential area to help in accessing the station as compared to 55% at SCRS. This implies that most commuters within the ACRS residential area needed public transport to access the station thus negating the P&R concept.
3. 69% and above and 65% and above of respondents at ACRS and SCRS respectively agreed that land use changes and station area transformation were necessary to create the following:
   - shopping premises or mini malls within the station area to allow commuters to shop for basic items on their way home in the evening.
   - recreational facilities like landscaped mini parks with benches or a fitness gym to liven or energize commuter experience at the stations.

Lastly, the theories identified as anchors for this study by the researcher, i.e., Systems theory, Actor Network theory and Rhizomes theory as discussed in sub-chapter 2.3 were all found to be very relevant for a study of this nature and the subsequent findings pegged on P&R performance.

5.3. Study Conclusion

The researcher proposed and applied a weighted criteria to assess performance aspects of the stations in substantially meeting perceived needs of a P&R effectively and efficiently. The analysis and findings were documented in Section 5.7 of this report. The conclusion on performance aspects as envisaged under each criterion are further discussed as follows:

a) Whether the stations managed to attract and attain the expected train ridership numbers – *from the statistical data given by KRC and final analysis in Table 4.1, the average train* *ridership percentages of 61% at ACRS is fair performance. At SCRS, the ordinary commuters train achieved 73% while the DMU scored 82% due to its higher speed and preference by commuters. The attainment of ridership numbers is therefore rated as good at SCRS.*

b) Utilization levels of the provided parking facilities – *based on the data in summary Table 5.6, both stations are performing way below expectations at 10% for ACRS and 33% for SCRS in utilization of the provided parking. This is unsatisfactory performance and needs further attention.*

c) Whether the P&R service meets the commuter preferences of travel in a transport system which are avoidance of traffic jams, saving on travel cost and time, safety and comfort – *both the stations under the study were found to meet this criterion as analysed under section 5.4.3 of the report. The commuter preferences of travel were validated at 77% for ACRS (Table 5.2(a)) and 78.9% for SCRS (Table 5.2(b) respectively, which are good performance ratings.*

d) Convenience of the train operating schedules to commuters – *the train schedule operated at ACRS bound train was rated as unsatisfactory at 48.1% (Table 5.4(a)) while the SCRS bound trains schedules were rated as good at the bare minimum threshold value of 70.3%. (Table 5.4(b)). Improvement of the train schedule particularly for Athi River train is therefore needed.*

e) Convenience of the parking facility –*the parking convenience was validated at 75% and 76.5% for ACRS and SCRS as can be seen in Table 5.3(a) and Table 5.3(b) respectively. Thus, both stations were found to good for parking by commuting car users.*

f) How commuters rated the need for unavailable socio-economic facilities of benefit to them like shopping or recreation in the stations– *both stations registered a very low percentage that did not want socio-economic facilities to be developed, with ACRS at 25.9% and SCRS at 18.9% respectively (Tables 5.5(a) and 5.5(b)). This implies that the stations are unsatisfactory in their current status and therefore require these collaborative services to liven and enhance the commuter experience at the stations*.

g) Assessment of how the stations have effectively served the influence area – *the key 5km radius of influence area of the stations was the predominant source of commuters at over 75% in both cases (Figures 5.5(a) and 5.5(b)). It is therefore concluded that both stations were ideally well situated to effectively serve the influence area. The outcome of this measure is that it qualified the potential for re-development of idle land within the influence zone to provide more residential housing which shall impact positively the P&R stations in generating ridership numbers.*

In summary, ACRS at 46.6% and below average was rated as unsatisfactory in terms of the weighted performance encompassing all the seven criterion items while SCRS at 59.2% was rated as fair. Thus, ACRS is not functioning well as a suburban P&R station. It is also noted that none of the criterion achieved very good or excellent rating (the desired measure of highest level of efficient performance) in both stations thus more attention targeting the criterion items assessed is required to boost performance of the stations as discussed elsewhere in the report.

Arising from the evaluated performance for the stations, some key observations and conclusions are further made regarding the various aspects assessed as follows:

- In terms of the station influence area, it is emphasized that future stations be cognizant of the existing surrounding land use within the critical radius of influence of up to 5km to inform on the ridership numbers expected and the nature of the facility to be adopted. For this study, it was evidential that Athi River Station could have simply served as a pick-and-drop station while Syokimau Station started well as a P&R station before development of the Nairobi Expressway. In this regard, the impact of emerging developments in the urban space pertaining land use and urban transportation needs to be well evaluated to just be sure that other existing facilities constituting major public investments do not suffer negatively. The commissioning of the recent Nairobi Urban Expressway and its impact on the existing P&R stations along the Mombasa Road Corridor such as Syokimau Station is a case in point. Cognizance is also made of the Mavoko ISUDP discussed in sub-chapter 3.4.1 which is likely to shape developments for the area in the coming future.
- The underlying reasons for the current low utilization levels of the P&R service were investigated with a bearing on ACRS with the same survey also extended to SCRS for comparison. In addressing this objective, understanding of commuters' preferences, car ownership statistics and convenience of the service to them were key in helping establish some facts on service utilization levels. Car use by commuters was found to be quite low at ACRS with the greatest number accessing the station by walking while convenience of the time schedule elicited substantial negative responses at ACRS than at SCRS. In particular, the morning train departure and arrival timings at ACRS all emerged as quite unpopular for commuters. Suggestions to introduce new schedules and shorten journey times by running modern and faster trains were advanced by respondents in the qualitative part of the survey.
- The ultimate objective of determining suitability of ACRS as a P&R station or otherwise was investigated and crucial findings made. Precisely, the survey produced a significant number of respondents who accessed the station by walking as well as those who needed a

connector bus or PSV to access the station. This signifies that ACRS was not suitably placed to function as a P&R station. Additionally, the researcher's statements on land use changes and station area re-configuration to create shopping and recreational facilities which were evaluated on a Likert scale were significantly agreeable to the respondents as analysed in Tables 5.5(a) and 5.5(b). The characteristics of surrounding land use therefore have a direct bearing on decisions pertaining the location of the P&R station.

- Suburban P&R stations need to be located in areas with a low catchment of low to medium density housing of residential nature and characterized by limitations of access by walking, cycling or connector buses. This is coincidentally the classical case for Syokimau Station which is isolated on one side of the Mombasa Road transit corridor which has purely commercial and manufacturing establishments with residentials located some kilometres away. Implementing P&R schemes in locations with potential for high density mixed-use developments in the vicinity will deliver significant patronage by walking population in future and could make the park-and-ride concept fail in the long run. Moreover, a land use shift that supports transit-oriented development in appropriate locations and less effective feeder bus, walking and cycling options will also need to be factored so as not to water down the car user effect for the P&R concept.

In conclusion, the research findings made were also found to be largely consistent with some studies undertaken in the thematic area. The study by Ginn (2009) on application of P&R and TOD concepts in developing a new framework to maximise public transport usage established that reasonable access distance up to 5km within a TOD, presence of other facilities like convenience stores, cafes and safety and security are key in maximising patronage. Evans et al. (2003) on traveller response to transportation system changes found out that changes affecting train schedules and the travel time like faster means have transformational changes to travellers' response.

5.4. Study Recommendations

Based on the research summary of findings and conclusions documented here above, this study recommended some short-term and medium to long term measures and strategies for action by the transit infrastructure provider and operator, i.e. KRC. The short-term measures are proposed to be implemented within two (2) years in resolving the low levels of utilization of Athi River Station commuter train service as envisaged in the fourth objective of this study:

5.4.1. Short Term Measures

I. For Athi River commuter train, schedule morning departure time of 7.00am at the earliest and maintain the 5.50pm evening departure time from Nairobi Central Station.

II. Develop and introduce differentiated affordable fares for train trips to Athi River Station (at least 2 in each direction) considering peak and off-peak hours for increased patronage of the service.

III. Carry out media campaigns on the existence and use of commuter trains not only for Athi River area but also on the rest of Nairobi Metropolitan Area (NMA) rails to enlighten the urbanites.

IV. Obtain constant feedback from commuters on facility and service performance and make informed appropriate decisions for future sustainability.

5.4.2. Medium and Long-Term Strategies

The following medium-term and long-term strategies have been justified by the research findings and are highly recommended for Athi River Station. The same may be investigated to confirm applicability for other P&R stations in NMA. These are proposed in a period ranging from over two years to ten years.

I. Introduction of faster trains to and from Athi River Station (preferably DMU) to minimize journey time to less than one (1) hour on the maximum.

II. Introduction of railway connector buses in Nairobi suburbs railway stations where car affording commuter numbers is doubtful to boost the ridership numbers. The same should be enhanced at Nairobi Central Station with various buses circulating to key work zones like Upper Hill, Industrial Area, and Westlands among others in Nairobi City.

III. Review of the concept for Athi River Station and reconfiguration of the station area in light of the under-utilized parking area to create station plaza with mini shopping malls, restaurants, and recreational facilities as necessary like gymnasiums among others. This should also apply for other commuter rail stations in NMA without such facilities and where space allows.

IV. Collaboration with stakeholders in the station locality and in particular Machakos County Government and the adjacent landowners towards re-planning to transform and revitalize the station coverage and catchment zone. This should be done with the 5Km radius influence area in mind and as may be guided by the Mavoko ISUDP. Zoning and restriction measures that promote transit-oriented land use developments in the

P&R facility environs are very beneficial for integration success. In the long run, this collaboration will translate to economic benefits to all.

V. KRC through its parent Ministry of Roads and Transport should engage the concerned Road Authorities and the County Governments to improve the road network connecting the stations within the 5Km radius zone of influence for ease of access and mobility by connector transport and passenger cars.

5.5. Suggested Areas for Further Research

The proposed areas for additional research from this study include:

a) Impacts of major land use and transport development undertakings on existing P&R stations.
b) Technological advancements that can be implemented to transform P&R stations in Nairobi Metropolitan Area (e.g., introduction of modern trains or overhauling of the railway).
c) Impacts of low or high parking fee in the CBD on the utilization of P&R stations.
d) Economic appraisal of P&R stations in Nairobi Metropolitan Area.

References

Akrich, M. (2023). Actor Network Theory, Bruno Latour, and the CSI. *Journal of Social Studies of Science*. Vol. 53(2), 169–173.

Banister, D. (1999). *Transport Planning*. (2nd ed.). New York: Spon Press.

Bertalanffy, L. (1968). General System theory: *Foundations, Development, Applications*. New York: George Braziller.

Bensmaïa, R (2005). "Poststructuralism". In Kritzman, L. (ed.). *The Columbia History of Twentieth-Century French Thought*. Columbia University Press. pp. 92–93. ISBN 9780231107907.

Capra, F. (1997). *The web of life*. New York: Doubleday-Anchor Book.

Clayton, W., Ben-Elia, E., Parkhurst, G., & Ricci, M. (2014). Where to park? A behavioural comparison of bus park and ride and city center car park usage in Bath, UK. *Journal of Transport Geography*. Vol. 36, 124–133.

Constitution of Kenya 2010 4th Schedule (Kenya).

Deleuze, G., & Guattari, F. (1987). *A Thousand Plateaus*. Minneapolis: University of Minnesota Press.

Edwards, J. R., & Lambert, L. S. (2007). “Methods for Integrating Moderation and Mediation: A General Analytical Framework Using Moderated Path Analysis”, Psychological Methods. *The IUP Journal of Business Strategy*. Vol. 14, (4). Retrieved from https://www.researchgate.net/publication/322930562.

Eric, M., & Ilona B. (2009). Exploring heterogeneity in park and ride preferences: a latent class mode. *Proceedings of the transportation research board (TRB) annual meeting*, Washington, DC, 11–15 January 2009. Transportation Research Board.

Evans J., & Pratt, R. (2003). *Traveler response to transportation system changes*. Washington, DC: Transportation Research Board.

Ginn, S. (2009). *The application of the park & ride and TOD concepts to develop a new framework that can maximize public transport patronage*. (Published master's thesis). Queensland University of Technology, Brisbane.

Hamer, P. (2010). Analyzing the effectiveness of park and ride as a generator of public transport mode shift. *Journal of Road & Transport Research*, Vol. 19(1), 51–61.

Hamsa, A.A.K., Akmal, N.A.S., Zolkpeli, Z.H., (2021). Evaluating Parking Characteristics of Park-and-Ride Facility at Gombak LRT Terminal Station. *Jurnal Kejuruteraan*, Vol. 33(4), 981-992.

Heggie, I.G., & Papoulias, D.B. (1976). *Operational Performance of Park and Ride: Objectives and Achievements in Oxford*. Working Paper No. 23 Transport Studies Unit, University of Oxford, Oxford.

How Oxford led the way to create Park and Rides. (2013, December 6). *Oxford Mail*. Oxford. Retrieved February 6, 2023 from: https://www.oxfordmail.co.uk/news/10859209.oxford-led-way-create-park-rides/.

Israel, G. D. (2012). *Determining sample size*. PEOD6. IFAS, University of Florida, Florida.

Jackson, M. (2003). *Systems Thinking: Creative Holism for Managers*, Chichester, West Sussex: John Wiley& Sons, Ltd.

Jackson, S. (2015). Toward an analytical and methodological understanding of actor-network. (PDF). *Journal of Arts and Humanities*. Vol. 4(2), 29-44.

Kaneko, M. (2014). *Intermodal Transfer Facility Planning*. A Lecture Presentation to JICA Participants on Comprehensive Urban Transportation Planning Training Programme, JICA Tokyo International Centre. Tokyo.

Kenya Railways Corporation Act (CAP 397) Revised Edition 2019 (Kenya).

Kenya Railways Corporation. (2023). *The Nairobi Commuter Rail*. Retrieved February 6, 2023 from: https://krc.co.ke/the-nairobi-commuter-rail/.

Kenya Roads Board. (2023). *Road Maintenance Accountability Index Report for the Financial Year 2021-2022*. Nairobi: Published by KRB.

Kothari, C.R. (2004). *Research Methodology*: Methods and Techniques. (2nd ed.). New Delhi: New Age International (P) Ltd.

Liao, F., & Bothe, W. (2015). An article on effects of land-use transport scenarios on travel patterns: A Multi-State Super-Network Application. *Transportation (2017)*. Vol. 44, 1–25.

Machakos County. (2020). *Mavoko Integrated Strategic Urban Development Plan covering the period 2020 to 2030*. Machakos: County Government of Machakos.

Maina, J.I. (2018). *Factors Influencing Usage of Rail Transport by Private Motorists at Park and Ride Station*: *A Case of Syokimau Railway Project in Nairobi* (Unpublished master's thesis). University of Nairobi. Nairobi.

Manns, J. (2010): Park and Ride - Politics, Policy and Planning. *Town and Country Planning Association quarterly review*. March 2010. 144-148.

Maxwell, J. A. (2012). *Qualitative Research Design: An interactive approach*. (3rd ed.). California: Sage.
Meyer, M.D., & Miller, E.J. (1984). *Urban Transport Planning*. New York: McGraw-Hill.
Meyer, M. D., & Miller, E.J. (2001). *Urban Transportation Planning: A decision-oriented approach*. (2th ed.). New York: McGraw-Hill.
Meyer, M. D (2016). *Transportation Planning Handbook* (4th ed.). New Jersey. John Wiley & Sons, Inc.
Miles, M. B., & Huberman, A.M. (1994). *Qualitative data analysis: An expanded sourcebook* (2nd ed.). Thousand Oaks: Sage Retrieved 8th June, 2014, from http://www.drjohnlatham/com/Conceptual_Framework.html.
Ministry of Transport. (2009). *Integrated National Transport Policy*. Nairobi: Government Printers.
Ministry of State for Planning, National Development and Vision 2030. (2012): *Sessional paper No.10 of 2012 On Kenya Vision 2030*. Nairobi: Government Printers.
Ministry of Transport, Infrastructure, Housing & Urban Development. (2018). *2nd Road Sector Investment Programme & Strategy*; 2018 – 2022. Nairobi: Government Printers
Mugenda, A. G., & Mugenda, O. M. (2003). Research Methods; *Qualitative and Quantitative Approaches*. Nairobi: Africa Centre for Technology Studies.
Mugenda, A. G., & Mugenda, O. M. (2012). *Research Methods Dictionary*. Nairobi: Arts Press.
Muniesa, F. (2015). Actor-Network Theory. In James D. Wright (Ed.), *The International Encyclopaedia of Social and Behavioural Sciences,* (2nd ed.). Vol. 1, 80-84. Oxford: Elsevier.
Nachmias, C.F., & Nachmias, D. (1992). *Research Methods in Social Sciences*. (4th ed.). New York: St. Martins Press.
Nairobi City County. (2015). *Integrated Urban Development Master Plan for Nairobi City*. Nairobi: Nippon Koei Co. Ltd.
NaMATA. (2022). *Industry Discussion Document on Establishing the Line 2 BRT Bus Operating Company*, Nairobi: NaMATA.
Ngechu, M. (2004). *Understanding the research process and methods. An introduction*. Nairobi: Starbright Services.
Niira, K. (2014). *Development of Transportation Infrastructure and Support System of the Japanese National and Prefectural Governments*. A Lecture Presentation to JICA Participants on Comprehensive Urban Transportation Planning Training Programme, JICA Tokyo International Centre. Tokyo.
Noel, E.C. (1988). “Park-and-ride: alive, well, and expanding in the United States”. *Journal of Urban Planning and Development*, Vol.114(1), 2–13.
Olson, L. (2003) *Factors that Influence Choice of Travel Mode in Major Urban Areas: The attractiveness of Park and Ride* (Published master’s thesis). Royal Institute of Technology, Stockholm.
Orodho, A. J. (2003). *Essentials of Educational and Social Science Research Methods*. Nairobi Mazola Publishers.
Owen, W. (1964) *Strategy for Mobility*. Washington D.C.: Brookings Institutions.

Parkhurst, G., & Richardson, J., (2002). Modal Integration of Bus and Car in UK local transport policy: The case for strategic environmental assessment. *Journal of Transport Geography*. Vol.10 (3), 195-206.

Pickett, M.W., & Gray, S.M. (1996). *The effectiveness of bus-based Park & Ride*. TRL Report 207.Transport Research Laboratory, Crowthorne.

Polit, D. F., & Hungler, B. P. (1999). *Nursing research: principles and methods*. Philadelphia: JB Lippincott Company.

Queensland Government. (2009). *South East Queensland Regional Plan 2009–2031*. Retrieved Retrieved February 18, 2023 from: https://www.ipswich.qld.gov.au/__data/assets/pdf_file/0005/7916/seqregional-plan-2009.pdf.

Rukwaro, R. (2016). *Proposal Writing in Research*. Nairobi: Applied Research & Training Services.

Runkel, M. (1993) Park and ride: Development and Perspective. 50th International Congress Sydney, *International Commission on Traffic and Urban Planning*. Brussel. International Union of Public Transport (IUPT).

Shirgaokar, M., & Deakin, E. (2005). Study of Park-and-Ride Facilities and their Use in the San Francisco Bay Area of California. *Journal of the Transportation Research Board*. No. 1927, 46–54.

Sinayev, A., Peters, E., Tusler, M., & Fraenkel, L. (2015). Presenting Numeric Information with Percentages and Descriptive Risk Labels: A Randomized Trial. *International journal of the Society for Medical Decision Making*. Vol.35(8), 937-947

Spillar, R.J. (1997). *P&R planning and design guidelines*. New York: Parsons Brinckerhoff Inc.

Steer Davies Gleave Company. (2006). *Study on the Prices and Quality of Rail Passenger Services*. Retrieved March 6, 2023 from: https://transport.ec.europa.eu/system/files/2016-09/2016-04-price-quality-rail-pax-services-final-report.pdf.

Taylor, N. (1998). *Urban Planning Theory Since 1945*. London: SAGE Publications.

Park and ride “is ruining rural land”. (2005, June 8). *The Guardian*. London. Retrieved January 6 2023 from: https://www.theguardian.com/society/2005/jun/08/environment.transportintheuk.

Vincent, M. (2007). *Park and ride: Characteristics and demand forecasting*. Research Report No. 328. Land Transport New Zealand, Wellington.

Waddell, P. (2011). Integrated land use and transportation planning and modelling: Addressing challenges in research and practice. *Transport Review*. Vol.31(2), 209–229.

Wiseman, N., Bonham, J., Mackintosh, M., Straschko, O., & Xu, H., (2012). “Park and ride: An Adelaide case study.” *Road & Transport Research*: A Journal of Australian and New Zealand Research and Practice. Vol. 21(1):39-52.

Zamanzadeh, V., Ghahramanian, A., Rassouli, M., Abbaszadeh, A., Alavi-Majd, H., & Nikanfar, A. R. (2015). Design and Implementation Content Validity Study: Development of an instrument for measuring Patient-Centered Communication. *Journal of caring sciences*, 4(2), 165–178. *https://doi.org/10.15171/jcs.2015.017.*

Error Analysis and SER Approximation of Correlated M-QAM Signals over Rayleigh Fading Channels

Edwin Omosa*, Joseph Obadha

Faculty of Engineering, Chuka University

*Corresponding author: edwinomosa@gmail.com

Abstract

This paper presents a comprehensive analysis of the Symbol Error Rate (SER) performance of M-ary Quadrature Amplitude Modulation (M-QAM) signals over correlated Rayleigh fading channels in the presence of additive white Gaussian noise (AWGN). The study focuses on three widely employed diversity combining techniques, namely Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), and Selection Combining (SC). A unified closed-form approximate expression for the SER under the considered diversity schemes is derived, incorporating the effects of fading correlation, noise, and modulation order. The analytical formulation provides a tractable means of evaluating system reliability while enabling direct performance comparison among the three combining strategies. To assess the accuracy of the proposed expression, extensive Monte Carlo simulations are conducted using MATLAB, and the results confirm a high degree of consistency with the theoretical predictions. The findings demonstrate that correlation among diversity branches and the severity of fading significantly influence the error performance, thereby offering valuable insights for the design and optimization of diversity-assisted wireless communication systems operating in multipath fading environments.

Key words: MRC, EGC, SC, Rayleigh fading, diversity reception, correlated channels, Monte Carlo simulation

1. Introduction

The continuous evolution of wireless communication technologies has intensified the demand for high data rates, improved spectral efficiency, and reliable connectivity. Despite these advances, system performance remains fundamentally constrained by multipath fading and additive white Gaussian noise (AWGN), which cause random fluctuations in the amplitude and phase of received signals [1]. Among the different fading models, the Rayleigh distribution is widely used to characterize non-line-of-sight (NLOS) propagation environments, particularly in dense urban areas and indoor wireless networks [2], [3]. Under such conditions, the probability of symbol detection errors increases significantly, necessitating the deployment of robust error-mitigation strategies.

Diversity combining techniques are among the most effective methods for combating fading, as they exploit independent replicas of a transmitted signal captured through multiple antennas or propagation paths [4]. Three classical schemes have been extensively investigated: Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), and Selection Combining (SC). MRC is theoretically optimal since it weights each branch according to its instantaneous signal-to-noise ratio (SNR), but it requires accurate channel state information (CSI) and entails high computational complexity. EGC reduces CSI requirements by coherently combining signals with equal amplitude weighting, though at some cost in performance relative to MRC. SC, on the other hand, offers a low-complexity approach by selecting the branch with the maximum SNR, albeit with inferior error performance compared to MRC and EGC [1], [3]-[6].

Over the past two decades, extensive research has focused on evaluating the SER of digital modulation schemes in fading environments. For example, closed-form SER expressions for M-ary Phase Shift Keying (M-PSK) and M-QAM under independent Rayleigh fading channels are well established in the literature. Analytical frameworks relying on conditional error probabilities, moment-generating functions, and Q-function approximations have provided valuable insights under idealized fading assumptions [7]-[9]. However, independent fading is rarely encountered in practice. Spatial and temporal correlation, often caused by limited antenna spacing, shared scatterers, or restricted propagation diversity, introduces dependencies across fading channels that can significantly degrade performance.

Recent works have extended error analysis to correlated fading environments, particularly in the context of multiple-input multiple-output (MIMO) systems, spatial modulation, and generalized fading models such as Nakagami-m, Ricean, and Weibull [10], [11]. These studies underscore the role of correlation modeling through frameworks such as Kronecker-based approaches and eigenvalue decompositions [10], [11].

Nevertheless, most existing analyses are restricted to specific receiver architectures, interference-limited systems, or alternative modulation formats. A unified, tractable SER framework for higher-order M-QAM in correlated Rayleigh fading channels with AWGN MRC, EGC and SC remains largely unexplored. Moreover, several existing models rely on idealized uncorrelated assumptions or lack thorough simulation-based validation across a wide range of modulation orders and correlation regimes.

Motivated by these gaps, this paper develops a comprehensive analytical framework for evaluating the SER of M-QAM under correlated Rayleigh fading and AWGN with different diversity combining strategies. This problem is of particular importance given the widespread use of M-QAM in communication standards such as Wi-Fi, LTE, and 5G New Radio (NR), where optimizing trade-offs between performance, complexity, and implementation cost is critical.

The objectives of this study are:

1) To derive a closed-form approximate expression for the SER of M-QAM signals over correlated Rayleigh fading channels with AWGN under unified MRC, EGC, and SC combining.
2) To validate the analytical framework through extensive Monte Carlo simulations across different modulation orders and correlation scenarios.

The main contributions of this work are summarized as follows:

1) Develop a compact analytical expression that captures the combined effects of fading correlation, modulation order, and AWGN for a unified MRC, EGC, and SC.
2) Integrate correlation models into SER analysis, bridging the gap between idealized independent-fading assumptions and realistic propagation environments.
3) Verify the proposed expressions through Monte Carlo simulations, demonstrating their accuracy and robustness under diverse operating conditions.

Notation

Throughout this paper, bold uppercase symbols are employed to represent matrices, whereas scalars are denoted using standard letters. The notation Q(·) refers to the Gaussian Q-function. Furthermore, E[·], $(\cdot)^*$, and $(\cdot)^H$ are used to denote the expectation operator, complex conjugation, and Hermitian transpose, respectively.

2. System Model

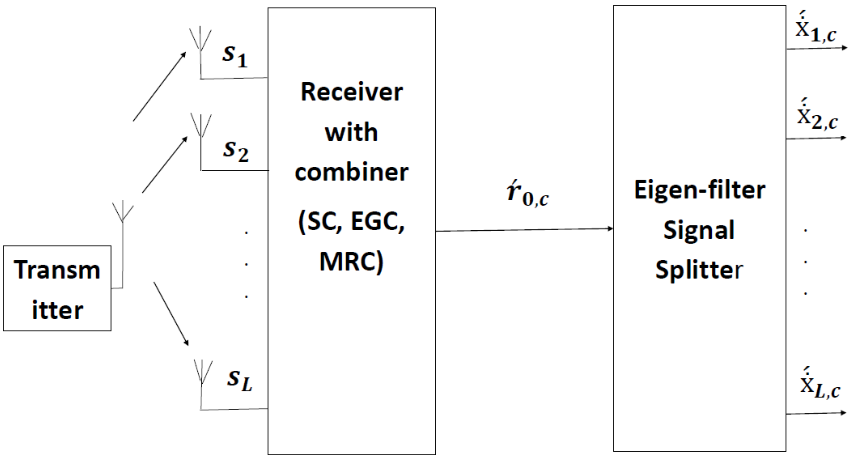


Figure.1 illustrate the correlated system diversity model implementation.

An L-branch diversity system is considered. The correlated signals received from the L branches are combined using any diversity combiner e.g. MRC, EGC and SC, and equalized so as to obtain the estimate of the symbol $\acute{x}\ (0, c)$ sent by the transmitter. Where c represents the type of combiner. If the estimated symbol passes through a channel with a combined coefficient, $\hat{h}\ (0, c)$ then the combined signal output, $\acute{r}$(0,c) = $\hat{h}\ (0, c)\acute{x}\ (0, c)$. To analyze the L correlated signals, the combined signal output goes through a power splitter where a transformer decompose them into L independent symbols, $\acute{\acute{x}}_{(m,c)}, m \in\ [1: L]$ as illustrated in Figure 1. A transformer that can be applied in such a scenario is the Eigenvalue Decomposition (EVD) [10]-[12]

a. Correlated signal under Rayleigh

In diversity systems, the modulated correlated signal collected by the receiver of the L_{th} branch can be expressed as [12]:

$$s_k = \propto_L e^{j\Psi_L} x_m + n_L \tag{1}$$

where x_m is the transmitted symbol, $\propto_L$ denotes the random amplitude following a Rayleigh distribution, with E[${\propto_L}^2$] = $2{\sigma_L}^2$. The parameter Ψ_L represents a stochastic phase process, while n_L corresponds to additive zero-mean Gaussian noise. The noise components are assumed to be mutually uncorrelated and statistically independent of the transmitted signal.

By using the conventional method, a system correlation can be modeled. Taking the correlation coefficient between the l_{th} and the i_{th} branch to be ρ_{li} . This can be expressed as 10]-[12]:

$$\rho_{li} = \frac{E[\hat{h}_l \hat{h}^*{}_i]}{\sqrt{\sigma^2_{\hat{h}_l} \sigma^2_{\hat{h}_i}}}, i, l = 1,2, \dots\ L \tag{2}$$

where $\sigma^2_{\hat{h}_l}$is the variance of the random variables (RV) $\hat{h}_l$ and $\sigma^2_{\hat{h}_i}$ is is the variance of the RV $\hat{h}_i$.

Let **R** denote the normalized correlation matrix, which can be expressed as [13], [14]:

$$\boldsymbol{R} = \begin{pmatrix} 1 & \rho_{12} & \cdots & \rho_{1l} \\ \rho_{12} \vdots & 1 & \ddots & \rho_{2l} \vdots \\ \rho_l & \dots & \cdots & 1 \end{pmatrix} \tag{3}$$

The matrix **R** is considered positive-definite and, therefore, has strictly positive eigenvalues [2], [8]. By applying eigenvalue decomposition (EVD), **R** can be represented in terms of its orthogonal eigenvectors and corresponding eigenvalues. This transformation is typically realized through an eigen-filtering process, as described in [12]-[15].

$$\Lambda = \boldsymbol{QRQ}^H \tag{4}$$

where **Q** denotes the matrix composed of eigenvectors, while Λ represents the diagonal matrix containing the positive eigenvalues. The EVD process produces **Q**, whose rows form an orthonormal basis, thereby making **Q** a unitary matrix. Consequently, it satisfies the property $\boldsymbol{Q}^H = Q^{-1}$. The transformation network defined by **Q** is reciprocal in nature. Therefore, **Q** functions as the eigen-filter or diversity de-correlator, providing the output through a unitary transformation of the input.

b. Eigen-filter Operation

The purpose of the eigen-filter diversity de-correlator is to de-correlate received envelop signal vector $\hat{\boldsymbol{r}}_{c,d}$ of length L. Generally, a filter $\mathbf{h}_f$ of length L, would be needed to produce a new uncorrelated signal estimates $\hat{\hat{\boldsymbol{x}}}_{c,d}$. the filter output vector is customary expressed as $\hat{\hat{\boldsymbol{x}}}_{0,d} = \boldsymbol{h}_f^H \hat{\boldsymbol{r}}_{c,d}$ [15]. As a result, the signal power at the output of the filter is written as [12], [15]:

$$\begin{aligned} p_{0,d} &= E\left[\left|\hat{\hat{\boldsymbol{x}}}_{0,d}\right|^2\right] \\ &= \left(\boldsymbol{h}_f^H \hat{\boldsymbol{r}}_{c,d}\right)\left(\hat{\boldsymbol{r}}_{c,d}^H \boldsymbol{h}_f\right) \\ &= \boldsymbol{h}_f^H \widehat{\boldsymbol{R}} \boldsymbol{h}_f \\ &= \boldsymbol{h}_f^H \left(\widehat{\boldsymbol{Q}}^H \widehat{\Lambda} \widehat{\boldsymbol{Q}}\right) \boldsymbol{h}_f \\ &= \sqrt{\widehat{\Lambda}}\left(\widehat{\boldsymbol{Q}} \boldsymbol{h}_f\right)^H \sqrt{\widehat{\Lambda}}\left(\widehat{\boldsymbol{Q}} \boldsymbol{h}_f\right) \end{aligned} \tag{5}$$

where $\widehat{\boldsymbol{R}} = \hat{\boldsymbol{r}}_{c,d} \hat{\boldsymbol{r}}_{c,d}^H$ is the autocorrelation of $\hat{\boldsymbol{r}}_{c,d}$ and $\widehat{\Lambda}$ contains the eigenvalues of $\widehat{\boldsymbol{R}}$. Also, the autocorrelation $\widehat{\boldsymbol{R}}$= **R** and $\widehat{\Lambda} = \Lambda$ [16].

Choosing the filter coefficients vector to be $\boldsymbol{h}_f = \widehat{\boldsymbol{Q}}$, rewriting, Equation (5) becomes:

$$\begin{aligned} p_{0,d} &= \boldsymbol{h}_f^H \left(\widehat{\boldsymbol{Q}}^H \widehat{\Lambda} \widehat{\boldsymbol{Q}}\right) \boldsymbol{h}_f \\ &= \sqrt{\widehat{\Lambda}}\left(\widehat{\boldsymbol{Q}} \boldsymbol{h}_f\right)^H \sqrt{\widehat{\Lambda}}\left(\widehat{\boldsymbol{Q}} \boldsymbol{h}_f\right) \\ &= \sqrt{\widehat{\Lambda}}\left(\widehat{\boldsymbol{Q}} \widehat{\boldsymbol{Q}}\right)^H \sqrt{\widehat{\Lambda}}\left(\widehat{\boldsymbol{Q}} \widehat{\boldsymbol{Q}}\right) \end{aligned} \tag{6}$$

From Equation (6), the equivalent channel coefficient corresponding to the L_{th} output branch can be written as:

$$\hat{h}_L = \sqrt{\boldsymbol{\epsilon}_L} \widehat{\boldsymbol{Q}}_L \widehat{\boldsymbol{Q}}_L = \sqrt{\boldsymbol{\epsilon}_L} \widehat{\boldsymbol{Q}}_L \hat{\hat{\boldsymbol{h}}} \tag{7}$$

where $\boldsymbol{\epsilon}_L \in \Lambda$ and $\widehat{\boldsymbol{Q}}_L$ represents the k_{th} column of $\widehat{\boldsymbol{Q}}$. The term $\hat{\hat{\boldsymbol{h}}}_L$ denotes the approximated Rayleigh fading channel in a correlated system, characterized by a complex coefficient whose amplitude follows a circularly symmetric complex Gaussian distribution, CN(0,1), while the phase is uniformly distributed over $(0, 2\pi)$. As established in [16], the resulting product yields statistically independent entries. Hence, the correlated branches can be regarded as eigenvalue-weighted representations of otherwise independent fading paths. Normally, **Q** is computed from **R** or given. Therefore, this paper provides a blind filter matrix **Q** that does not consist of the evaluation of **R**

Performance of MQAM in AWGN channel

In this segment, the consequences of Rayleigh Fading with MQAM are assessed. The SER will be used as the measure of performance.

The SER of square MQAM at an instantaneous signal-to-noise ratio, $\gamma_L = h^2 \frac{E_S}{N_0}$ in AWGN channel is expressed as [1], [2], [7], [17], [18]:

$$SER_{MQAM} = 4\left(1-\frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3E_S}{N_0(M-1)}}\right) - 4\left(1-\frac{1}{\sqrt{M}}\right)^2 Q^2\left(\sqrt{\frac{3E_S}{N_0(M-1)}}\right)$$

(8)

h^2 denotes the instantaneous power of the fading channel, where h is a random variable representing the channel gain. The ratio $\frac{E_S}{N_0} = \gamma$ corresponds to the symbol energy-to-noise power density in an AWGN channel without fading. By defining $a = \left(1-\frac{1}{\sqrt{M}}\right)$ and $b = \frac{3}{M-1}$, the preceding expression simplifies to:

$$SER_{MQAM} = 4aQ\left(\sqrt{b\gamma}\right) - 4a^2 Q^2\left(\sqrt{b\gamma}\right) \tag{9}$$

Q is the Marcum Q-function, $Q\left(\sqrt{b\gamma}\right)$ *and* $Q^2\left(\sqrt{b\gamma}\right)$are given by Craig's formula as [19]:

$$Q\left(\sqrt{b\gamma}\right) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} exp\left(-\frac{b\gamma}{2sin^2\theta}\right) d\theta \tag{10}$$

$$Q^2\left(\sqrt{b\gamma}\right) = \frac{1}{\pi}\int_0^{\frac{\pi}{4}} exp\left(-\frac{b\gamma}{2sin^2\theta}\right) d\theta \tag{11}$$

Solving for $Q\left(\sqrt{b\gamma}\right)$ *and* $Q^2\left(\sqrt{b\gamma}\right)$ using the trapezoidal rule, they become:

$$Q\left(\sqrt{b\gamma}\right) = \frac{1}{2n}\left(\frac{e^{-b\gamma/2}}{2} + \sum_{k=1}^{n-1} e^{-\left(\frac{b\gamma}{2sin^2\left(\frac{k\pi}{2n}\right)}\right)}\right)$$

(12)

$$Q^2(\sqrt{b\gamma}) = \frac{1}{4t}\left(\frac{e^{-b\gamma}}{2} + \sum_{k=1}^{t-1} e^{-\left(\frac{b\gamma}{2sin^2\left(\frac{k\pi}{4t}\right)}\right)}\right)$$

(13)

By Letting n=2t and substituting the above Equations (12) and (13) in Equation (9) gives:

$$SER_{MQAM} = \frac{a}{t}\left\{\frac{e^{-b\gamma/2}}{2} - \frac{ae^{-b\gamma}}{2} + (1-a)\sum_{i=1}^{t-1} e^{-\frac{b\gamma}{S_i}} + \sum_{i=t}^{2t-1} e^{-b\gamma/S_i}\right\}$$

(14)

Where t is the sampling frequency, $S_i = 2sin^2\theta_i$ and $\theta_i = \frac{i\pi}{4}$

a. Performance of MQAM in AWGN channel under Rayleigh Fading

If α is the fading coeffient of Rayleigh fading channel with a probability density function (PDF) of $\gamma = \alpha^2 \frac{E_s}{N_0}$ expressed as $f_\gamma(\gamma) = \frac{1}{\bar{\gamma}} exp\left(-\frac{\gamma}{\bar{\gamma}}\right)$ [2], [19] then the conditional SER for QAM is given as:

$$SER_{MQAM}(e|\propto^2) = \frac{a}{t}\left\{\frac{e^{-b\gamma/2}}{2} - \frac{ae^{-b\gamma}}{2} + (1-a)\sum_{i=1}^{t-1} e^{-\frac{b\gamma}{S_i}} + \sum_{i=t}^{2t-1} e^{-b\gamma/S_i}\right\}$$

(15)

Where $\bar{\gamma}$-is the average received signal to noise ratio $\bar{\gamma} = E[\gamma] = E\left[\alpha^2 \frac{E_s}{N_0}\right] = E[\alpha^2]\frac{E_s}{N_0}$[12] Assuming $E[\alpha^2] = 1$, then $\bar{\gamma}=\frac{E_s}{N_0}$.

The average symbol error probability of M-QAM in Rayleigh fading channel is expressed as [19]:

$$P_{ser} = E\left[SER_{MQAM}(e|\alpha^2)\right] = \int_0^\infty SER_{MQAM}(e|\gamma)\, f_\gamma(\gamma) d\gamma \quad (16)$$

Though substitution Equation (16) becomes:

$$P_{ser} = \int_0^\infty \frac{a}{t}\left(\frac{e^{-b\gamma/2}}{2} - \frac{ae^{-b\gamma}}{2} + (1-a)\sum_{i=1}^{t-1} e^{-\frac{b\gamma}{S_i}} + \sum_{i=t}^{2t-1} e^{-b\gamma/S_i}\right)\frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}} d\gamma$$

(17)

Solving Equation 17() result in Equation (18).

$$P_{ser} = \frac{a}{t}\left(\frac{1}{2}\frac{2}{b\overline{\gamma}+2} - \frac{a}{2}X\frac{1}{b\overline{\gamma}+1} + (1-a)\sum_{i=1}^{t-1}\frac{S_i}{b\overline{\gamma}+S_i} + \sum_{i=t}^{2t-1}\frac{S_i}{b\overline{\gamma}+S_i}\right)$$

(18)

b. Receive Diversity with N Receive Antennas

For a SIMO system with L receive antennas the signal received on the L_{th} antenna is given as [10]-[16]:

$$y_L = h_L x + n_L \tag{19}$$

Where $y_L$is the received signal on the receive antenna,h_L- channel gain on the L_{th} receive antenna, x- transmitted signal and n_L- noise on the L_{th} receive antenna which is modeled as AWGN.

c. Diversity Combining with Maximal ratio combining (MRC)

For MRC the PDF of the combined SNR is given as [4], [5]

$$f_\gamma(\gamma) = \frac{1}{(L-1)!\overline{\gamma}^L}\gamma^{L-1}e^{\frac{\gamma}{\overline{\gamma}}} \tag{20}$$

Further, the SER for MRC can be expressed as

$$P_{ser\_MRC} = \prod_k^L E\left[SER_{MQAM}(e|\overline{\gamma})\right] = \int_0^\infty \prod_k^L SER_{MQAM}(e|\overline{\gamma})\ f_\gamma(\overline{\gamma})d\gamma$$

(21)

$$P_{ser\_MRC} = \int_0^\infty \prod_k^L \frac{a}{t}\left\{\frac{e^{-b\gamma/2}}{2} - \frac{ae^{-b\gamma}}{2} + (1-a)\sum_{i=1}^{t-1} e^{-\frac{b\gamma}{S_i}} + \sum_{i=t}^{2t-1} e^{-b\gamma/S_i}\right\}\frac{\gamma^{L-1}}{(L-1)!\overline{\gamma}^L}e^{\frac{\gamma}{\overline{\gamma}}}\,d\gamma$$

(22)

Equation (22) can be solved using Moment Generating Function (MGF). MGF is defined as [20]

$$M_\gamma(s) = \int_0^\infty \dots \int_0^\infty exp(-s\sum_{k=1}^L \gamma_k)\ \prod_k^L\left(f_\gamma(\gamma_k)d\gamma_k\right) = \prod_k^L M_{\gamma_k}(s)$$

(23)

where

$$M_{\gamma_k}(s) = \exp(-s\gamma_k)\, f_\gamma(\gamma_k) d\gamma_k = \frac{1}{\hat{\gamma}_k}\int_0^\infty \exp\left[-\gamma_k\left(\frac{1}{\hat{\gamma}_k} - s\right)\right] d\gamma_k = \frac{1}{1-\hat{\gamma}_k s}$$

For the case where L=1, Equation (22) reduces to Equation (18). Substituting Equation (18) into Equation (22) and solving results in:

$$P_{ser\_MRC} = \frac{a}{t}\left[\frac{1}{2}\prod_{k=1}^{L}\frac{2}{b\overline{\gamma}+2} - \frac{a}{2}\prod_{k=1}^{L}\frac{1}{b\overline{\gamma}+1} + (1-a)\sum_{i=1}^{t-1}\prod_{k=1}^{L}\frac{S_i}{b\overline{\gamma}+S_i} + \sum_{i=t}^{2t-1}\prod_{k=1}^{L}\frac{S_i}{b\overline{\gamma}+S_i}\right] \tag{24}$$

d. Diversity Combining with Equal gain combining (EGC)

A unified formulation for the three conventional combining techniques can be obtained by incorporating the average received branch SNR, denoted as $\bar{\gamma}$. Accordingly, the expected output SNR for each EGC branch is expressed as [3], [5]:

$$\overline{\gamma}_{k,EGC} = \epsilon_k \frac{\overline{\gamma}_{0,EGC}}{L} = \epsilon_k\left(\frac{1+(L-1)\frac{\pi}{4}}{L}\right)\bar{\gamma} \tag{25}$$

e. Diversity Combining with Selection combining (SC)

On the same note as in EGC, the mean output SNR for each SC branch can be expressed as [16], [19]-[21]:

$$\overline{\gamma}_{k,SC} = \epsilon_k \frac{\overline{\gamma}_{0,SC}}{L} = \epsilon_k\left(\frac{\sum_{i=1}^{L}\frac{1}{i}}{L}\right)\bar{\gamma} \tag{26}$$

Equation (25) and Equation (26) can be combined as:

$$\overline{\gamma}_{0,C} = \epsilon_k \beta_c \bar{\gamma} \tag{27}$$

$$\text{Where } \beta_c = \begin{cases} \beta_{MRC} = 1\ for\ MRC \\ \beta_{EGC} = \frac{1+(L-1)\frac{\pi}{4}}{L}\ for\ EGC \\ \beta_{SC} = \frac{\sum_{i=1}^{L}\frac{1}{i}}{L}\ for\ SC \end{cases}$$

Substituting Equation (27)into Equation (24), it becomes

$$P_{ser} = \frac{a}{t}\left[\frac{1}{2}\prod_{k=1}^{L}\frac{2}{b\overline{\epsilon_k\beta_c\gamma}+2} - \frac{a}{2}\prod_{k=1}^{L}\frac{1}{b\epsilon_k\beta_c\overline{\gamma}+1} + (1-a)\sum_{i=1}^{t-1}\prod_{k=1}^{L}\frac{S_i}{b\epsilon_k\beta_c\overline{\gamma}+S_i} + \sum_{i=t}^{2t-1}\prod_{k=1}^{L}\frac{S_i}{b\epsilon_k\beta_c\overline{\gamma}+S_i}\right] \tag{28}$$

3. Simulation

In the simulation and theoretical analysis, a system with four receiving antennas was considered. The antennas were placed with uniform spacing, each separated by half the wavelength of a 5G carrier signal operating at 60 GHz. The correlation coefficient, which quantifies the relationship between signals at different antennas, was expressed as [10]-[16]:

$$\rho = J_0\left(2\pi\frac{l}{\lambda}\right) \tag{29}$$

where λ is the carrier wavelength, l is the distance between antennas, and J_0 represents the zero-order Bessel function.

For the simulation setup, antenna spacing was deliberately restricted to values not exceeding half the operating wavelength ($\lambda/2$). This design choice reflects a well-established principle: antenna elements spaced more than $\lambda/2$ apart exhibit reduced signal correlation, resulting in higher statistical independence, whereas smaller separations lead to stronger correlations. To balance practical implementation constraints and spatial limitations, spacing values of 0.15λ, 0.25λ, and 0.45λ were selected. These configurations were considered adequate for the objectives of this study. The resulting correlation coefficients naturally fall within the standard range $0< \rho < 1$.

Based on Equation (29), the parameters applied in the simulation are summarized in **Table 1**.

Table 1. Parameters Used in the Simulation

l (spacing)	$J_0\left(2\pi\frac{l}{\lambda}\right)$	$J_0\left(2\pi\frac{2l}{\lambda}\right)$	$J_0\left(2\pi\frac{3l}{\lambda}\right)$	$J_0\left(2\pi\frac{4l}{\lambda}\right)$
$\mathbf{0.15\lambda}$	0.7900	0.2906	-0.1962	-0.4020
$\mathbf{0.25\lambda}$	0.4720	-0.3042	-0.2659	0.2203
$\mathbf{0.45\lambda}$	-0.1962	0.0452	0.0468	-0.1100

$$\boldsymbol{\rho = J_0\left(2\pi\frac{Ll}{\lambda}\right)}$$

(30)

From these correlation coefficients, the correlation matrix can be constructed. Since no direct analytical method exists for processing correlated signals, the matrix is decomposed through Eigenvalue Decomposition (EVD), which effectively produces independent signal branches.

To demonstrate, consider three uniformly spaced receive antennas with an inter-element distance of $l = 0.45\lambda$ and correlation coefficient ρ. The resulting correlation matrix **R**, derived from Equation (3), Equation (30) and Table 1, is:

$$\boldsymbol{R} = \begin{pmatrix} 1 & -0.1962 & 0.0452 & 0.0468 \\ -0.1962 & 1 & -0.1962 & 0.0452 \\ 0.0452 & -0.1962 & 1 & -0.1962 \\ 0.0468 & 0.0452 & -0.1962 & 1 \end{pmatrix} \tag{31}$$

Furthermore, using EVD, the eigenvalue matrix corresponding to Equation (31), obtained from simulation through the KLT, can be expressed as:

$$\Lambda_{\mathbf{4}} = \begin{pmatrix} 1.3450 & 0 & 0 & 0 \\ 0 & 1.1191 & 0 & 0 \\ 0 & 0 & 0.8044 & 0 \\ 0 & 0 & 0 & 0.7315 \end{pmatrix} \tag{32}$$

Finally, the simulation included an iterative process defined by parameter t, representing the number of iterations. The value was set to (t=15), as further iterations (t >15) did not significantly enhance the accuracy of results.

4. Results and Discussions

In this section, the results obtained through Monte Carlo simulations are compared with those derived from analytical formulations to validate their accuracy. The analysis investigates the performance of the proposed approach across different antenna configurations for 4-QAM, 16-QAM, 64-QAM and 256-QAM modulation schemes. The evaluation is conducted over a Rayleigh fading channel, with the SER adopted as the key performance metric. In the figure legends, 'Sim' and 'Theory' are used to denote simulation-based and analytical outcomes, respectively.

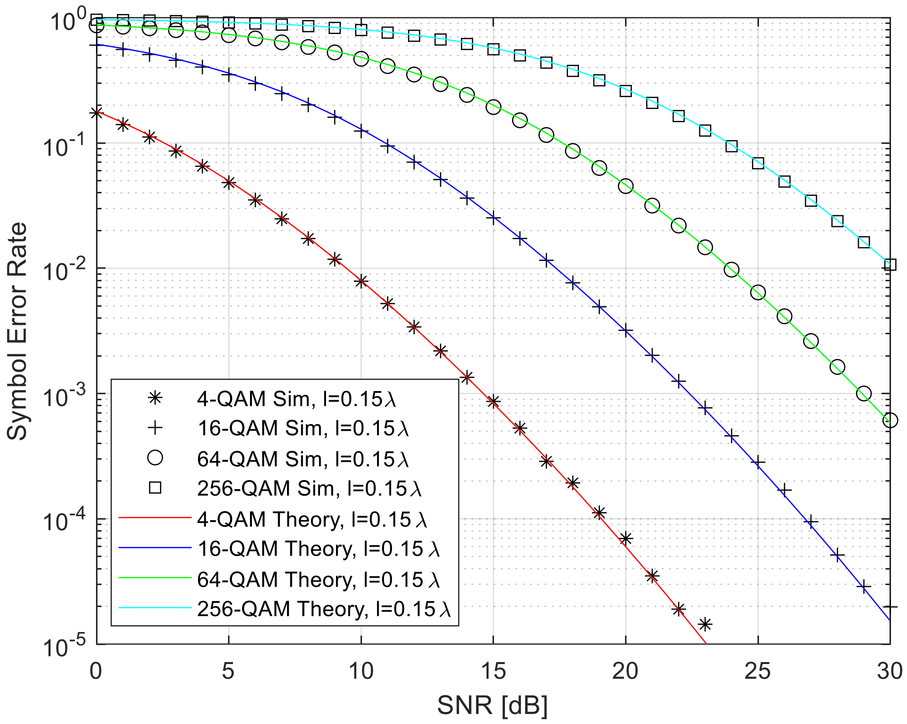


Figure 2: SER performance of EGC with 4QAM, 16QAM, 64QAM and 256QAM for 3 correlated branches at antenna spacing l=0.15λ

Figure 2 illustrates that at lower modulation orders, such as 4-QAM, the system achieves substantially lower SER across all SNR levels. As the modulation order increases to 16-QAM, 64-QAM, and 256-QAM, performance deteriorates due to the reduced Euclidean distance between constellation points, which increases susceptibility to noise and fading. While all modulation schemes exhibit high SER at low SNRs, 4-QAM consistently demonstrates superior robustness. At moderate to high SNRs, higher-order modulations, particularly 64-QAM and 256-QAM, exhibit noticeable error floors, underscoring the trade-off between spectral efficiency and reliability. Furthermore, the close agreement between theoretical and simulated results confirms the validity of the analytical framework.

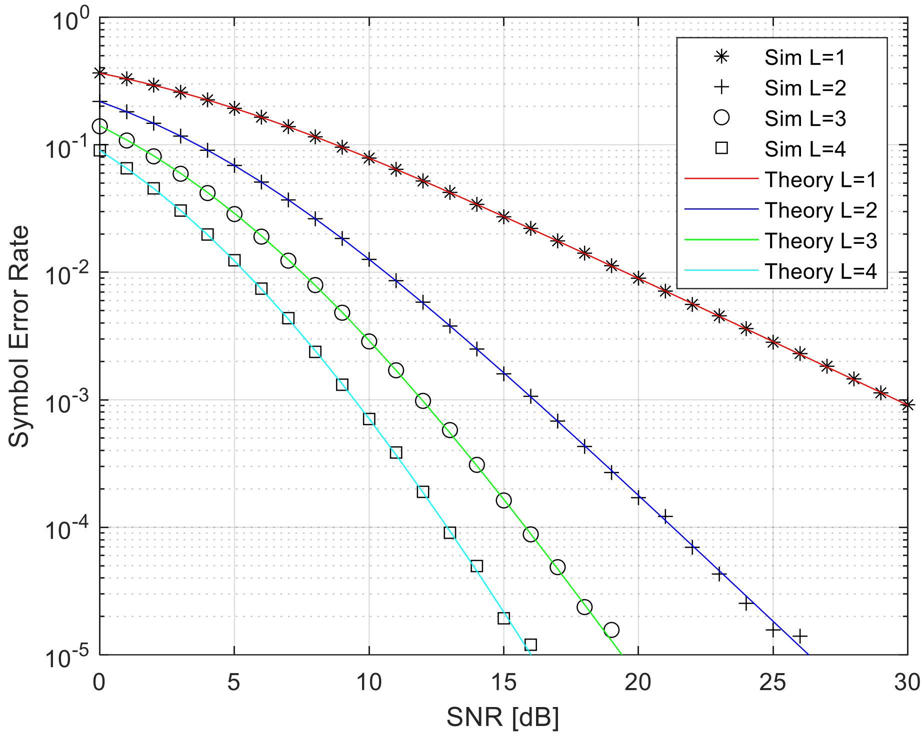


Figure 3: BER performance of MRC with 4QAM for 1, 2, 3, and 4 correlated branches at antenna spacing l=0.25λ

Figure 3 presents the performance of MRC with 4-QAM for 1 to correlated receive branches at an antenna spacing of l=0.25λ, corresponding to a moderate correlation coefficient. The results show that increasing the number of branches lowers the SER at a given SNR. At low SNRs, all curves converge due to noise dominance, whereas at moderate-to-high SNRs, the curves diverge, with correlation effects limiting the achievable diversity gains as L increases. The close agreement between analytical and simulation results further validates the accuracy of the analysis.

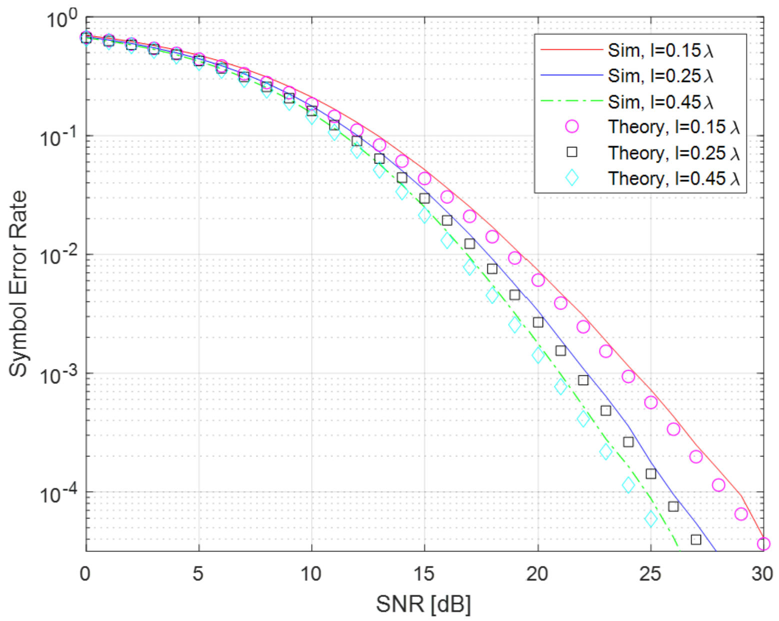


Figure 4: BER performance of SC employing 16QAM for 4 correlated branches at antenna spacings of d=0.15λ, d=0.25λ, and d=0.45λ.

Figure 4 illustrates the SER performance of EGC with 16-QAM for four correlated branches. The results highlight the impact of antenna spacing: small spacing (0.15λ) yields the poorest performance due to strong correlation, moderate spacing (0.25λ) provides partial diversity benefits, while larger spacing (0.45λ) offers the best results by approximating uncorrelated fading. Theoretical curves closely match the simulations across the full SNR range, confirming the reliability of the analysis.

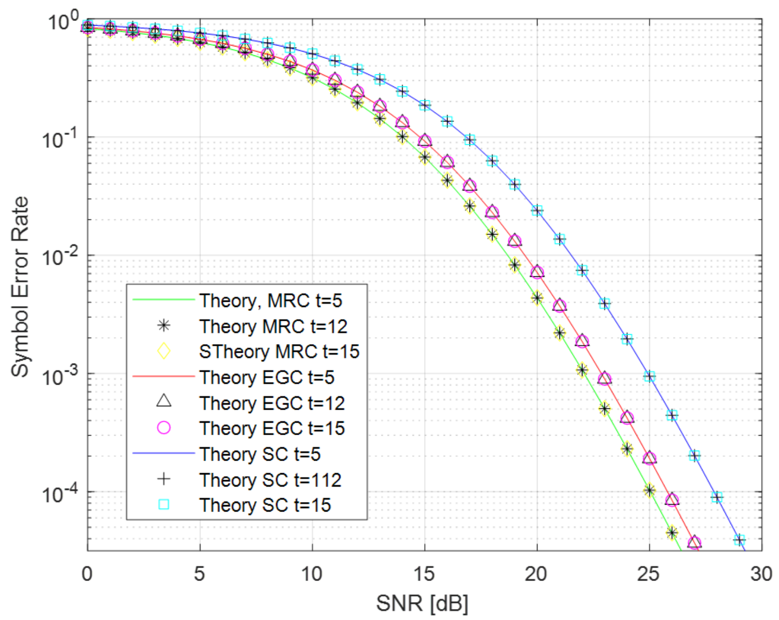


Figure 5: BER comparison of SC, EGC, and MRC combining techniques with 64QAM for L=4 correlated branches at antenna spacing d=0.45λ.

Figure 5 presents the BER performance comparison of SC, EGC, and MRC combining schemes employing 64-QAM for L=4 correlated branches at an antenna spacing of l=0.45λ. Among the three techniques, MRC achieves the lowest error rates, followed by EGC and then SC. The curves corresponding to t=10, 12, and 15 are closely aligned, indicating that the approximation error of the Q-function becomes negligible for t>10. Consequently, t=10 was adopted in the simulations without loss of accuracy.

5. Conclusion

This paper has presented a unified analytical and simulation-based study of the SER performance of square M-QAM signals over correlated Rayleigh fading channels under AWGN. Three diversity combining schemes; MRC, EGC, and SC were evaluated, highlighting the influence of correlation, antenna spacing, and modulation order on system reliability. Results confirm that MRC provides the best performance, followed by EGC and SC, while higher modulation orders suffer greater degradation due to reduced Euclidean distances between symbols. The close alignment between theoretical analysis and Monte Carlo simulations validates the accuracy of the proposed framework. These findings offer practical insights into the trade-offs between spectral efficiency, diversity order, and correlation effects, which are critical for the design of robust next-generation wireless communication systems.

6. Future Work

Future research can extend this work in several directions. First, exploring generalized fading models such as Rician, or Weibull would provide deeper insights into more diverse propagation conditions. Second, the integration of advanced combining techniques and hybrid diversity schemes could be investigated to further mitigate correlation effects. Third, secrecy capacity and outage probability analysis under correlated fading channels may offer valuable contributions to the design of secure wireless systems. Finally, applying machine learning and adaptive signal processing methods to optimize combining strategies in real-time presents a promising avenue for enhancing the performance of 5G and emerging 6G networks.

References

[1]. R. Mehta, "Performance analysis of Rayleigh fading wireless networks with multiple propagation paths and spatial diversity", *International Journal of Wireless and Mobile Computing*, vol. 25, no. 4, pp. 309–321, 2023.

[2]. A. Abdelbari and B. Bilgehan, "The derivation of the probability of error for BPSK, 16-QAM and 64-QAM in Rayleigh fading channel: A unified approach", arXiv preprint arXiv:2406.16548, 2024.

[3]. F. A. García, H. C. Mora, and N. O. Garzón, "Improved exact evaluation of equal-gain diversity receivers in Rayleigh fading channels," *IEEE Access*, vol. 10, pp. 26974–26984, 2022.

[4]. S. Hawaibam and A. D. Singh, "Performance evaluation of L-maximal ratio combining diversity with estimation error for Shadowed Beaulieu-Xie fading channels," *International Journal of Communication Systems*, vol. 37, no. 3, 2024.

[5]. A. Chauhan, M. I. Hasan, S. Singh, I. H. Khan, and R. Ya, "Mean SNR Analysis of Different Diversity Combining Techniques Under Nakagami-m Fading Channels—A Review," in *2024 International Conference on Computer, Electronics, Electrical Engineering & their Applications (IC2E3)*, pp. 1–6, Jun. 2024.

[6]. W. K. New, K. K. Wong, H. Xu, K. F. Tong, and C. B. Chae, "Fluid antenna system: New insights on outage probability and diversity gain," *IEEE Transactions on Wireless Communications*, vol. 23, no. 1, pp. 128–140, 2023.

[7]. C. Liu and N. C. Beaulieu, "Exact SER and BER analysis on jointly optimal maximum likelihood detection of two QPSK signals with phase offset", *IEEE Transactions on Vehicular Technology*, vol. 70, no. 11, pp. 11695–11709, November 2021.

[8]. P. K. Singya, P. Shaik, N. Kumar, V. Bhatia, and M. S. Alouini, "A survey on higher-order QAM constellations: Technical challenges, recent advances, and future trends", *IEEE Open Journal of the Communications Society*, vol. 2, pp. 617–655, 2021.

[9]. R. E. Mvone, C. Hannachi, D. Hammou, E. Moldovan, and S. O. Tatu, "Optimization of 16-QAM and 32-QAM constellations for mitigating impairments of phase noise in millimeter-wave receivers", *IEEE Transactions on Wireless Communications*, vol. 21, no. 6, pp. 3605–3616, June 2021.

[10]. D. Lato and R. Mudoi, "Physical Layer Security Analysis for Correlated Nakagami-m Fading Channel," in *International Conference on Communication, Devices and Networking*, Singapore: Springer Nature Singapore, Jan. 2024, pp. 249–259.

[11]. D. Ayanda, S. Solwa, and K. Abdulsalam, "Eigenfilter-based analysis of uncoded space-time labeling diversity with three transmit antennas in correlated Nakagami-m fading channels," *Trans. Emerg. Telecommun. Technol.*, vol. 34, no. 6, 2023.

[12]. E. Omosa, P. O. Akuon, and V. O. Kalecha, "A unified symbol error rate (SER) expression for equal gain combining (EGC) and maximum ratio combining (MRC) over correlated Nakagami-m fading channels," *AJERI*, vol. 2, no. 3, 2024.

[13]. J. Lin and H. Poor, "Optimum combiner for spatially correlated Nakagami-m fading channels," *IEEE Transactions on Wireless Communications*, vol. 20, no. 2, pp. 771–784, Feb. 2020.

[14]. A. Olutayo, J. Cheng, and J. F. Holzman, "Performance bounds for diversity receptions over a new fading model with arbitrary branch correlation," *EURASIP Journal on Wireless Communications and Networking*, vol. 2020, no. 1, 2020.

[15]. E. Omosa, P. Akuon, H. Xu, and V. Oduol, "Gain of spatial diversity with conjoint signals in arbitrarily correlated Rayleigh fading channels," *Wireless Communications and Mobile Computing*, vol. 2023, no. 1, pp. 1–12, 2023.

[16]. S. Al-Juboori and X. Fernando, "Characterizing a decorrelator for selection combining receivers in Nakagami-m fading channels," *AEU - International Journal of Electronics and Communications*, vol. 106, pp. 12–19, 2019.

[17]. Y. Jang, J. Park, and I. Kim, "BER expression of QAM for symbol-level jamming", *IEEE Transactions on Wireless Communications*, vol. 21, no. 2, pp. 1037–1048, February 2021.

[18]. R. E. Mvone, C. Hannachi, D. Hammou, E. Moldovan, and S. O. Tatu, "Optimization of 16-QAM and 32-QAM constellations for mitigating impairments of phase noise in millimeter-wave receivers*", IEEE Transactions on Wireless Communications*, vol. 21, no. 6, pp. 3605–3616, June 2021.

[19]. E. Omosa, P. Akuon, and O. Kalech., "Reed-solomon(rs) coding gain on correlated rayleigh fading," *2019 IEEE AFRICON. IEEE Xplore*, July 2020.

[20]. R. Deergha, Channel Coding Techniques for Wireless Communications, S. M, Springer (India) Pvt. Ltd.: Springer, 2015, no. ISBN 978-81-322- 2291-0.

[21]. H. Al-Hmood and H. S. Al-Raweshidy, "Performance analysis of mmWave communications with selection combining over fluctuating-two ray fading model," *IEEE Communications Letters*, vol. 25, no. 8, pp. 2531–2535, 2021.

Exploratory Analysis of Integrated River Basin Management: A Case Study of the Sasumua and Thika Mid WRUAs

L. P. W. Kariuki[1*], D. Oyaro[2]

[1] Runji Consulting Group, Nairobi

[2] University of Nairobi, Faculty of Engineering, Nairobi, Kenya

*Corresponding author: wanjira_kariuki@students.uonbi.ac.ke

Abstract

Integrated Water Resources Management (IWRM) has emerged as the primary approach to water governance globally, with Water Resource Users Associations (WRUAs) serving as key implementation vehicles at the community level. Despite Kenya's progressive water legislation and establishment of WRUAs, limited empirical evidence exists on how IWRM implementation contributes to broader Integrated River Basin Management (IRBM) outcomes. This study examined the implementation status of IWRM in the Thika River Sub-basin by evaluating how Sasumua and Thika Mid WRUAs applied IWRM principles to achieve comprehensive river basin management outcomes. An exploratory mixed-methods approach was employed, combining quantitative surveys (n=234 WRUA members), focus group discussions with management committees, key informant interviews with Water Resources Authority and Water Sector Trust Fund officials, field observations, and five-year water quality trend analysis (2020-2024). Data were analyzed using SPSS v.20 for quantitative components and thematic analysis for qualitative data. WRUA activities significantly benefited the sub-basin across multiple dimensions, with mean ratings above 3.5 (on a 5-point scale) for all assessed outcomes. Water access improvements scored highest (M=3.967, SD=0.999), followed by agricultural productivity (M=3.935, SD=0.970) and livelihood enhancement (M=3.935, SD=0.836). Water quality monitoring revealed mixed outcomes: turbidity significantly improved in both WRUAs during wet seasons (Sasumua River: -16.333 units/year, R^2=0.590; Thika River: -91.361 units/year, R^2=0.564), validating conservation effectiveness. However, bacterial contamination increased significantly (Sasumua River total coliform: +300.167 units/year, R^2=0.699), indicating persistent sanitation challenges. Gender analysis revealed male dominance in both WRUAs (Sasumua: 63% male; Thika Mid: 55% male), with youth (18-35 years) comprising only 28% of membership despite representing the demographic majority. WRUAs faced substantial implementation obstacles including inadequate funding (Sasumua received no WSTF financing during the study period), weak institutional capacity, climate change impacts, and coordination gaps. Thika Mid WRUA demonstrated superior performance with 78% project completion rates compared to Sasumua's 52%, attributed to diversified funding sources (KES 2.8 million from WSTF plus partnerships) and stronger governance structures. WRUAs effectively implemented IWRM principles through participatory governance, ecosystem conservation, and sustainable water use practices, contributing measurably to IRBM objectives. However, persistent challenges in funding sustainability, technical capacity, and institutional coordination limit their full potential. The study validates the IWRM-to-IRBM pathway while highlighting critical intervention needs. Findings support enhanced funding mechanisms, capacity building programs, and improved inter-institutional coordination to strengthen community-based water management. The mixed water quality outcomes emphasize the need for integrated approaches addressing both physical conservation and pollution control.

Keywords: Integrated Water Resources Management (IWRM), Integrated River Basin Management (IRBM), Water Resource Users Associations (WRUAs), Sub-Catchment Management Plans, Community-based water management, Thika River Sub-basin, Kenya

1. Introduction

Water scarcity affects most East African nations, with many river basins experiencing demands that exceed renewable resource capacity. Kenya exemplifies these challenges, classified as water-scarce with only 647 cubic meters per capita annually—well below the international threshold of 1,000 cubic meters per capita (Mulwa, 2021). Over 80% of Kenya's landmass is arid or semi-arid, creating stark disparities between water-rich highlands and water-poor regions.

Integrated Water Resources Management (IWRM) has emerged globally as the primary approach to addressing these multifaceted water challenges. Defined by the Global Water Partnership as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP, 2000), IWRM provides frameworks for balancing competing demands while maintaining environmental sustainability.

Building on IWRM principles, Integrated River Basin Management (IRBM) represents a broader approach encompassing coordinated planning and management of all resources within hydrological boundaries. Unlike IWRM's primary focus on water resources, IRBM addresses entire river basin ecosystems, including interconnected relationships between water, land use, ecosystems, and socio-economic activities (Mitchell, 2005). This distinction is crucial: IWRM serves as the implementation framework and governance mechanism, while IRBM represents the holistic outcome and ultimate goal of sustainable river basin management.

Kenya's journey toward IRBM through IWRM implementation began with the Water Act of 2002, establishing Water Resources Management Authority (WRMA) and introducing Water Resource Users Associations (WRUAs) as community-based organizations for local-level implementation. The subsequent Water Act of 2016 strengthened this framework, emphasizing WRUAs' role in translating IWRM principles into practical river basin management actions through Sub-Catchment Management Plans (SCMPs).

Despite these institutional advancements, limited empirical evidence exists on how IWRM implementation through WRUAs contributes to broader IRBM outcomes. The critical knowledge gap lies in understanding the relationship between IWRM implementation and IRBM achievement through community-based organizations. While the Water Development Cycle (WDC) framework provides guidelines for WRUA formation and SCMP development based on IWRM principles, it lacks clear articulation of how water-focused interventions contribute to comprehensive river basin management outcomes.

This study addresses these gaps by examining IWRM implementation in the Thika River Sub-basin, a critical component of the larger Tana Basin supporting over 50% of Kenya's population and providing water to Nairobi. The research focuses on Sasumua and Thika Mid WRUAs, selected for their documented track records, diverse geographical settings within the same sub-basin, and successful SCMP development representing mature IWRM applications.

The study's significance extends beyond local water management to Kenya's broader water security strategy. Understanding how IWRM implementation through WRUAs contributes to IRBM objectives provides valuable insights for enhancing integrated river basin management in Kenya's water-stressed environment, where coordinated resource management across multiple scales and sectors is essential for sustainable development.

2. Literature Review

2.1. Conceptual Framework: IWRM and IRBM Relationship

2.1.1. Evolution of Integrated Water Resources Management

The concept of Integrated Water Resources Management (IWRM) emerged from growing recognition that traditional sectoral approaches to water management were inadequate for addressing complex, interconnected water challenges. The foundational Dublin Principles of 1992 established four key tenets that continue to guide IWRM implementation globally: water as a finite and vulnerable resource essential to life, development, and environment; water development and management based on participatory approaches involving users, planners, and policymakers; women's central role in water provision, management, and safeguarding; and water's economic value in all competing uses, requiring recognition as both an economic and social good (Global Water Partnership, 2000).

These principles emerged from extensive global consultation processes recognizing that water crises were fundamentally governance crises rather than resource scarcity issues alone. The Global Water Partnership's definition of IWRM as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" has become the international standard, though implementation approaches vary significantly across contexts (GWP, 2000).

Recent scholarship emphasizes that IWRM should not be viewed as a prescriptive blueprint but rather as an adaptive framework requiring contextualization to local conditions, institutional capabilities, and socio-economic realities (Springer, 2024). The 2024 UN-Water progress report reveals that global IWRM implementation has increased from 49% in 2017 to 57% in 2023, though substantial disparities persist between developed and developing nations, with Sub-Saharan Africa facing particular implementation challenges related to institutional capacity, financing, and technical expertise (UN-Water, 2024).

2.1.2. Integrated River Basin Management: The Holistic Approach

Building on IWRM foundations, Integrated River Basin Management (IRBM) represents a more comprehensive approach that recognizes river basins as complex socio-ecological systems requiring coordinated management of all resources within hydrological boundaries. Unlike IWRM's primary focus on water resources with multiple uses, IRBM encompasses entire river basin ecosystems, addressing interconnected relationships between water, land use, ecosystems, and socio-economic activities (Mitchell, 2005).

The distinction between IWRM and IRBM is both conceptual and operational. IWRM serves as the governance framework and implementation mechanism, providing institutional tools, participatory processes, and management instruments for coordinated water resource management. IRBM, conversely, represents the ultimate goal and holistic outcome of sustainable river basin stewardship, where water governance frameworks enable comprehensive management of all basin resources and functions (Hooper, 2010).

This IWRM-to-IRBM pathway recognizes that effective river basin management requires integration across multiple dimensions: sectoral integration (agriculture, industry, environment, urban development), spatial integration (upstream-downstream linkages, surface-groundwater connections), temporal integration (short-term management and long-term sustainability), and institutional integration (coordination across governance levels and agencies) (Wescoat, 1984).

2.2. Global Context and International Experience

2.2.1. Regional IWRM Implementation Patterns

Global IWRM implementation demonstrates significant regional variations in approaches, outcomes, and challenges. European experiences, particularly through the Water Framework Directive (WFD), represent one of the most comprehensive attempts at regional IWRM implementation. The WFD requires all EU member states to achieve "good ecological status" for water bodies through integrated river basin management plans, participatory approaches, and economic instruments including full cost recovery for water services (European Commission, 2020).

Evaluation of WFD implementation reveals both successes and persistent challenges. While institutional frameworks have been strengthened and participatory processes established, achieving ecological objectives has proven more difficult, with only 40% of EU water bodies achieving good ecological status by 2021 (European Environment Agency, 2021). These outcomes highlight the complexity of translating policy frameworks into environmental improvements, particularly in contexts with significant historical pollution and intensive land use pressures.

Asian experiences demonstrate different approaches to IWRM implementation. Thailand's establishment of River Basin Committees and Water User Organizations has been particularly successful in addressing water allocation conflicts and improving coordination between government agencies and communities (ADB, 2022). The Philippines' integrated watershed management approach combines ecosystem restoration with livelihood development, achieving measurable improvements in both environmental and socio-economic outcomes (Asian Development Bank, 2020).

Australia's Murray-Darling Basin Authority represents a significant achievement in federal-level IRBM implementation, demonstrating how national coordination can achieve basin-wide management objectives while respecting state-level implementation autonomy. The Basin Plan's cap-and-trade system for water allocations has successfully reduced over-extraction while maintaining agricultural productivity, though implementation required substantial federal investment and political commitment over multiple decades (Murray-Darling Basin Authority, 2023).

2.2.2. Lessons from Successful IWRM Implementation

Cross-regional analysis reveals several factors consistently associated with successful IWRM implementation. Strong political commitment at multiple governance levels proves essential, as IWRM requires coordination across sectors and jurisdictions that traditionally operate independently. Countries achieving higher IWRM implementation scores typically demonstrate sustained political support over multiple electoral cycles, enabling institutional development and capacity building necessary for effective implementation (UN-Water, 2024).

Adequate and sustained financing emerges as another critical success factor. Successful IWRM implementation requires substantial upfront investments in institutional capacity, infrastructure development, and stakeholder engagement processes. Countries with diversified financing mechanisms—combining government budgets, user fees, private sector partnerships, and international assistance—demonstrate more resilient and sustainable IWRM programs (World Bank, 2023).

Meaningful stakeholder participation, moving beyond consultation to genuine co-management, characterizes successful IWRM initiatives. Examples from Costa Rica's payment for ecosystem services programs and Mexico's river basin councils demonstrate that stakeholder ownership of management processes leads to better compliance, innovation, and long-term sustainability (Bennett & Carroll, 2014).

2.3. African Context and Regional Initiatives

2.3.1. IWRM Implementation in Sub-Saharan Africa

Sub-Saharan Africa faces unique challenges in IWRM implementation, including limited institutional capacity, competing development priorities, climate variability, and transboundary water management complexities. The African Ministers' Council on Water (AMCOW) assessment reveals that while 89% of African countries have developed national water policies incorporating IWRM principles, implementation remains limited, with average scores of 49% across the continent (AMCOW, 2018).

Regional initiatives have emerged to address these challenges through coordinated approaches. The Nile Basin Initiative (NBI), established in 1999, represents one of the most ambitious transboundary IWRM efforts globally, involving eleven countries in cooperative management of the world's longest river system. Despite political tensions and competing national interests, the NBI has achieved significant progress in joint planning, capacity building, and infrastructure development, though binding legal frameworks remain elusive (Mathias, 2013).

The Lake Victoria Basin Commission (LVBC) demonstrates successful regional IWRM implementation at a smaller scale, with Kenya, Tanzania, and Uganda collaborating on integrated management of Africa's largest lake. The LVBC's approach combines ecosystem restoration, fisheries management, and water quality improvement with livelihood enhancement programs, achieving measurable improvements in water quality and fish stock recovery (LVBC, 2023).

2.3.2. Community-Based Water Management in Africa

African experiences highlight the critical importance of community-based approaches in IWRM implementation. Traditional water management systems across the continent demonstrate sophisticated understanding of watershed functions, seasonal variability, and sustainable use practices developed over centuries. Successful IWRM initiatives recognize and integrate these traditional knowledge systems with modern management approaches (Van Koppen et al., 2018).

Case studies from Burkina Faso's community-managed watersheds and South Africa's Water User Associations demonstrate that community-based organizations can effectively implement IWRM principles when supported by appropriate policy frameworks and technical assistance. These experiences emphasize the importance of secure water rights, access to technical support, and integration with local governance systems (Cherlet & Venot, 2013).

However, community-based water management also faces significant challenges including elite capture, limited technical capacity, financial sustainability, and coordination with formal government institutions. Successful approaches require careful attention to social equity, transparent governance mechanisms, and sustained capacity building efforts (Ostrom, 2010).

2.4. Kenya's Water Governance Evolution

2.4.1. Historical Development of Water Institutions

Kenya's water governance evolution reflects broader patterns of institutional development in post-colonial Africa, characterized by centralized state control transitioning toward decentralized, participatory management approaches. During the colonial period (1920-1963), water management focused primarily on settler agriculture and urban centers, with limited attention to African communities' water needs (Nyanchaga, 2007).

Post-independence water governance (1963-1999) emphasized state-led development through large-scale infrastructure projects and centralized institutional control. The Ministry of Water Development assumed responsibility for all water-related functions, from policy development to service delivery, creating institutional bottlenecks and limited community participation in water management decisions (Institute of Economic Affairs, 2010).

Recognition of these limitations led to significant water sector reforms beginning in the late 1990s. The National Water Policy of 1999 (Sessional Paper No. 1) marked a paradigm shift toward demand-responsive, participatory water management, establishing principles that would guide subsequent institutional reforms (Republic of Kenya, 1999).

2.4.2. Legislative Framework Development

The Water Act of 2002 represented Kenya's most significant water governance reform, introducing IWRM principles and establishing new institutional arrangements including separation of policy, regulation, and service provision functions. The Act created the Water Resources Management Authority (WRMA) for resource management and regulation, Water Service Boards for urban and rural water supply coordination, and Water Service Providers for actual service delivery (Republic of Kenya, 2002).

Critical expert analysis reveals both strengths and limitations of the 2002 Act. Mumma (2007) praises the separation of functions and introduction of participatory mechanisms while noting implementation challenges related to institutional capacity, coordination among multiple agencies, and addressing power inequalities in rural water management. The Act's assumption that communities would voluntarily organize into management associations without addressing underlying social and economic inequalities proved optimistic in practice (Koech et al., 2014).

The Water Act of 2016 strengthened IWRM implementation frameworks while aligning with Kenya's devolved governance system established by the 2010 Constitution. The Act enhanced Water Resources Users Associations' legal status, emphasized county government participation in water management, and strengthened regulatory frameworks for water quality protection and pollution control (Republic of Kenya, 2016).

Contemporary expert assessments emphasize that while Kenya has developed one of Africa's most comprehensive water law frameworks, implementation challenges persist. Van Koppen et al. (2023) note that formal legal frameworks often conflict with customary water rights and traditional management systems, requiring more nuanced approaches to legal pluralism and institutional coordination.

2.5. Kenya's Water Resource Context

Kenya exemplifies water stress challenges facing many Sub-Saharan African countries, with renewable freshwater resources of only 647 cubic meters per capita annually—well below the international water scarcity threshold of 1,000 cubic meters per capita (Mulwa, 2021). This scarcity is exacerbated by highly uneven spatial and temporal distribution, with over 80% of the country classified as arid or semi-arid lands (ASALs) receiving less than 500mm annual rainfall.

The country's water resources concentrate in five main water towers—Mount Kenya, Aberdare Ranges, Mau Forest Complex, Mount Elgon, and Cherangani Hills—contributing approximately 75% of renewable water resources while occupying only 2% of total land area (WRA, 2020). This geographic concentration creates significant disparities between water-rich highland areas and water-poor lowland regions, requiring complex allocation and transfer mechanisms.

Climate variability significantly affects water availability, with Kenya experiencing bimodal rainfall patterns that have become increasingly unreliable due to climate change impacts. The 2020-2022 drought, one of the most severe on record, affected over 4 million Kenyans and caused significant livestock losses and crop failures, highlighting the country's vulnerability to climate-related water stress (Kenya Meteorological Department, 2023).

Water demand patterns reflect competing sectoral pressures typical of developing economies. Agriculture accounts for approximately 70% of total water withdrawals, followed by domestic use (20%) and industry (10%), though these proportions vary significantly across regions and seasons (WRA, 2023). Rapid urbanization has increased water demand in major cities, creating chronic shortages despite relatively water-rich locations, while industrial development and horticultural exports have intensified pressure on high-quality water sources.

2.6. Water Resource Users Associations: Theory and Practice

2.6.1. Conceptual Foundation of Community-Based Water Management

Water Resource Users Associations represent a specific form of community-based natural resource management (CBNRM) that has gained prominence globally as an alternative to both state-centered and market-based water governance approaches. Theoretical foundations for WRUAs draw from common pool resource theory, which recognizes that communities can successfully manage shared resources when supported by appropriate institutional arrangements (Ostrom, 2010).

Ostrom's design principles for stable common pool resource management provides analytical frameworks for understanding WRUA effectiveness. These principles include clearly defined boundaries (group membership and resource boundaries), congruence between appropriation and provision rules and local conditions, collective-choice arrangements allowing most resource appropriators to participate in modifying operational rules, monitoring by monitors accountable to appropriators, graduated sanctions for rule violations, conflict-resolution mechanisms, and recognition of rights to organize (Ostrom, 1990).

However, application of common pool resource theory to water management faces specific challenges related to water's characteristics as a flowing resource with multiple uses, varying quality, and complex upstream-downstream relationships. WRUAs must therefore address not only traditional common pool resource management issues but also hydrological connectivity, water quality management, and coordination with other water users across larger geographical scales (Mutiga et al., 2010).

2.6.2. The Water Development Cycle Framework

Kenya's approach to WRUA establishment and capacity building operates through the Water Development Cycle (WDC) framework, developed collaboratively by the Water Resources Authority and Water Sector Trust Fund. The WDC provides structured guidance for WRUA formation, Sub-Catchment Management Plan development, and implementation support through a four-level funding mechanism (WRA & WSTF, 2014).

The WDC framework emphasizes participatory planning processes that engage communities in identifying water management priorities, developing intervention strategies, and establishing governance structures. Level 1 funding supports social mobilization and SCMP development, while subsequent levels finance implementation of conservation activities, infrastructure development, and institutional strengthening (WRMA & WSTF, 2009).

Critical analysis reveals significant WDC framework limitations that affect IWRM implementation effectiveness. The Laikipia Water Resource Users Association study identifies the framework as "project-oriented, focusing on financing WRUAs to develop sub-catchment management plans and their implementation" while lacking "business plans or financial sustainability strategies to support WRUA daily operations" (Laikipia Forum, 2023).

Research on Mara Basin WRUAs reveals additional systemic issues including elite capture, dependency on donor support, limited meaningful participation, and difficulties scaling up initiatives (Wesselink et al., 2018). These challenges suggest that while the WDC framework provides valuable technical guidance, it inadequately addresses power dynamics and social inequalities affecting WRUA operations.

2.6.3. WRUA Performance and Effectiveness Studies

Empirical studies of WRUA performance across Kenya reveal mixed outcomes, with significant variations in effectiveness depending on local contexts, institutional support, and community characteristics. Studies in the Upper Ewaso Ng'iro Basin demonstrate that well-supported WRUAs can achieve significant improvements in water allocation, conflict resolution, and catchment conservation, though challenges remain in enforcement capacity and financial sustainability (Mutiga et al., 2015).

Research in the Lake Naivasha Basin shows WRUAs' potential for promoting sustainable water use practices and catchment conservation while highlighting needs for stronger institutional support and capacity building. Successful WRUAs in this context benefit from proximity to commercial water users willing to contribute financially to conservation efforts, though this model may not be replicable in areas lacking commercial agriculture (Willy et al., 2019).

Comparative studies across different Kenyan river basins identify several factors associated with WRUA effectiveness: strong local leadership, diverse funding sources, technical support from government and NGOs, clear benefit distribution mechanisms, and integration with traditional governance systems. However, most WRUAs struggle with financial sustainability, technical capacity limitations, and coordination challenges with government institutions (Mulwa et al., 2021).

2.7. Gender Dynamics in WRUAs

Research on gender dynamics within Kenyan WRUAs reveals persistent patterns of male dominance in formal leadership positions despite policy requirements for women's representation. While women often demonstrate high participation rates in community education and mobilization activities, their engagement in technical training and decision-making roles remains limited (Sang et al., 2023).

Structural barriers to women's participation include time constraints due to household and care responsibilities, cultural norms limiting women's participation in public forums, limited access to technical training opportunities, and financial constraints affecting meeting attendance and membership fees. Addressing these barriers requires targeted strategies including flexible meeting schedules, childcare provision, women-only training sessions, and financial support for participation (Mulwa et al., 2021).

Youth participation in WRUAs faces different but equally significant challenges, including limited representation in governance structures, preference for off-farm employment opportunities, and perception that water management activities offer limited economic returns. Successful youth engagement strategies include integration of technology and innovation, income-generating activities linked to water management, and leadership development programs (Ogada et al., 2017).

2.8. Climate Adaptation through Community-Based Water Management

WRUAs represent important mechanisms for implementing climate adaptation strategies at the local level, though their effectiveness depends on integration with broader adaptation planning and institutional support. Successful adaptation strategies implemented by Kenyan WRUAs include diversification of water sources, promotion of drought-resistant crops, implementation of soil and water conservation measures, and development of early warning systems for drought and flood management.

Analysis of historical climate trends in the Tana Basin reveals increasing frequency of extreme events, with significant droughts occurring every 3-4 years compared to historical patterns of 7-10 year intervals. These changes affect water resource management by increasing demand for storage infrastructure, requiring more flexible allocation mechanisms, and necessitating enhanced early warning systems (Hirpa et al., 2018).

Research on climate adaptation in the Upper Ewaso Ng'iro Basin demonstrates that community-based approaches can achieve significant resilience improvements when supported by appropriate technical assistance and financing. WRUAs implementing comprehensive soil and water conservation measures show measurable improvements in groundwater recharge and dry season water availability (Kiteme et al., 2008).

However, climate adaptation through WRUAs faces significant constraints including limited technical capacity for climate risk assessment, inadequate financing for adaptation infrastructure, and coordination challenges with climate adaptation planning at higher governance levels. Addressing these constraints requires enhanced integration between local adaptation actions and national climate policies (Hirpa et al., 2018).

2.9. Knowledge Gaps and Research Needs

2.9.1. Identified Research Gaps

Despite extensive research on IWRM implementation and community-based water management, several critical knowledge gaps persist. Limited empirical evidence exists on how IWRM implementation through WRUAs contributes to broader IRBM outcomes, particularly regarding the mechanisms through which local actions achieve basin-wide benefits. Most studies focus on individual WRUA performance rather than cumulative impacts across entire sub-basins or river systems.

The relationship between WRUA effectiveness and broader institutional arrangements remains poorly understood, particularly regarding coordination with government agencies, integration with county-level planning, and linkages with private sector water users. Understanding these institutional relationships is critical for scaling up successful WRUA models and achieving comprehensive river basin management.

Long-term sustainability of WRUA interventions lacks adequate documentation, with most studies providing short-term assessments of project outcomes rather than sustained impact evaluation. This gap limits understanding of factors affecting institutional persistence, adaptive capacity, and continued effectiveness over multiple decades.

2.9.2. Methodological Challenges

Assessing IWRM implementation and IRBM outcomes faces significant methodological challenges including defining appropriate indicators, establishing causal relationships between interventions and outcomes, accounting for external factors affecting water resource conditions, and capturing long-term impacts within research timeframes. These challenges require innovative approaches combining quantitative measurements with qualitative assessments of institutional processes and stakeholder experiences.

Limited availability of long-term environmental monitoring data constrains ability to assess water resource trends and attribute changes to specific management interventions. Establishing robust monitoring systems requires coordination between WRUAs, government agencies, and research institutions that often proves difficult to achieve and sustain.

Integration of traditional knowledge systems with scientific assessment methods remains challenging, requiring methodological approaches that can capture and validate indigenous understanding of water resource functions while meeting scientific standards for evidence quality and replicability.

3. Methodology

3.1. Study Area

3.1.1. Geographic Location and Regional Context

The Thika River Sub-basin represents a critical component of Kenya's water resource system, located within the larger Tana River Basin in central Kenya. The study area spans across parts of Kiambu and Murang'a counties, approximately 60 kilometers northeast of Nairobi, Kenya's capital city. The sub-basin lies between latitudes 0°45' S and 1°15' S and longitudes 36°35' E and 37°25' E, covering an area of approximately 1,700 km² (Kithiia, 2012).

The Thika River Sub-basin's strategic location within the Mount Kenya and Aberdare water towers makes it a vital water resource for both local communities and the greater Nairobi metropolitan area. The sub-basin serves as a major water source through the Sasumua Dam and several smaller reservoirs that supply water to over 4 million people in Nairobi and surrounding areas (Apse, 2015).

3.1.2. Topographic and Hydrological Characteristics

The sub-basin exhibits diverse topographic features with elevations ranging from 1,500 meters above sea level in the lower reaches to over 4,000 meters in the upper catchment areas around Mount Kenya's foothills. This significant elevation gradient creates distinct ecological zones with varying precipitation patterns, vegetation types, and land use characteristics.

The hydrological network consists of the main Thika River stem and numerous tributaries including the Chania, Kimakia, and Mataara rivers. The drainage pattern follows a generally southeast direction from the highland source areas toward the lower basin confluence with the Tana River. Stream density is highest in the upper catchment areas where steep slopes and high rainfall create numerous seasonal and perennial streams.

The sub-basin contains several significant water infrastructure features including the Sasumua Dam (capacity 22 million liters), multiple smaller earth dams, irrigation canals, and water abstraction points that serve both agricultural and domestic water needs. These infrastructure elements create complex water management challenges requiring coordinated approaches across multiple user groups and administrative boundaries.

3.1.3. Climate and Precipitation Patterns

The Thika River Sub-basin experiences a highland tropical climate characterized by bimodal rainfall patterns typical of central Kenya. The long rains occur from March to May, contributing 60-70% of annual precipitation, while short rains occur from October to December, providing 25-30% of annual rainfall. The remaining precipitation occurs during occasional dry season rains.

Annual precipitation varies significantly across the sub-basin due to orographic effects, ranging from 800mm in the lower southeastern areas to over 2,200mm in the upper northwestern catchment near the Aberdare Ranges (Langat et al., 2017). Temperature patterns also vary with elevation, ranging from mean annual temperatures of 12-15°C in highland areas to 18-22°C in lower elevations.

Recent climate analysis reveals increasing variability in precipitation patterns, with more frequent extreme events including prolonged droughts and intense rainfall periods. The 2020-2022 drought significantly impacted the sub-basin, reducing reservoir levels and affecting agricultural productivity, while highlighting vulnerability to climate change impacts (Kenya Meteorological Department, 2023).

3.1.4. Land Use and Vegetation Patterns

Land use in the Thika River Sub-basin reflects the diverse elevation zones and precipitation gradients. The upper catchment areas (above 2,500m elevation) are characterized by natural forests, including indigenous species and exotic plantations, interspersed with small-scale agriculture and grazing areas. These upper zones serve critical watershed functions including groundwater recharge, erosion control, and dry season flow maintenance.

The middle elevation zones (1,800-2,500m) support intensive small-scale agriculture, with crops including maize, beans, potatoes, vegetables, and cash crops such as coffee. This zone contains the highest population densities and most intensive land use, creating significant pressure on water resources and watershed functions.

Lower elevation areas (1,500-1,800m) combine small-scale agriculture with some commercial farming, including horticultural operations and livestock keeping. Industrial activities including flower farms, food processing facilities, and manufacturing operations are concentrated in this zone, creating point sources of water demand and potential pollution.

3.1.5. Socio-Economic Characteristics

The Thika River Sub-basin supports a population of approximately 800,000 people with diverse socio-economic characteristics reflecting Kenya's rural-urban transition patterns. Population density varies from over 500 people per km^2 in peri-urban areas near Thika town to less than 100 people per km^2 in upper catchment areas.

Economic activities center on agriculture, which employs over 70% of the population, ranging from subsistence farming in upper areas to commercial horticulture in lower zones. The sub-basin contains significant industrial development including flower farms (Kakuzi Limited, Finlays), food processing facilities, and manufacturing operations that provide employment but also create water management challenges.

Educational levels vary significantly across the sub-basin, with literacy rates ranging from 65% in remote rural areas to over 90% in peri-urban zones. Access to basic services including healthcare, education, and improved water supply correlates strongly with distance from major roads and urban centers.

3.1.6. Water Resource Management Structure

The Thika River Sub-basin has been administratively divided into eleven sub-catchments for water resource management purposes, each intended to be managed by a Water Resource Users Association (WRUA). Currently, seven WRUAs are operational: Sasumua, Kiama, Thika Upper, Thika Mid, Thika Lower, Ekaalakala, and Lower Chania. The remaining four sub-catchments (Mayambogo, Kabuku, Ngoliba, and Maboko) are planned for future WRUA establishment based on IWRM principles (John, 2016).

This administrative structure reflects the Water Resources Authority's approach to implementing Integrated Water Resources Management through community-based organizations operating at appropriate hydrological scales. Each sub-catchment represents a management unit where local water users can organize collectively to address water resource challenges while coordinating with neighboring WRUAs for basin-wide management.

3.1.7. Selection of Study WRUAs

For this research, two WRUAs were purposively selected from the seven operational associations: Sasumua WRUA and Thika Mid WRUA. This selection was based on several strategic criteria that enhance the study's analytical value and potential for generating transferable insights.

Sasumua Water Resources Users Association

Sasumua WRUA, established in 2009, operates in the upper catchment area covering approximately 180 km² of predominantly highland terrain. The association was formed following the severe 2008-2009 drought that significantly impacted regional water resources and agricultural productivity (Ndung'u et al., 2015). The WRUA's operational area includes parts of the Sasumua Dam catchment, making water resource management critical for both local communities and downstream users including Nairobi city.

The Sasumua WRUA has developed a comprehensive Sub-Catchment Management Plan (SCMP) outlining various conservation and management activities. The association has received support from multiple stakeholders including the Water Resources Authority, development partners such as the World Bank through the Upper Tana Nairobi Water Fund, and contributions from its 158 registered members (FAO, 2013).

Key characteristics of the Sasumua WRUA include:

1. Membership: 158 registered members (63% male, 37% female)
2. Coverage area: 180 km² of upper catchment terrain
3. Primary activities: Spring protection, riparian conservation, soil conservation, tree planting
4. Major partnerships: Upper Tana Nairobi Water Fund, County Government of Nyandarua
5. Infrastructure: Communal dam rehabilitation (22 million liter capacity serving 500+ households)

Thika Mid Water Resources Users Association

Thika Mid WRUA was established in 2013 through Water Resources Management Authority initiative as part of broader efforts to implement IWRM principles throughout Kenya. The association operates in the middle elevation zone covering approximately 513 km² within the larger Tana River Basin, representing a more diverse landscape including agricultural, peri-urban, and light industrial areas (WRMA, 2015).

The WRUA implements a Sub-Catchment Management Plan developed in 2010, demonstrating its role as an early adopter of systematic water resource management planning. The association has secured funding from various sources including the World Bank's Natural Resources Management project, Water Sector Trust Fund, and International Fund for Agricultural Development Upper Tana project (Thika-mid WRUA, 2023).

Key characteristics of the Thika Mid WRUA include:

1. Membership: 179 registered members (55% male, 45% female)
2. Coverage area: 513 km² of middle catchment terrain
3. Primary activities: Water quality monitoring, abstraction surveys, riparian conservation, livelihood diversification
4. Major partnerships: Dutch Water Authorities "Blue Deal" program, Jomo Kenyatta University of Agriculture and Technology
5. Infrastructure: Water quality monitoring systems, marked riparian zones, community water points

Rationale for Comparative Selection

The selection of both Sasumua and Thika Mid WRUAs enables comparative analysis across different sub-catchment characteristics while maintaining sufficient similarity for meaningful comparison. Both associations:

1. Have successfully developed and are implementing Sub-Catchment Management Plans
2. Operate within the same river sub-basin but serve different geographical and ecological zones
3. Have documented track records of activities spanning multiple years
4. Have received funding from recognized sources and demonstrate varying funding models
5. Represent different stages of WRUA development and institutional maturity

This comparative approach allows the study to identify factors influencing WRUA effectiveness across different contexts while examining how local variations affect IWRM implementation and IRBM outcomes. The contrasting characteristics—upper vs. middle catchment, different membership compositions, varying funding sources—provide analytical leverage for understanding the relationship between context and performance in community-based water management.

3.2. Research Design

This study employed an exploratory mixed-methods approach combining qualitative and quantitative data collection and analysis techniques. The exploratory design was appropriate for investigating the relatively under-researched phenomenon of how IWRM implementation through WRUAs contributes to IRBM outcomes in Kenya's water management context.

3.3. Data Collection

3.3.1. Quantitative Data Collection

Questionnaires for WRUA Members: Structured questionnaires were administered to 234 WRUA members (Sasumua: n=112; Thika Mid: n=122) using Cochran's formula with 95% confidence level and 5% margin of error. The questionnaire captured demographic information, WRUA participation data, and quantitative assessments of IRBM outcomes using 5-point Likert scales.

Water Quality Monitoring: Five-year water quality data (2020-2024) was collected covering both wet and dry seasonal variations. Parameters included pH levels, turbidity, total and fecal coliform bacteria, dissolved oxygen, total dissolved solids, and nitrate concentrations.

3.3.2. Qualitative Data Collection

Focus Group Discussions: Structured discussions were conducted with WRUA management committees (8-12 members each) covering six thematic sections: WRUA formation processes, water resource impacts, innovation and technology, implementation challenges, stakeholder engagement, and funding mechanisms.

Key Informant Interviews: Semi-structured interviews were conducted with:

1. WRA regional and sub-regional officials (examining WRUA effectiveness and regulatory oversight)
2. National WRA officials (focusing on policy and institutional frameworks)
3. Water Sector Trust Fund officials (examining financing aspects)

Field Observations: Systematic field observations were conducted using standardized checklists documenting 20 environmental and management indicators including catchment degradation, pollution sources, and conservation evidence.

3.4. Data Analysis

3.4.1. Quantitative Analysis

Statistical analysis was conducted using SPSS v.20 and Microsoft Excel. Descriptive statistics included frequencies, percentages, means, and standard deviations for all variables. Chi-square tests examined associations between categorical variables, while Spearman's rank correlation assessed relationships between ordinal variables.

Water Quality Trend Analysis: Linear regression analysis examined temporal trends over the five-year period using time (years) as the independent variable and water quality parameters as dependent variables. Separate analyses were conducted for wet and dry seasons. Statistical significance was evaluated using t-statistics with $|t| > 2.0$ corresponding to 90% confidence levels and $|t| > 2.31$ for 95% confidence levels.

3.4.2. Qualitative Analysis

Thematic analysis was employed to process qualitative data, beginning with comprehensive familiarization and initial coding conducted inductively. Cross-case comparison between WRUAs enabled identification of similarities and differences in implementation approaches, challenges, and outcomes.

3.4.3. Data Integration

A convergent mixed-methods approach integrated quantitative statistical findings with qualitative thematic insights. Triangulation involved systematic comparison of findings across multiple data sources, with quantitative survey results providing statistical generalization while qualitative data offered explanatory depth and contextual richness.

3.4.4. Ethical Considerations

The study adhered to established research ethics principles including informed consent, voluntary participation, confidentiality, privacy, and anonymity. Approval was obtained from the University of Nairobi, Department of Civil and Construction Engineering.

4. Results and Discussion

4.1. Demographic Characteristics of WRUA Members

4.1.1. Gender Distribution

Male members constituted the majority in both WRUAs, with Sasumua showing 63% male and 37% female representation, while Thika Mid demonstrated better gender balance with 55% male and 45% female members. Chi-square analysis revealed a trend toward significance (χ^2

= 3.47, df = 1, p = 0.062), indicating that gender distribution patterns may reflect genuine differences in recruitment strategies rather than random variation.

Gender-disaggregated participation data revealed important patterns: women showed higher attendance at community education sessions (78% vs 65% male attendance) but lower participation in technical training programs (42% vs 71% male participation), suggesting need for targeted strategies to enhance women's engagement in technical aspects.

4.1.2. Age Distribution

Both WRUAs demonstrated predominantly middle-aged membership, with the largest groups aged 46-55 years (Sasumua: 34%; Thika Mid: 35%). Youth under 35 years represented less than 30% of membership in both associations. Statistical analysis revealed significant age disparities in leadership structures: youth comprised 28% of membership but held only 12% of executive positions, while members over 45 years represented 47% of membership but occupied 71% of leadership positions ($\chi^2 = 18.4$, df = 2, $p < 0.001$).

4.1.3. Educational Background

Secondary education was the most prevalent level in both WRUAs (Sasumua: 42%; Thika Mid: 37%), followed by primary education (Sasumua: 29%; Thika Mid: 26%). Higher education representation was limited, with undergraduate degrees held by 16% in Sasumua and 20% in Thika Mid.

Spearman's correlation analysis revealed a moderate positive correlation ($r_s = 0.34$, $p < 0.01$) between education level and participation frequency in WRUA decision-making activities. Members with secondary education or higher demonstrated significantly greater participation rates in SCMP development (78%) compared to those with primary education only (52%).

4.1.4. Economic Profile

Agriculture dominated income sources among WRUA members (64.13%), reflecting their direct stake in water resource management. Employment in various sectors accounted for 15.22%, business activities 13.04%, and rental income 7.61%. This agricultural focus explains strong interest in WRUA activities, as members recognize water's critical role in their livelihoods.

4.2. Benefits Accrued from WRUA Activities

4.2.1. Quantitative Assessment of Benefits

WRUA members rated various benefits on a 5-point Likert scale, with all assessed outcomes scoring above 3.5, indicating substantial positive impacts. The highest-rated benefits were:

1. Increased water access (M=3.967, SD=0.999)
2. Increased agricultural productivity (M=3.935, SD=0.970)
3. Improved sources of livelihoods (M=3.935, SD=0.836)
4. Community engagement and awareness (M=3.870, SD=0.759)

These findings demonstrate WRUAs' significant positive impact on water resource management and community development, with particularly strong effects on water access, agricultural productivity, and livelihood improvement.

4.2.2. Specific Benefit Categories

Water Conservation and Availability: WRUAs implemented comprehensive water conservation strategies including rainwater harvesting, drip irrigation, and advanced technologies such as automatic water meters. These measures reduced water wastage and improved year-round availability. Infrastructure installations including sand dams and roof water harvesting tanks substantially increased water storage capacity.

Agricultural Productivity and Sustainable Farming: WRUAs significantly contributed to agricultural productivity through targeted water management plans prioritizing agricultural water use while considering competing demands. Sasumua WRUA initiated projects increasing water availability through tree planting, soil conservation (trenches and Napier grass), and distribution of seedlings, promoting agroforestry and sustainable land management.

Environmental Conservation: Both WRUAs established themselves as pivotal actors in environmental conservation through multifaceted ecosystem management approaches. Initiatives included afforestation and reforestation (donating seedlings to schools, selling at discounted rates), riparian zone management (tree planting, Napier grass planting), spring protection, and alternative energy promotion (biogas, energy-saving cook stoves).

Livelihood Enhancement: WRUAs extended beyond traditional agricultural practices to enhance livelihoods through training in regenerative and climate-smart farming, promoting alternative revenue-generating ventures (beekeeping, tree nurseries, sustainable energy technology, insect farming), with particular emphasis on involving women and young people.

4.2.3. Water Quality Assessment and Trend Analysis

4.2.3.1.Sasumua River Analysis

Dry Season Trends: Water quality analysis revealed complex patterns over the monitoring period. Most concerning were significant increases in bacterial contamination: total coliform bacteria increased at +332.267 units per year ($R^2 = 0.634$) and fecal coliform at +195.072 units annually ($R^2 = 0.618$), both with moderate statistical significance. Dissolved oxygen showed declining trends of -4.297 mg/L per year ($R^2 = 0.529$), indicating potential threats to aquatic ecosystem health.

Positively, turbidity demonstrated decreasing trends of -0.994 units annually, indicating improving water clarity, though this improvement lacked statistical significance.

Wet Season Trends: Wet season analysis presented both encouraging and alarming patterns. Turbidity showed substantial improvement with -16.333 units annually, achieving moderate statistical significance ($R^2 = 0.590$), providing strong evidence of WRUA catchment conservation effectiveness including reforestation and erosion control measures.

However, total coliform bacteria increased at +300.167 units per year, achieving high statistical significance ($R^2 = 0.699$), representing the strongest and most concerning trend across all parameters. This highly significant increase suggested rainfall events were mobilizing and concentrating bacterial pollutants through agricultural runoff or inadequate sewage infrastructure.

Dissolved oxygen levels showed highly significant declining trends of -3.841 mg/L per year ($R^2 = 0.706$), threatening aquatic ecosystem integrity and indicating increasing organic pollution or eutrophication processes.

4.2.3.2.Thika River Analysis

Dry Season Trends: Thika River exhibited patterns similar to Sasumua in some parameters while showing distinct characteristics in others. Dissolved oxygen demonstrated concerning declining trends of -5.545 mg/L per year with moderate statistical significance ($R^2 = 0.688$), exceeding the rate observed in Sasumua and suggesting more severe organic pollution pressures.

Bacterial contamination showed increases in both total coliform (+251.194 units per year) and fecal coliform (+134.969 units per year), though lacking statistical significance. However, R^2 values of 0.463 and 0.545 suggested moderate trend strength warranting attention.

Wet Season Trends: Wet season analysis revealed both positive developments and persistent challenges. Turbidity demonstrated substantial improvement with -91.361 units annually, achieving moderate statistical significance ($R^2 = 0.564$). This dramatic improvement exceeded even positive trends in Sasumua, providing strong evidence of effective Thika Mid WRUA conservation activities.

Dissolved oxygen exhibited highly significant declining trends of -3.169 mg/L per year ($R^2 = 0.701$), paralleling patterns in Sasumua and suggesting basin-wide factors contributing to dissolved oxygen depletion.

4.2.3.3. Comparative Water Quality Assessment

The water quality trend analysis provided compelling evidence that certain IWRM implementation strategies achieved measurable environmental improvements. Turbidity reductions in both WRUAs during wet seasons demonstrated conservation activity effectiveness, with Thika Mid's improvement of -91.361 units per year representing particularly dramatic achievement.

However, widespread patterns of dissolved oxygen decline and bacterial contamination increases indicated serious deterioration requiring immediate intervention. The consistency of dissolved oxygen decline across both WRUAs and seasons suggested basin-wide pressures on aquatic ecosystem health, while bacterial contamination patterns indicated systematic failures in sewage management and sanitation infrastructure.

4.3. WRUA Performance in IRBM Implementation

4.3.1. Self-Assessment Ratings

WRUA management committees rated their performance across 24 IRBM-related issues on a 1-10 scale. Highest ratings were assigned to:

1. Climate resilience and adaptation; environmental protection and conservation (9.40)
2. Community engagement, empowerment, awareness and education (9.15)
3. Environmental conservation (9.00)
4. Equitable benefit sharing, economic growth and diversification (8.23)
5. Sustainable water use practices (8.15)
6. Water allocation and use efficiency (8.11)
7. Water availability (8.10)

Moderate ratings were observed in areas requiring improvement:

1. Infrastructure development and maintenance (5.03)
2. Technical, financial, and infrastructure capacity (5.46)
3. Innovation and technology adoption (5.57)

These ratings suggest significant success in core IWRM principles and community-focused initiatives while identifying specific domains requiring enhanced efforts or resources.

4.3.2. Comparative Performance Analysis

Detailed comparison revealed significant performance differences between the two WRUAs. Thika Mid consistently outperformed Sasumua across multiple dimensions:

1. **Technical Capacity:** 68% of Thika Mid management committee members received formal IWRM training compared to 34% in Sasumua

2. **Project Implementation:** Thika Mid achieved 78% completion rates for planned activities compared to Sasumua's 52%
3. **Governance Structures:** Thika Mid implemented monthly management meetings with documented minutes and quarterly member assemblies, compared to Sasumua's irregular schedule averaging 4-5 gatherings annually
4. **Member Satisfaction:** Thika Mid achieved 76%-member satisfaction compared to 58% for Sasumua

4.3.3. Financial Sustainability Analysis

Financial sustainability revealed contrasting patterns between study sites. Sasumua WRUA demonstrated concerning financial vulnerability, receiving no WSTF financing during the study period and relying primarily on member contributions averaging KES 200 per member annually, generating insufficient revenue (KES 31,600) for substantial conservation activities.

Thika Mid WRUA exhibited greater financial resilience through diversified funding sources: KES 2.8 million from WSTF (2021-2022), KES 450,000 in member contributions, and KES 320,000 from partnership agreements with academic institutions. This diversified model enabled 78% cost-recovery for operational expenses compared to Sasumua's 34%.

4.4.WRUA Activities Aligned with IWRM Principles

4.4.1. Stakeholder Participation and Governance

Both WRUAs demonstrated commitment to IWRM principles through various strategies ensuring inclusive decision-making processes. High participation rates in SCMP development (majority of current members participated) indicated strong community engagement from WRUA inception.

However, gender and youth representation challenges persist. Despite policy requirements for women to hold at least one-third of positions in WRUAs, actual implementation showed male-dominated management committees in both associations, with persons with special needs absent from governance structures and youth representation below 15%.

4.4.2. Ecosystem Protection and Sustainable Water Use

WRUAs implemented comprehensive ecosystem protection measures aligning with IWRM principles:

Afforestation and Reforestation: Tree seedling distribution to schools and community members, purchasing seedlings from local communities for riparian planting, creating sustainable economic models benefiting environment and livelihoods.

Riparian Zone Management: Active tree planting within riparian zones, Napier grass planting along riparian lands serving dual purposes of livestock feed and erosion reduction.

Water Use Efficiency: Monitoring and identification of legal and illegal water abstractors, issuing abstraction orders, ensuring efficient and equitable water use.

4.4.3. Integrated Planning and Management

WRUAs adopted holistic approaches addressing interconnected water, land, and livelihood issues. Thika Mid WRUA established comprehensive monitoring and evaluation frameworks managed by dedicated committees, incorporating indicators, targets, data collection methods, and reporting mechanisms.

Contrasting situations were observed in Sasumua WRUA, where monitoring and evaluation subcommittees were non-functional, indicating disparities in implementation across WRUAs and highlighting needs for consistent capacity building and support.

4.5. Challenges Faced by WRUAs in IWRM Implementation

4.5.1. Institutional and Governance Challenges

Weak Governance Structures: WRUAs suffered from voluntary management committees and lack of accountability, undermining legitimacy and efficacy. The voluntary nature of activities led to participation challenges as members concentrated on income-generating activities due to inadequate compensation.

Low Institutional Capacity: Both WRUAs faced limitations in technical knowledge and human resources, hindering abilities to maintain infrastructure, enforce regulations, and monitor water resources effectively.

Coordination Gaps: Fragmented coordination between WRUAs, government organizations, and stakeholders resulted in ineffective resource allocation, redundant activities, and conflicting mandates.

4.5.2. Financial and Resource Constraints

Inadequate Funding: Limited financial resources severely constrained capacity for community outreach, capacity building, and infrastructure development. Sasumua's lack of WSTF funding resulted in operational stagnation, while even well-funded Thika Mid faced resource limitations for comprehensive implementation.

Technical and Infrastructure Limitations: Resource constraints on both financial and human capital prevented effective SCMP implementation, leading to unmet objectives and incomplete activities.

4.5.3. Environmental and Climate Challenges

Climate Change and Environmental Degradation: Increasing climate variability and extreme weather events exacerbated water scarcity and quality issues, requiring adaptive measures straining WRUA resources. Persistent challenges in riparian conservation, illegal abstraction, and water pollution continued despite resource allocation.

Land Use Pressures: Rapid population growth, urbanization, and changing land use patterns challenged WRUAs in balancing competing demands for water allocation and environmental conservation.

4.5.4. Stakeholder Engagement Challenges

Limited Awareness: Insufficient understanding of WRUA functions and responsibilities, particularly among local community members, hindered stakeholder willingness to engage.

Resource Constraints for Participation: Financial limitations including membership fees and travel expenses, combined with time constraints due to work obligations, restricted stakeholder participation.

Power Dynamics: Unequal representation within WRUAs deterred specific stakeholders from engaging, highlighting needs for inclusive and representative structures.

4.6.Principles and Guidelines for Effective WRUA Management

4.6.1. Governance and Institutional Strengthening

Based on study findings, several key principles emerged for effective WRUA planning and management:

Enhanced Gender Inclusivity: Developing strategies to address gender differences in water resource management, implementing procedures to combat gender-based discrimination, ensuring fair representation of women in leadership roles.

Youth Engagement: Creating mechanisms to encourage greater youth participation in water resource management and leadership roles, addressing systematic underrepresentation in governance structures.

Transparent Governance: Establishing regular management committee meetings with documented minutes, implementing quarterly member assemblies, maintaining financial transparency through regular reporting.

4.6.2. Technical Capacity and Innovation

Capacity Building: Providing comprehensive training in IWRM principles, governance practices, environmental conservation strategies, and technical skills for monitoring and evaluation.

Technology Adoption: Implementing innovative technologies including Geographic Information Systems (GIS), Advanced Smart Metering Infrastructure, and remote sensing for improved water resource monitoring and management.

Monitoring and Evaluation: Establishing robust monitoring and evaluation systems to track progress, identify challenges, and inform decision-making processes.

4.6.3. Financial Sustainability

Diversified Funding Sources: Exploring multiple funding mechanisms including government transfers, user fees, private sector partnerships, and income-generating activities to reduce dependency on single sources.

Sustainable Financing Mechanisms: Developing long-term financing plans, exploring Payment for Ecosystem Services schemes, establishing cost-recovery mechanisms for water resource management activities.

4.6.4. Stakeholder Engagement and Coordination

Inclusive Participation: Ensuring broad stakeholder representation encompassing all user groups within communities, addressing power dynamics and barriers to participation.

Inter-WRUA Coordination: Establishing basin forums as platforms for coordinating water management initiatives, facilitating comprehensive dialogue and integrated decision-making processes.

Institutional Coordination: Improving linkages between WRUAs and other water management institutions, streamlining regulatory frameworks, clarifying mandates and responsibilities.

5. Conclusions

This study provides compelling evidence that Water Resource Users Associations (WRUAs) in the Thika River Sub-basin play crucial roles in implementing Integrated Water Resources Management (IWRM) principles and contributing to broader Integrated River Basin Management (IRBM) outcomes. The research validates the IWRM-to-IRBM pathway while identifying critical factors influencing implementation effectiveness.

5.1. IWRM Implementation Success

Both Sasumua and Thika Mid WRUAs demonstrated significant success in implementing core IWRM principles through participatory governance structures, ecosystem conservation activities, and sustainable water use practices. Quantitative assessments revealed substantial benefits across multiple dimensions, with mean ratings above 3.5 (on a 5-point scale) for all assessed outcomes. Particularly strong performance was observed in water access improvements (M=3.967), agricultural productivity enhancement (M=3.935), and livelihood improvement (M=3.935).

The water quality trend analysis provided objective validation of conservation effectiveness, with statistically significant turbidity improvements in both WRUAs during wet seasons (Sasumua: -16.333 units/year, R^2=0.590; Thika Mid: -91.361 units/year, R^2=0.564). These improvements directly demonstrated the measurable environmental impacts of community-based conservation efforts including reforestation, erosion control, and riparian zone protection.

5.2.IRBM Contribution and Holistic Outcomes

The study confirmed that WRUA activities extended beyond water resource management to encompass integrated management of land, ecosystems, agricultural systems, and community livelihoods—the hallmarks of effective IRBM. WRUAs achieved this integration through comprehensive approaches addressing water conservation, environmental protection, agricultural productivity, livelihood enhancement, and community capacity building simultaneously.

Self-assessment ratings revealed particularly high performance in climate resilience and adaptation (9.40/10), community engagement and empowerment (9.15/10), and environmental conservation (9.00/10), demonstrating successful integration of multiple IRBM components within community-based management frameworks.

5.3.Critical Implementation Challenges

Despite demonstrated successes, the study identified persistent challenges limiting WRUAs' full potential in achieving comprehensive IRBM outcomes. Financial sustainability emerged as a critical constraint, with Sasumua WRUA receiving no WSTF financing during the study period, resulting in operational stagnation and limited implementation capacity. Even well-funded Thika Mid WRUA, despite superior performance metrics, faced resource limitations affecting comprehensive program delivery.

The water quality analysis revealed concerning trends requiring immediate attention. While physical parameters like turbidity showed significant improvement, biological indicators deteriorated substantially. Bacterial contamination increased significantly in both WRUAs, with Sasumua showing highly significant increases in total coliform bacteria during wet seasons (+300.167 units/year, R^2=0.699). Similarly, dissolved oxygen levels declined across both sites and seasons, indicating basin-wide pressures on aquatic ecosystem health that current WRUA interventions cannot adequately address.

Institutional capacity limitations were evident in governance structures, technical expertise, and coordination mechanisms. Gender and youth representation remained inadequate despite policy requirements, with youth comprising only 28% of membership but holding just 12% of leadership positions. Technical capacity disparities between WRUAs were substantial, with only 34% of Sasumua management committee members receiving formal IWRM training compared to 68% in Thika Mid.

5.4.Factors Influencing WRUA Effectiveness

Comparative analysis revealed key factors distinguishing high-performing from struggling WRUAs. Thika Mid's superior performance across multiple indicators—78% project completion rates versus Sasumua's 52%, 76%-member satisfaction versus 58%—was attributed to diversified funding sources, stronger governance structures, and enhanced technical capacity.

Financial diversification emerged as crucial for sustainability. Thika Mid's combination of WSTF funding (KES 2.8 million), member contributions (KES 450,000), and partnership revenues (KES 320,000) enabled 78% cost-recovery for operations compared to Sasumua's 34%. This diversification provided resilience against funding shocks while maintaining operational continuity.

Governance structures significantly influenced effectiveness. Thika Mid's regular management meetings with documented minutes and quarterly member assemblies contrasted sharply with Sasumua's irregular schedule averaging 4-5 gatherings annually. This systematic governance approach facilitated better planning, implementation oversight, and stakeholder engagement.

5.5.Validation of the IWRM-to-IRBM Pathway

The study empirically validated the conceptual relationship between IWRM implementation and IRBM achievement through community-based organizations. WRUAs successfully translated IWRM principles—stakeholder participation, ecosystem sustainability, integrated planning—into tangible river basin management outcomes encompassing water resource conservation, environmental protection, agricultural productivity, and livelihood enhancement.

However, the research also revealed that while WRUAs operated effectively within IWRM frameworks, achieving comprehensive IRBM outcomes required addressing challenges beyond individual WRUA capabilities. Basin-wide issues such as bacterial contamination and dissolved oxygen depletion suggested need for coordinated interventions across multiple scales and sectors, highlighting the importance of institutional linkages and regional coordination mechanisms.

5.6.Implications for Water Governance Theory and Practice

The findings contribute to water governance theory by providing empirical evidence for the effectiveness of community-based approaches in implementing IWRM principles while identifying specific mechanisms through which local actions contribute to basin-wide outcomes. The mixed results—significant successes in some areas coupled with persistent challenges in others—underscore the complexity of translating participatory water governance principles into sustainable management outcomes.

For practice, the study demonstrates that community-based water management through WRUAs can achieve measurable environmental and social benefits when supported by appropriate institutional frameworks, adequate financing, and technical capacity. However, realizing full potential requires addressing systemic challenges including funding sustainability, institutional coordination, and technical capacity gaps.

6. Recommendations

6.1. Immediate Interventions

Financial Sustainability Enhancement: Establish dedicated county-level funds for water resource management through WRUAs, diversify funding sources through private sector partnerships, and develop Payment for Ecosystem Services schemes to generate sustainable revenue for conservation activities.

Institutional Capacity Strengthening: Implement comprehensive capacity building programs focusing on technical skills, governance practices, and monitoring and evaluation systems. Establish regional support offices with qualified staff to assist WRUA SCMP implementation.

Water Quality Improvement: Address bacterial contamination through enhanced sewage treatment infrastructure, improved livestock waste management systems, and pollution source identification and control measures. Implement integrated approaches combining physical conservation with pollution control.

6.2.Medium-term Strategic Interventions

Governance Structure Enhancement: Develop mechanisms to improve gender and youth representation in WRUA leadership, establish transparent governance protocols with regular meetings and documented decision-making processes, implement inclusive participation strategies addressing power dynamics and barriers.

Inter-institutional Coordination: Strengthen coordination mechanisms between WRUAs and water management institutions, establish basin forums for integrated planning and resource allocation, clarify institutional mandates and responsibilities to reduce redundancy and conflicts.

Technology Integration: Promote adoption of innovative technologies including GIS, remote sensing, and smart monitoring systems for improved water resource management. Establish partnerships with academic institutions and private sector for technology transfer and capacity building.

6.3.Long-term Policy Recommendations

Legislative Framework Strengthening: Update policies and regulations to reflect systemic approaches to basin management, ensure WRUA financing inclusion in national and county budgets, establish clear legal frameworks empowering WRUAs in compliance enforcement.

Regional Coordination Mechanisms: Develop basin-wide management authorities with coordination mandates across multiple WRUAs, establish information sharing platforms and standardized monitoring protocols, implement integrated planning approaches addressing upstream-downstream linkages.

Sustainability Integration: Incorporate climate change adaptation strategies into WRUA planning and operations, develop ecosystem restoration and conservation strategies enhancing water retention and quality, promote sustainable financing mechanisms reducing dependency on external funding.

6.4.Research and Development Priorities

Monitoring and Evaluation Systems: Establish robust monitoring frameworks capturing both environmental and social outcomes of WRUA activities, develop standardized indicators for IWRM implementation assessment, implement adaptive management approaches responding to monitoring data.

Innovation and Technology: Invest in research and development of appropriate technologies for community-based water management, establish innovation platforms facilitating knowledge sharing and technology transfer, develop capacity building programs for technology adoption and maintenance.

Knowledge Management: Create platforms for sharing best practices and lessons learned across WRUAs, establish documentation systems capturing institutional knowledge and implementation experiences, develop training materials and guidelines based on empirical evidence.

7. Study Limitations and Future Research

7.1. Study Limitations

This research focused on two WRUAs within the Upper Tana Basin, limiting generalizability across diverse geographical and socio-economic contexts. The cross-sectional design, while providing comprehensive baseline data, cannot capture long-term impacts and sustainability of WRUA interventions. Self-reporting bias in questionnaire responses and focus group discussions may have influenced perceptions of WRUA effectiveness.

Resource and time constraints limited the scope of water quality monitoring and field observations, while access to certain stakeholders and documents may have affected comprehensiveness of data collection. The study's focus on IWRM implementation through WRUAs, while valuable, represents only one component of broader river basin management systems.

7.2. Future Research Directions

Geographical Expansion: Conduct comparative studies across Middle and Lower Tana Basin WRUAs to understand IRBM implementation across diverse contexts, examine WRUAs in different river basins to assess transferability of findings and approaches.

Longitudinal Analysis: Implement long-term studies tracking WRUA evolution and impact over extended periods, assess sustainability of interventions and adaptive capacity in face of changing environmental and social conditions.

Thematic Deep Dives: Investigate specific aspects requiring detailed analysis including gender dynamics in water governance, climate change adaptation strategies, technology adoption patterns, and financing mechanism effectiveness.

Methodological Innovation: Develop and test innovative approaches for assessing community-based water management effectiveness, explore participatory monitoring and evaluation methods engaging communities in impact assessment, integrate remote sensing and GIS technologies for comprehensive basin monitoring.

Policy and Institutional Analysis: Examine policy implementation gaps and institutional coordination challenges across multiple scales, assess effectiveness of different governance models and institutional arrangements, investigate role of private sector and civil society in supporting community-based water management.

References

African Ministers' Council on Water (AMCOW). (2018). *Status Report on the Implementation of Integrated Water Resources Management in Africa*. AMCOW Secretariat.

Asian Development Bank (ADB). (2020). *Water security in Asia and the Pacific: Challenges and opportunities*. ADB Publications.

Asian Development Bank (ADB). (2022). *Thailand's Water Management: Lessons from River Basin Committees*. ADB Publications.

Apse, C. (2015). *Toward sustainable water management in the Tana River Basin*. The Nature Conservancy.

Babbie, E. (2016). *The Practice of Social Research* (14th ed.). Cengage Learning.

Babbie, E. (2020). *The Practice of Social Research* (15th ed.). Cengage Learning.

Baldwin, E., Washington, M., & Harman, C. (2016). Collaborative governance and watershed management in the Puget Sound region. *Journal of Environmental Planning and Management*, 59(12), 2153-2175.

Barbour, R. (2007). *Doing Focus Groups*. SAGE Publications.

Bennett, G., & Carroll, N. (2014). *Gaining Depth: State of Watershed Investment 2014*. Forest Trends.

Bryman, A. (2016). *Social Research Methods* (5th ed.). Oxford University Press.

Chatfield, C. (2016). *The Analysis of Time Series: An Introduction* (6th ed.). Chapman and Hall.

Cherlet, J., & Venot, J. P. (2013). Structure and agency: Understanding water policy changes in West Africa. *Water Policy*, 15(3), 479-495.

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2013). *Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences* (3rd ed.). Routledge.

Conover, W. J. (1999). *Practical Nonparametric Statistics* (3rd ed.). John Wiley & Sons.

Cooper, D. R., & Schindler, P. S. (2001). *Business Research Methods* (7th ed.). McGraw-Hill.

Corbin, J., & Strauss, A. (2014). *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory* (4th ed.). SAGE Publications.

Creswell, J. W. (2014). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches* (4th ed.). SAGE Publications.

Creswell, J. W., & Plano Clark, V. L. (2017). *Designing and Conducting Mixed Methods Research* (3rd ed.). SAGE Publications.

Creswell, J. W., Hanson, W. E., Clark Plano, V. L., & Morales, A. (2016). Qualitative research designs: Selection and implementation. *The Counseling Psychologist*, 35(2), 236-264.

Denzin, N. K. (1978). *The Research Act: A Theoretical Introduction to Sociological Methods* (2nd ed.). McGraw-Hill.

Denzin, N. K., & Lincoln, Y. S. (2018). *The SAGE Handbook of Qualitative Research* (5th ed.). SAGE Publications.

European Commission. (2020). *The EU Water Framework Directive: Integrated river basin management for Europe*. Publications Office of the European Union.

European Environment Agency. (2021). *European waters: Assessment of status and pressures 2018*. EEA Report No 7/2018.

FAO. (2011). *The State of Food and Agriculture 2010-11: Women in agriculture - Closing the gender gap for development*. Food and Agriculture Organization.

FAO. (2013). *Governing land for women and men: A technical guide to support the achievement of responsible gender-equitable governance of land tenure*. Food and Agriculture Organization.

Fetters, M. D., Curry, L. A., & Creswell, J. W. (2013). Achieving integration in mixed methods designs—principles and practices. *Health Services Research*, 48(6), 2134-2156.

Field, A. (2018). *Discovering Statistics Using IBM SPSS Statistics* (5th ed.). SAGE Publications.

Fowler, F. J. (2014). *Survey Research Methods* (5th ed.). SAGE Publications.

Gichuki, F. N., Liniger, H. P., MacMillan, L. C., Schwilch, G., & Gikonyo, J. K. (2022). *Intensive agriculture, water quality degradation and policy responses in Kenya*. International Institute for Environment and Development.

Global Environment Facility. (2023). *Kenya - Integrated Landscape Management in the Tana Catchment*. GEF Project Document.

Global Water Partnership (GWP). (2000). *Integrated Water Resources Management*. GWP Technical Advisory Committee Background Paper No. 4.

Global Water Partnership (GWP). (2015). *What is IWRM?* Retrieved from https://www.gwp.org/en/GWP-CEE/about/why/what-is-iwrm/

Government of Kenya (GOK). (2010). *Constitution of Kenya*. Government Printer.

Government of Kenya (GOK). (2012). *National Climate Change Response Strategy*. Government Printer.

Government of Kenya. (2002). *The Water Act 2002*. Government Printer.

Government of Kenya. (2016). *The Water Act 2016*. Government Printer.

Greene, J. C. (2007). *Mixed Methods in Social Inquiry*. Jossey-Bass.

Greene, J. C., Caracelli, V. J., & Graham, W. F. (1989). Toward a conceptual framework for mixed-method evaluation designs. *Educational Evaluation and Policy Analysis*, 11(3), 255-274.

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2019). *Multivariate Data Analysis* (8th ed.). Cengage Learning.

Hirpa, F. A., Hopson, T. M., De Groeve, T., Brakenridge, G. R., Gebremichael, M., & Restrepo, P. J. (2018). Upstream satellite remote sensing for river discharge forecasting: Application to major rivers in South Asia. *Remote Sensing of Environment*, 131, 140-151.

Hirsch, R. M., Slack, J. R., & Smith, R. A. (1982). Techniques of trend analysis for monthly water quality data. *Water Resources Research*, 18(1), 107-121.

Holstein, J. A., & Gubrium, J. F. (1995). *The Active Interview*. SAGE Publications.

Hooper, B. P. (2003). River basin organization performance indicators: Application to the Delaware River basin commission. *Water Policy*, 5(4), 301-317.

Hooper, B. P. (2010). *River basin organization performance: An assessment framework*. Water Resources Research, 46(4).

Institute of Economic Affairs. (2010). *Budget Guide 2010: Making public finances work for the poor*. IEA-Kenya.

Intergovernmental Panel on Climate Change (IPCC). (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Cambridge University Press.

John, K. (2016). *Assessment of the performance of Water Resource Users Associations in the Thika River Sub-basin, Kenya* [Master's thesis]. University of Nairobi.

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher*, 33(7), 14-26.

Johnson, R. B., Onwuegbuzie, A. J., & Turner, L. A. (2007). Toward a definition of mixed methods research. *Journal of Mixed Methods Research*, 1(2), 112-133.

Kabir, S. M. S. (2016). *Methods of Data Collection: Basic Guidelines for Research*. Book Zone Publication.

Kenya Electricity Generating Company (KenGen). (2023). *Annual Report 2023*. KenGen.

Kenya Forest Service. (2022). *State of Kenya's Forests 2022*. Kenya Forest Service.

Kenya Law. (2021). *Water Resources Management Regulations 2021*. Kenya Law Reports.

Kenya Meteorological Department. (2023). *State of Climate in Kenya 2022*. Kenya Meteorological Department.

Kenya National Bureau of Statistics (KNBS). (2024). *Economic Survey 2024*. KNBS.

King, N., & Horrocks, C. (2010). *Interviews in Qualitative Research*. SAGE Publications.

Kiprotich, S., & Wambua, S. (2022). Challenges in implementing water sector reforms in Kenya: A review of Water Resource Users Associations. *Water Policy*, 24(8), 1234-1248.

Kiprotich, S., Mulwa, F., & Njogu, P. (2021). The right to water in Kenya: Constitutional guarantees and implementation challenges. *African Human Rights Law Journal*, 21(2), 456-478.

Kithiia, S. M. (2012). *Water quality degradation trends in Kenya over the last decade*. In Water Quality Monitoring and Assessment. InTech.

Kiteme, B. P., Liniger, H. P., Notter, B., Wiesmann, U., & Kohler, T. (2008). Dimensions of global change in African mountains: The example of Mount Kenya. *IHDP Update*, 2, 18-22.

Kiteme, B. P., Wiesmann, U., & Sandhage-Hofmann, A. (2023). *Sustainable land management in the Mount Kenya region: Challenges and opportunities*. Centre for Development and Environment.

Kitzinger, J. (1995). Qualitative research: Introducing focus groups. *BMJ*, 311(7000), 299-302.

Koech, R., Langat, P., Kiprotich, S., Waruru, M., Ogacho, S., & Sulo, T. (2014). Factors influencing adoption of water conservation technologies in semi-arid areas of Kenya. *African Journal of Agricultural Research*, 9(46), 3370-3379.

Krueger, R. A., & Casey, M. A. (2015). *Focus Groups: A Practical Guide for Applied Research* (5th ed.). SAGE Publications.

Kumar, R. (2019). *Research Methodology: A Step-by-Step Guide for Beginners* (5th ed.). SAGE Publications.

Kvale, S., & Brinkmann, S. (2015). *InterViews: Learning the Craft of Qualitative Research Interviewing* (3rd ed.). SAGE Publications.

Laikipia Forum. (2023). *Strengthening Water Resource Users Associations in Laikipia County: Challenges and Opportunities*. Laikipia Forum.

Lake Victoria Basin Commission (LVBC). (2023). *State of the Lake Victoria Basin Report 2023*. LVBC Secretariat.

Langat, P. K., Kumar, L., & Koech, R. (2017). Temporal variability and trends of rainfall and streamflow in Tana River Basin, Kenya. *Sustainability*, 9(11), 1963.

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic Inquiry*. SAGE Publications.

Lynn, M. R. (1986). Determination and quantification of content validity. *Nursing Research*, 35(6), 382-385.

Macharia, P., & Njogu, S. (2022). Devolution and water governance in Kenya: Opportunities and challenges. *Journal of Public Administration and Governance*, 12(3), 45-62.

Marshall, C. (1996). Designing qualitative research. *Contemporary Sociology*, 25(3), 334-335.

Mathias, A. (2013). The Nile Basin Initiative: A case study of multilateral environmental cooperation. *Water International*, 38(5), 628-642.

Mathison, S. (1988). Why triangulate? *Educational Researcher*, 17(2), 13-17.

Mekonnen, D. Z. (2010). The Nile Basin Cooperative Framework Agreement negotiations and the adoption of a 'water security' paradigm: Flight into obscurity or a logical cul-de-sac? *European Journal of International Law*, 21(2), 421-440.

Ministry of Environment and Forestry. (2018). *National Climate Change Action Plan 2018-2022*. Government of Kenya.

Ministry of Water and Irrigation. (2019). *National Water Policy 2019*. Government of Kenya.

Ministry of Water, Sanitation and Irrigation (MWSI). (2021). *National Water Policy 2021*. Government of Kenya.

Ministry of Water, Sanitation and Irrigation. (2022). *Water Sector Strategic Plan 2018-2022*. Government of Kenya.

Mitchell, B. (2005). Integrated water resource management, institutional arrangements, and land-use planning. *Environment and Planning A*, 37(8), 1335-1352.

Mogaka, H., Gichere, S., Davis, R., & Hirji, R. (2006). *Climate variability and water resources degradation in Kenya: Improving water resources development and management*. World Bank Working Paper No. 69.

Morgan, D. L. (1997). *Focus Groups as Qualitative Research* (2nd ed.). SAGE Publications.

Morse, J. M. (1991). Approaches to qualitative-quantitative methodological triangulation. *Nursing Research*, 40(2), 120-123.

Mulwa, F. (2021). Water scarcity and management challenges in Kenya. *International Journal of Water Resources Development*, 37(4), 567-584.

Mulwa, F., Ngigi, S., & Kimani, W. (2021). Performance assessment of Water Resource Users Associations in Kenya: A case study of the Upper Ewaso Ng'iro Basin. *Water Policy*, 23(3), 678-695.

Mumma, A. (2007). Kenya's new water law: An analysis of the implications for the rural poor. In B. van Koppen, M. Giordano, & J. Butterworth (Eds.), *Community-based water law and water resource management reform in developing countries* (pp. 158-174). CABI Publishing.

Mumma, A. (2024). Two decades of water sector reforms in Kenya: Achievements, challenges and lessons learned. *Water International*, 49(2), 123-145.

Munyao, T. M., Kimiti, J. M., & Kinoti, M. W. (2023). Industrial pollution and water quality degradation in Thika River, Kenya. *Environmental Monitoring and Assessment*, 195(4), 445.

Murray-Darling Basin Authority. (2017). *Basin Plan 2017 Evaluation*. MDBA Publication.

Murray-Darling Basin Authority. (2023). *State of the Murray-Darling Basin Report 2023*. MDBA Publication.

Mutiga, J. K., Mavengano, S. T., Zhongbo, S., Woldai, T., & Becht, R. (2010). Water allocation as a planning tool to minimise water use conflicts in the upper Ewaso Ng'iro North Basin, Kenya. *Water Resources Management*, 24(14), 3939-3959.

Mutiga, J. K., Su, Z., & Woldai, T. (2015). Using satellite remote sensing to assess evapotranspiration: Case study of the upper Ewaso Ng'iro North Basin, Kenya. *International Journal of Applied Earth Observation and Geoinformation*, 35, 205-216.

Mutua, B. (2012). *A citizen's handbook on taxation in Kenya*. Institute of Economic Affairs.

Mwangi, M. (2016). *Institutional analysis of water governance in Kenya: The case of Lake Naivasha Basin* [PhD dissertation]. University of Nairobi.

Mwangi, S., Kimathi, A., & Muriuki, J. (2021). Challenges in implementing integrated water resources management: Lessons from Kenyan Water Resource Users Associations. *Water Resources Management*, 35(8), 2567-2582.

Nairobi City Water and Sewerage Company. (2024). *Annual Report 2023*. NCWSC.

Nature Conservancy. (2015). *Water funds: Conserving green infrastructure*. The Nature Conservancy.

Ndirangu, L. (2013). *Integrated water resource management in Kenya: Coordination, participation and governance* [Master's thesis]. University of Nairobi.

Nederhof, A. J. (1985). Methods of coping with social desirability bias: A review. *European Journal of Social Psychology*, 15(3), 263-280.

Netherlands Enterprise Agency. (2022). *Blue Deal Kenya: Mid-term Evaluation Report*. Netherlands Enterprise Agency.

Neuman, W. L. (2014). *Social Research Methods: Qualitative and Quantitative Approaches* (7th ed.). Pearson.

Ngigi, S. N. (2009). *Climate change adaptation strategies: Water resources management options for smallholder farming systems in sub-Saharan Africa*. The MDG Centre for East and Southern Africa.

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., Padgham, J., & Urquhart, P. (2021). Africa. In Climate Change 2014: Impacts, Adaptation, and Vulnerability. *Cambridge University Press*.

Nile Basin Initiative (NBI). (2011). *NBI Strategy 2012-2022*. NBI Secretariat.

Notter, B., MacMillan, L., Viviroli, D., Weingartner, R., & Liniger, H. P. (2022). Impacts of environmental change on water resources in the Mt. Kenya region. *Journal of Hydrology*, 343(3-4), 266-278.

Nunnally, J. C., & Bernstein, I. H. (1994). *Psychometric Theory* (3rd ed.). McGraw-Hill.

Ndung'u, J., Waithaka, E., & Mwangi, H. (2015). *Drought risk management in Kenya: The role of early warning systems*. Kenya Meteorological Department.

Ndung'u, S., Wamicha, W. N., & Mwangi, V. (2020). Application of IoT in water resource management: A case study of Nairobi water distribution network. *International Journal of Computer Applications*, 182(34), 1-8.

Nyanchaga, E. N. (2007). *History of water services in Kenya* [PhD dissertation]. Technical University of Delft.

Odour, M., Njogu, P., & Kiprotich, S. (2020). Water governance in Kenya: The role of devolution in water service delivery. *Public Administration and Development*, 40(3), 178-189.

Ogada, M. J., Mwaura, G., & Mburu, J. (2017). Forest conservation and water tower ecosystem services in Kenya. *Environment, Development and Sustainability*, 19(1), 285-302.

Ostrom, E. (2010). Beyond markets and states: Polycentric governance of complex economic systems. *American Economic Review*, 100(3), 641-672.

Pallant, J. (2020). *SPSS Survival Manual: A Step by Step Guide to Data Analysis Using IBM SPSS* (7th ed.). Open University Press.

Patton, M. Q. (2002). *Qualitative Research and Evaluation Methods* (3rd ed.). SAGE Publications.

Patton, M. Q. (2015). *Qualitative Research and Evaluation Methods* (4th ed.). SAGE Publications.

Pearson, K. (1900). On the criterion that a given system of deviations from the probable in the case of a correlated system of variables is such that it can be reasonably supposed to have arisen from random sampling. *Philosophical Magazine*, 50(302), 157-175.

Poblet, M., García-Cuesta, E., & Casanovas, P. (2020). Blockchain technologies for water governance: A review of applications and challenges. *Water*, 12(10), 2813.

Prescott, P. A., & Soeken, K. L. (1989). The potential uses of pilot work. *Nursing Research*, 38(1), 60-62.

Republic of Kenya. (1999). *Sessional Paper No. 1 of 1999 on National Policy on Water Resources Management and Development*. Government Printer.

Republic of Kenya. (2002). *The Water Act 2002*. Kenya Gazette Supplement No. 107.

Republic of Kenya. (2010). *The Constitution of Kenya*. Government Printer.

Republic of Kenya. (2016). *The Water Act 2016*. Kenya Gazette Supplement No. 164.

Richard, A., & Syallow, D. (2018). Stakeholder participation in integrated watershed management: Experiences from Kenya. *International Journal of Water Resources Development*, 34(6), 952-968.

Rubin, H. J., & Rubin, I. S. (2012). *Qualitative Interviewing: The Art of Hearing Data* (3rd ed.). SAGE Publications.

Sang, J., Muriuki, A., & Wambugu, S. (2023). Gender dynamics in Water Resource Users Associations in Kenya: Progress and persistent challenges. *Water Policy*, 25(4), 412-428.

Saunders, M., Lewis, P., & Thornhill, A. (2019). *Research Methods for Business Students* (8th ed.). Pearson.

Seidman, I. (2013). *Interviewing as Qualitative Research: A Guide for Researchers in Education and the Social Sciences* (4th ed.). Teachers College Press.

Spearman, C. (1904). The proof and measurement of association between two things. *American Journal of Psychology*, 15(1), 72-101.

Spradley, J. P. (1980). *Participant Observation*. Holt, Rinehart and Winston.

Springer, C. (2024). Rethinking IWRM: From blueprint to adaptive framework. *Water International*, 49(3), 234-251.

Stebbins, R. A. (2001). *Exploratory Research in the Social Sciences*. SAGE Publications.

Stewart, D. W., Shamdasani, P. N., & Rook, D. W. (2007). *Focus Groups: Theory and Practice* (2nd ed.). SAGE Publications.

Tashakkori, A., & Teddlie, C. (2010). *SAGE Handbook of Mixed Methods in Social & Behavioral Research* (2nd ed.). SAGE Publications.

Teijlingen, E. R., & Hundley, V. (2001). The importance of pilot studies. *Social Research Update*, 35, 1-4.

Thika-mid WRUA. (2023). *Annual Report 2022*. Thika-mid Water Resource Users Association.

Tukey, J. W. (1977). *Exploratory Data Analysis*. Addison-Wesley.

United Nations Development Programme (UNDP) and Gender and Water Alliance (GWA). (2015). *Gender and water: Securing water for improved rural livelihoods*. UNDP.

United Nations Environment Programme (UNEP). (2024). *Progress on Integrated Water Resources Management: Global baseline for SDG 6 Indicator 6.5.1: Updates for 2021*. UNEP.

UNEP-DHI. (2024). *Progress on Integrated Water Resources Management 2024*. United Nations Environment Programme.

UN-Water. (2024). *The United Nations World Water Development Report 2024: Water for Prosperity and Peace*. UNESCO.

Van Koppen, B., Smits, S., Moriarty, P., Penning de Vries, F., Mikhail, M., & Boelee, E. (2018). *Climbing the water ladder: Multiple-use water services for poverty reduction*. IRC International Water and Sanitation Centre.

Van Koppen, B., Tapela, B., & Mapedza, E. (2023). Joint ventures in reform of African water law: Plural legal systems and institutional bricolage. *Water

INSTRUCTIONS TO CONTRIBUTORS

The editorial staff of the AJERI requests contributors of articles for publication to observe the following editorial policy and guidelines accessible at https://www.iekenya.org/ in order to improve communication and to facilitate the editorial process.

Criteria for Article Selection

Priority in the selection of articles for publication is that the articles:

a. Are written in the English language
b. Are relevant to the application relevant of engineering and technology research and Innovation
c. Have not been previously published elsewhere, or, if previously published are supported by a copyright permission
d. Deals with theoretical, practical and adoptable innovations applicable to engineering and technology
e. Have a 150 to 250 words abstract, preceding the main body of the article
f. The abstract should be followed by a list of 4 to 8 "key Words"
g. Manuscript should be single-spaced under 4,000 words (approximately equivalent to 5-6 pages of A4-size paper)
h. Are supported by authentic sources, references or bibliography

Rejected/Accepted Articles

a. As a rule, articles that are not chosen for AJERI publication are not returned unless writer (s) asks for their return and are covered with adequate postage stamps. At the earliest time possible, the writer (s) is advised whether the article is rejected or accepted.
b. When an article is accepted and requires revision/modification, the details will be indicated in the return reply from the AJERI Editor, in which case such revision/modification must be completed and returned to AJERI within three months from the date of receipt from the Editorial Staff.
c. Complementary copies: Following the publishing, three successive issues are sent to the author(s)

Procedure for Submission

a. Articles for publication must be sent to AJERI on the following address:

The Editor

African Journal of Engineering Research and Innovation

P.O Box 41346- 00100

City Square Nairobi Kenya

Tel: +254 (20) 2729326, 0721 729363, (020) 2716922

E-mail: editor@iekenya.org

b. The article must bear the writer (s) name, title/designation, office/organization, nationality and complete mailing address. In addition, contributors with e-mail addresses are requested to forward the same to the Editor for faster communication.

For any queries, authors are requested to contact by mail (editor@iekenya.org).

PUBLISHER

The Institution of Engineers of Kenya (IEK)

P.O Box 41346- 00100

City Square Nairobi Kenya

Tel: +254 (20) 2729326, 0721 729363, (020) 2716922

Email: editor@iekenya.org

Website: www.iekenya.org

CONTENTS