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Research Article

STORMWATER HARVESTING FOR SUSTAINABLE RURAL WATER SUPPLY, MUA HILLS SETTLEMENT, MACHAKOS COUNTY, KENYA

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ABSTRACT

Objectives: Water though vital to all life forms, is unevenly distributed globally, with some areas facing drought and others experiencing floods. Increasing population and economic growth exacerbate the challenges of water availability. In Africa, rising climate variability leads to more frequent droughts and floods, increasing vulnerability and complicating sustainable water resource development. This situation highlights the urgent need to address decreasing per capita freshwater resources, inefficient use, and poor management of existing water supplies.This study aimed to investigate the implication of stormwater harvesting on the sustainability of the rural water supply system. To do so, it assessed whether the existing water supply met water demand, while also delineating the factors that affected stormwater supply. It also evaluated the potential for stormwater harvesting in augmenting rural water supply. In consequence, the study tested two mutually reinforcing assumptions. First that there was no significant difference between the existing water supply and water demand in the Mua settlement. Second that stormwater harvesting had significant potential for water supply in the Mua settlement.

Methods: The study was anchored on the game theory, systems theory, evaporation and transpiration theory, theory of natural resources, and theory of integrated water resource management. Essential concepts in the study were sustainability and the Internet of water things. The study employed social and descriptive survey designs with qualitative and quantitative methods, using purposive, stratified, cluster, and random sampling techniques.

Results: The research found that in the Mua Hills settlement, water demand surpassed the supply of 8.7m^3/day as of 2024. It also established that stormwater harvesting was greatly hindered by the private land tenure that allowed residents to farm upstream, thereby polluting any dams built.

Conclusion: The study proposed strategies that could be employed to ensure stormwater harvesting for sustainable rural water supply. Based on spatial analysis, it delineated 29.64% of the settlement as entirely unsuitable for development. Further, the study recommended constructing small dams and water pans upstream to supply water downstream. The study emphasized the need for a catchment-based approach to water resource management. Correspondingly, it advocated for the development of catchment planning and management policies, and pertinent strategies. Together, these would ensure sustainable stormwater harvesting. Finally, the study suggested the need for further research on integrating land use and water resource conservation.

Keywords: Deforestation, Land use, Land cover, Storm water, Water resource, Water supply.

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INTRODUCTION

Water is vital to all life forms on Earth (Hossain, 2015). Unfortunately, like other natural resources, it is not evenly distributed worldwide. In 1997, the United Nations published a comprehensive review of the world's freshwater resources (Seckler, 1998). The assessment noted the effects of increasing population and economic development on water resource availability. It also asserted that by 2025, 70% of the world population would live in countries experiencing water stress and using more than 20% of their available resources (Arnell, 1999).

Among the sustainable development goals (SDGs) that need to be achieved by 2030 is SDG 6, which prioritizes access to clean water and sanitation with full recognition of the prevailing crises of insufficient safe drinking water. Climate variability, which is on the rise particularly in Africa, has caused an increase in the frequency of events such as prolonged droughts, dry spells, and flush floods (Pachpute *et al.*, 2009), thus, increasing the runoff coefficient. Climatic variability and drought in Africa have aggravated vulnerability and challenged sustainable water resource development (Oyebande, 2001 in the continent). In consequence, Oyebande (2001) recommended that to overcome the many, varied water problems in Africa, there is a need to examine the diminishing per capita freshwater resources, inefficient utilization, and poor management of the available water resources.

There is also SDG 11 on Sustainable Cities and Communities that acknowledge the current world status of 50% urbanization. This status challenges access to natural and contrived green spaces that promote physical and mental health and the provision of sufficient infrastructural systems. It is these systems which in turn facilitate access to clean water sanitation, health, jobs, and education (Koch & Krellenberg, 2018). Activities such as deforestation in hill slopes and land use changes, especially from agricultural to residential or commercial (rampant in rural areas in Africa), have increased mean surface runoff and decreased groundwater recharge (Pachpute *et al.*, 2009). It is advisable for water harvesting mechanisms such as stormwater harvesting to be adopted for use in harnessing the surface runoff water.

East African countries come second in population growth rate globally (Ashton & Turton, 2009). However, they have the lowest number of renewable freshwater resources in Sub-Saharan Africa (Gowing *et al.*, 2010). Due to their highly increasing population, these countries are very dependent on the most popular acceptable source of water, groundwater. Groundwater sources are already under intense pressure, and therefore the need for intervention by developing alternative water sources, such as harvesting the available rainwater and treating it for varied uses. In Kenya, the drive by the government to improve water services started in 1967, 3 years after independence, when basic facilities, among them water and sewerage, were nationalized to allow the government to provide and expand services to spur development (Chepyegon & Kamiya, 2018). Despite the efforts of the Kenyan government to enhance water coverage nationwide to sustain the economic development of the country, recent statistics indicate that the rate of improvement in water supply is unlikely to align with the long-term development goals of the nation. Machakos town has grappled with water shortages for decades, posing a hindrance to its development (Kyalo, 2018). The reliability of piped water in Machakos County has diminished, leading most residents to rely on borehole water supply. It has been identified that water inadequacy in Machakos town is primarily attributed to rapid population growth (Ibid).

Water resources are pivotal in various aspects of the environment, society, and economy (Arnell, 1999). Supply-side pressures, such as climate change affecting water availability and environmental degradation that reduces the usable water supply, contribute to the associated challenges. Demand-side pressures, including population growth leading to increased domestic, industrial, and agricultural water use demands, exacerbate the situation. Numerous major cities worldwide are currently experiencing stress on their water supply systems due to climate change, rainfall variability, and population growth (Sivakumar, 2011). Careless utilization of natural resources and accelerated environmental pollution have rendered a significant portion of the available water in the world too contaminated for domestic use, intensifying the critical nature of this situation (De Villiers, 2001).

In response to these inimical factors, society is augmenting traditional surface and groundwater sources with non-traditional sources such as stormwater harvesting, seawater desalination, and wastewater reuse (Paton *et al.*, 2014). Stormwater harvesting is as old as civilization and has been practiced in many countries and civilizations, including India, Egypt, Mesopotamia, by the Aztecs, Incas, and Mayas, and in Japan and China since time immemorial (Quinn *et al.*, 2020). Governments and people often remember this option only when water is unavailable, even for drinking purposes (Sivanappan, 2006, November). Stormwater harvesting is particularly attractive as a source of water supply as it provides other benefits, such as reducing the load on stormwater infrastructure or combined sewer systems, as well as reducing pollutant discharges to receiving waters (Pitt *et al*., 2012; Di Matteo *et al*., 2017).

Numerous researchers have examined stormwater harvesting practices across different global regions (Mahmoud *et al.*, 2015). Developed nations grappling with water shortages and substantial urban populations, such as Cape Town in South Africa and various Australian cities, widely implement stormwater harvesting on both local and regional scales. Interestingly, Mahmoud *et al.* (2015) discovered that stormwater harvesting is prevalent in several developed countries that are not experiencing water scarcity, including Germany and the USA. In Germany, major cities such as Berlin and Frankfurt harvest stormwater, aiming for sustainable integrated urban water management approaches. The USA also practices stormwater harvesting in various cities across diverse climatic zones, such as West Palm Beach (Florida), Seattle (Washington), Portland (Oregon), Santa Monica (California), New York City (New York), Annapolis (Maryland), and Washington DC. In the USA, stormwater harvesting primarily focuses on reducing discharge to a combined sewer system or for environmental purposes. Notably, research by Pitt *et al*., (2012) revealed that developing countries, particularly those highly urbanized but facing water shortages such as China and India, prioritize harvesting maximum runoff volume from urban areas with less emphasis on water quality. In developing countries with water shortages and significant rural populations, such as is common in Africa, rainwater harvesting predominantly concentrates on collecting roof runoff with storage in local tanks.

Problem statement

Urbanization, coupled with rising standards of living and education, leads to an inexorable rise in rural water demand that exceeds the supply. The UN General Assembly's (2010) created an essential benchmark for what the global community considers acceptable water service. Changes in water demand profoundly challenge the rural water sector in developing countries. To date, this challenge has been understood to predominantly circulate around the need to tackle the sustainability of rural water supply (RWS). Consistent with these challenges, this research highlighted the critical role of stormwater harvesting as a method of addressing this pressing rural challenge. Over the period from 1990 to 2010, the proportion of rural people with a water supply piped directly to their premises rose from 17% to 28%. Most current approaches toward RWS in developing countries find their roots in the 1980s and the International Decade for Drinking Water and Sanitation, when a concerted wave of action was undertaken to increase access to rural water and sanitation rapidly.

Urbanization, a crucial driver for changes in rural water, is not limited to major cities alone but also includes rapid growth in smaller towns and rural centers. This trend of urbanization is reshaping the rural water landscape, transforming "rural" areas formerly with dispersed settlement patterns into a mix of small towns, rural growth points, villages, and hamlets. Increased population growth, economic growth, and poverty reduction are other important drivers. Economic growth leads not only to a drop in overall poverty but also to the rapid emergence of new middle classes that feature increasingly well-educated people with disposable incomes and a consequent rapidly increasing rural development. This combination of urbanization and a rise in quality lifestyles and expectations is being reflected in the demand-supply cycle of the rural water sector. As rural settlements grow into bigger villages and small towns, it becomes more technically and financially feasible to have sustainable water supply mechanisms.

According to a rural studio carried out by M.A planning students, in the Department of Urban and Regional Planning at the UoN in 2023 on the theme "Greening Initiative and Climate Change Agenda: Driving Rural Development for Mua Hills, Machakos County-Kenya," the main problem of the Mua Hills settlement area in Machakos county is natural water resource degradation, land degradation, high population density, and wetland degradation. This specific case study in the Mua Hills settlement area of Machakos County provides a practical context for the research.

With the increasing awareness in the RWS sector, planning and managing sustainable water services requires a "systems approach." This approach entails analyzing the interactive nature of actors and rules to a particular water-related problem. A system may have many subcomponents that work together for the effectiveness of the whole. However, due to a lack of data and modeling techniques, approaches for applying systems modeling for water service delivery systems remain a big challenge. For this reason, this study sought to model the interaction of factors that perpetuated challenges to RWS delivery. It set out to develop a "solution system" that can inform systems-level RWS and strengthened it through policy and practice.

The integrated water resource management (IWSM) theory aims to develop, maintain, and restore water systems for this generation without compromising its use for future generations. Using the geographical information systems (GIS) and remote sensing (RS) geospatial techniques would greatly help the analysis of rural water sources. The two softwares were used to study rural water sources and map them.

Further, according to the natural resource economics theory, water can be defined as a pure private good. A private good is highly subtractable and readily excludable. An excellent example of water services is treated water available for delivery to retail industrial or household users. Water can also be classified under common pool resources, which are highly subtractable and have high exclusive costs. Such includes water in underground aquifers and surface watercourses. Finally, water as a public good means having low subtractability and high exclusion costs. Examples include water quality improvement projects. The theory notes that the necessity of water for life usually may override considerations of economic efficiency. As such government, intervention is necessary in the supply and pricing of water. Therefore, with the increased population and economic growth, this research aspired to make water a public good by ensuring sufficient quality water was available to all. The primary proposed solution for augmenting this rural challenge is the stormwater harvesting system, which entails collecting, storing, treating, and distributing water to all users.

At present, Mua Hill is mainly affected by inadequate water supply, rapid population growth, and the high rate of urbanization. The challenge of water inadequacy is primarily attributed to the degradation of natural water sources. Such realities call for alternative water sources; therefore, the primary goal of this study was to analyze how stormwater harvesting could augment RWS. The findings of this study will provide helpful knowledge on water resources and water catchment management.

Study objectives

The general objective of this study was to investigate the implication of stormwater harvesting on the sustainability of RWS systems. Derived secondary objectives were as follows:

1. To determine whether the existing water supply met the water demand in the Mua Hills settlement.
2. To examine factors that affected the use of stormwater in RWS in Mua Hills settlement.
3. To evaluate the potential for stormwater harvesting in augmenting RWS in the Mua Hills settlement.
4. To propose strategies that could be employed to ensure stormwater harvesting for sustainable RWS.

Research questions

1. To what extent did the existing water supply meet water demand in the Mua Hills settlement?
2. What factors affected the use of stormwater in RWS in Mua Hills settlement?
3. How can stormwater harvesting augment the RWS in the Mua Hills settlement?
4. What strategies could be employed to ensure stormwater harvesting for sustainable RWS?

Hypotheses of the study

- Null H_0 hypothesis: Existing water supply does not meet the water demand in Mua Hills settlement.
- Alternate H_1 hypothesis: Existing water supply does meet the water demand in Mua Hills settlement.
- Null H_0 hypothesis: Stormwater harvesting lacks great potential for water supply in the Mua settlement.
- Alternate H_1 hypothesis: Stormwater harvesting has great potential for water supply in the Mua settlement.

Theoretical framework

The study was anchored on the game theory, systems theory, evaporation and transpiration theory, theory of natural resources, and theory of IWSM. More specifically, essential concepts in the study were the concept of sustainability and the concept of the Internet of water things. The system theory was advocated for in this study as the proponent theory because it connects and integrates game theory, ET theory, natural resource economics theory, and IWRM theory (Fig. 1). Game theory identifies key participants as essential system elements, while ET theory highlights the subsystems constituting the RWS system. Natural resource economics theory elucidates the interplay of demand and supply, analogous to inputs and outputs in system theory. IWRM theory underscores the integration of organizational knowledge and statutory rules, crucial for managing water systems in rural areas.

The system theory was favored in this study due to its problem-solving prowess and ability to recognize patterns, facilitating adaptive action and revealing underlying trends. Furthermore, it provides a holistically understanding of complex issues. Moreover, it supports methodological pluralism, enabling a thorough analysis of reality by considering diverse perspectives and impact levels. Overall, the systems approach offers a robust framework for comprehensively understanding and addressing intricate challenges in RWS. However, it has a minor shortfall in that it assumes an underlying general order in the world, whereas social ordering is a continual and dynamic process, and all human social behavior is purposeful.

Conceptual framework

The conceptual framework illustrates how stormwater harvesting can be used to augment RWS (Fig. 2). On stormwater harvesting, criteria of analysis include slope, land cover, runoff coefficient, and catchment. The intervening variables include climate change, urbanization, population growth, and land use change. In addition, policy and legal framework were reviewed as they had considerable impact on the conservation of water resources and catchments. Finally, the expected output, sustainable RWS was measured in terms of reliability, accessibility, adequacy, and environmental conservation.

Operational definition of terms

- *Deforestation: This* involves the excessive utilization of natural resources, including the clearance of agricultural land, which results in an ongoing decrease in forested areas (Mfon *et al*., 2014).
- *Land use:* This encompasses human activities associated with the soil (Wills *et al*., 2017).
- *Land cover:* This encompasses natural features such as vegetation, water surfaces, and human-made structures that occupy a specific area (Di Gregorio, 2005).
- *A rural water system:* This is defined as one precisely planned to deliver domestic water services to an area predominantly outside an incorporated community (Arlosoroff *et al*., 1987).
- *Stormwater:* This refers to surface water in excessive amounts resulting from heavy rainfall (Walesh, 1991).
- *Water resources:* These are natural water reservoirs that have the potential to be useful for humans, serving as sources for drinking water supply or for irrigation (Shiklomanov, 1991).
- *Water supply:* This involves the delivery of water through public utilities, commercial entities, community initiatives, or individual

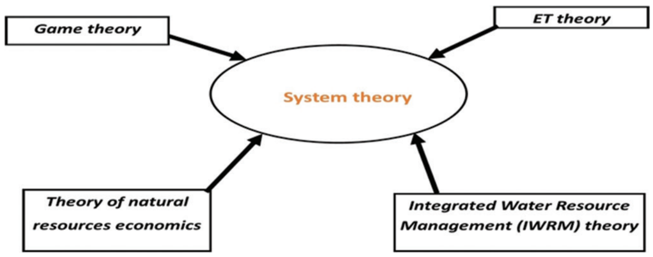

Fig. 1: Theoretical framework
Source: Loise Kitulu, 2024

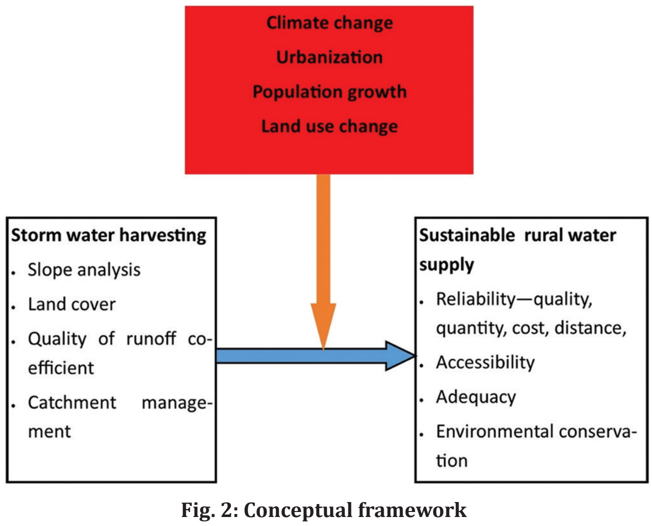

Fig. 2: Conceptual framework
Source: Loise Kitulu, 2024

efforts, typically facilitated by a network of pumps and pipes (Wagner *et al.*, 1959).

METHODS

Research design

Research design essentially spells out articulately, the procedures to be followed in carrying out an ascertained scientific inquiry. It first assembles together complementary research designs by appreciating aspects of the impeding inquiry in respect of its purpose, analytical basis, environment, and methods (Maringa, 2005; Gay, 1981; Mugenda and Mugenda, 2003). To this extent, a social survey descriptive research type (a fact-finding venture that seeks to determine and report on the current status of study subjects) that blends both the qualitative and quantitative research forms were selected for use here. It aided in the choice of the overall research methodology applied that included sampling design, research methods, techniques, field tools, and subsequent analysis in the study. Several factors were considered when determining the type of research design to be used: the availability of resources, the type of information desired, the ability to manipulate the independent variables, and the degree of control the researcher had.

Target population

Inclusion criteria

The study encompassed all residents of the Mua Hills settlement, ensuring a comprehensive representation of the community. In addition, relevant critical informants at the sub-county and county levels were included.

This approach was chosen as the study was focused solely on the Mua Hills settlement, which spans three sub-locations: Kyaani, Kyanda, and Mua Hills. The respective population of each sub-location, as per the 2019 Kenya population census reports, is detailed in Table 1 and Fig. 3.

Exclusion criteria

The study excluded anyone outside the area except the vital administrative or technical informants in the sub-county and county-levels.

Sampling

The sampling method used in this study offered two significant advantages: It expedited the data collection process and reduced costs (Kish, 1965; Casella *et al*., 2004). Key informants were identified using purposive sampling. The study area was divided into three groups based on the three sub-locations which engendered cluster sampling that was complemented with a measure of stratified sampling that recognized various hierarchies of social status in the study area. Choice of respondents was guided by the use of simple random sampling as prescribed by the Tippet's table of random numbers. This then is how samples for household questionnaires, business questionnaires, and focus group discussions (FGDs) within each subgroup were selected and this ensured representativeness of data. It enabled subsequent generalization in the findings and conclusions.

Sampling plan and sample size

A sample size was determined based on the five parameters of: Desired statistical power, effect size, significance criterion, estimated measurement variability, and whether a one - or two-tailed statistical analysis was planned. Miaoulis and Michener (1976) stated that three criteria are usually needed to determine the appropriate sample size: The level of confidence or risk, the level of precision, and the degree of variability in the measured attributes.

The theory of the central limit theorem guided the determination of the household and business questionnaire sample sizes. The theory generally states that the central limit theorem "starts" at an N of about 30. Thus, this research worked with a sample size of 33 (just to be on the safe zone, in terms of meeting threshold of the central limit) per subgroup, making the overall sample size 99 for both the household and business questionnaires.

Using purposive sampling, the following key informants were identified: Machakos Town sub-county physical planner, Machakos Town sub-county surveyor, Machakos Water and Sanitation Company (MACHWASCO) manager, and the environment expert at the Machakos Town sub-county. FGDs were used to identify issues and interpretations from homogenous groups with similar characteristics (Mugenda & Mugenda, 2003). This study considered three (3) FGDs: Men, women, and youth. Mugenda and Mugenda (2003) also noted that FGDs typically consisted of 8–10 members and discussions here would take 2–3 h. Thus, for this study, three members were picked for each cluster (men, women, and youth) in each sub-location to form FGDs of nine members each. Each sub-location provided nine members for FGDs: three men, three women, and three youths. These were picked using simple random sampling.

Table 1: Population data according to 2019 National Census data

Mua Hills Settlement population					
Sub-Location	**Male**	**%**	**Female**	**%**	**Total**
Kyaani	906	51.59	850	48.41	1,756
Kyanda	1,491	50.08	1,486	49.92	2,977
Mua Hills	2,110	51.83	1,961	48.17	4,071
TOTAL	4,507	100.0	4,297	100.0	8,804

Source: Loise Kitulu, 2024

Methods of data collection

Primary data collection

The first mode of data collection was an examination of existing documents, where Registry Index Maps were acquired from the Survey of Kenya and digitized. More primary data for GIS analysis were acquired from Google Earth and satellite data. Second, survey instruments were appropriately administered for household and business questionnaires. Both these types of questionnaires were prepared and fed into Kobo Collect, which was used for data collection and analysis. Interviews were carried out for the identified key informants.

The key informants for this case were the Machakos Town sub-county physical planner, Machakos Town sub-county surveyor, MACHWASCO manager, and the environment expert at the Machakos Town sub-county. In addition, the study also collected data from old members of the society through oral histories. Documenting how water scarcity had come up in the area was of great necessity. The observation method aided in filling in the mapping and taking photos of all existing water resources within the study area. Finally, the study conducted FGDs (Fig. 4).

Secondary data collection

Secondary data collection included a review of related literature, past research and reading journals, magazines, and articles and government archives. This research also referenced secondary data from acts, the constitution, government policies, and archives.

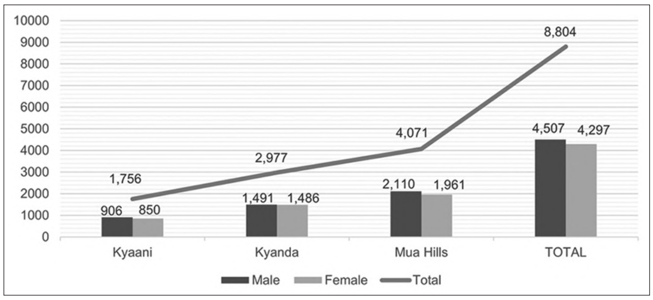

Fig. 3: Mua Hills settlement population – 2019 national census data
Source: Loise Kitulu, 2024

Research instruments

Structured interview schedules for use with key informants were prepared for the Machakos Town sub-county physical planner, Machakos Town sub-county surveyor, MACHWASCO manager, and the environment expert at the Machakos Town sub-county. Household and business questionnaires were also prepared and fed into the Kobo collect online application. In addition, structured interview schedules were prepared to guide the FGDs. Finally, observation matrices were assembled together to guide mapping and taking of photographs of all existing water resources within the study area.

Data analysis methods

The data collected were analyzed using Kobo Collect. Further descriptive data analysis was done through Microsoft Excel and Statistical Packages for the Social Sciences, while the GIS data analysis and modeling tools were put to use for location and mapping.

Data presentation methods

The analyzed data were presented in different forms; the qualitative data were presented in the form of descriptive-analytical reports. Data presentation forms such as maps, analytical line and bar graphs, pie charts, measures of central location, photographs, figures, and tables were also used.

RESULTS AND DISCUSSIONS

Findings on analysis of existing water supply vis-a-vis water demand in Mua Hill settlement

The study found that boreholes were the sources of water for the area. The Mua Hill is the catchment of the new dam, Miwongoni Dam, that is under construction to supply water to Machakos town. Thus, in addition, the water demand for Machakos town. The total water supply from all the public boreholes within the area came to 240 m^3/day against a demand of 248.7 m^3/day, assuming they functioned 12 h a day (Figs. 5 and 6, Tables 2 and 3). The Miwongoni dam is expected to raise the water supply to 17,500 m^3/day against a water demand of 25,000 m^3/day as of January 2024. Here below is a calculation of the water supply deficit at the hill settlement, excluding the town (Fig. 7 and Table 4).

Fig. 4: Focus group discussion at Mua Hills chief's office
Source: Loise Kitulu, 2024

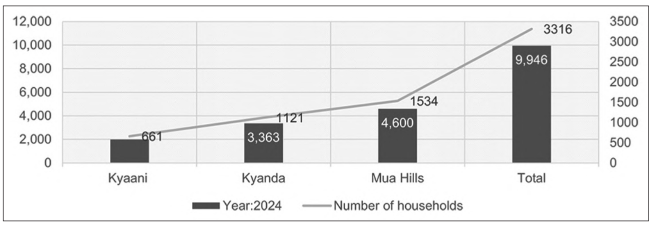

Fig. 5: Water supply demand profiles in Mua Hills Settlement
Source: Loise Kitulu, 2024

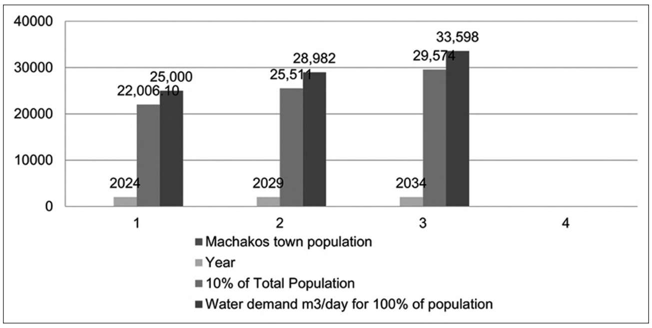

Fig. 6: Water demand profiles in Machakos town (population index used as 10% of population for visual comparability)
Source: Loise Kitulu, 2024

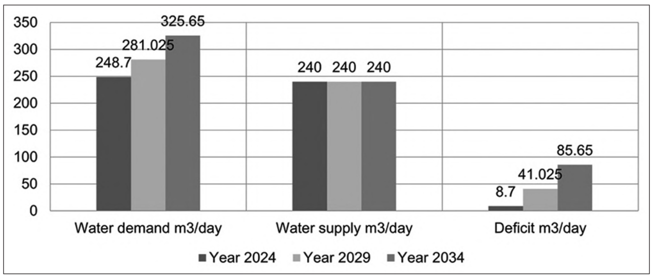

Fig. 7: Water supply deficit
Source: Loise Kitulu, 2024

Table 2: Calculation of water supply demand in Mua Hills Settlement

Sub-location	Year: 2024	Number of households	Water demand (L)
Kyaani	1,983	661	49,575
Kyanda	3,363	1121	84,075
Mua Hills	4,600	1534	115,050
Total	9,946	3316	248,700

Source: Loise Kitulu, 2024

Table 3: Calculation of water supply demand in Machakos town

Machakos town population	
Year	2024
Total Population	220,061
Water demand	25,000 m^3/day
Year	2029
Population	255,111
Water demand	28,982 m^3/day
Year	2034
Population	295,743
Water demand	33,598 m^3/day

Source: Loise Kitulu, 2024

Table 4: Calculation of water supply deficit

Year	Water demand (m^3/day)	Water supply (m^3/day)	Deficit (m^3/day)
2024	248.7	240	8.7
2029	281.025	240	41.025
2034	325.65	240	85.65

Source: Loise Kitulu, 2024

The study agreed with Sophocleous (2004) and An *et al.* (2021) that population growth, economic expansion, technological advancements, land use and urbanization, environmental degradation rates, government initiatives, and climate change affected water demand in an area. The rising water demand shown in the calculation, reflected a population of Mua Hills that had been rapidly growing. This had led to a lot of conversion of agricultural lands to residential use, and the cutting down of trees to provide timber for construction. It was compounded by a lack of adequate government initiatives to implement or repair the existing water system.

Conservation and restoration of the Mua hills land and flora will be critical for the people within it and Machakos town. There are untapped stormwater harvesting mechanisms that can be used to increase water supply in the area, especially for other uses such as agriculture, livestock, and construction, which were not even considered during the calculation of the water deficit. These include construction of dams, water pans, weirs, and conservation of natural water drains that discharge to the river tributaries. Therefore, there was a need to innovatively tap into the available water resources (using the various mechanisms on hand), maximize their use, and conserve the hill to ensure that maximum water was harnessed at the Miwongoni dam for supply to the Machakos town and even lower parts of the Mua ward.

Findings on factors affecting the use of stormwater in RWS in Mua Hill settlement

As per the field survey, stormwater as an alternative water supply mechanism was poorly practiced in the Mua Hills settlement. The only well-practiced activity was harvesting rainwater from rooftops, which served the homesteads for only primary domestic uses for short periods of time. The main challenge on this milestone was inadequate rainfall due to deforestation and increased population in the area.

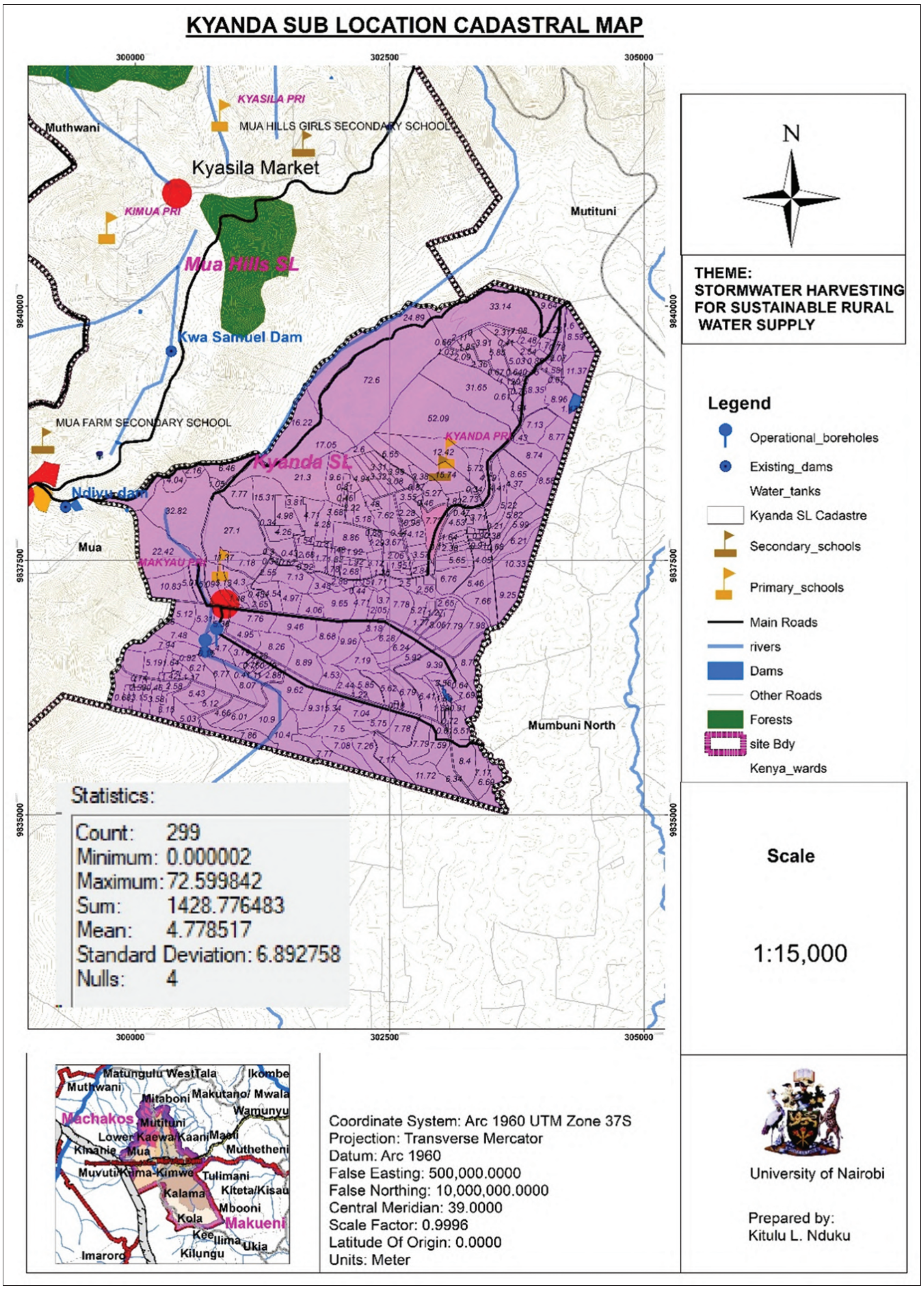

Fig. 8: Cadastral map of Kyanda sub-location
Source: Sacco *et al.*, 2021, adapted using GIS from records of the Survey of Kenya

In summary, the failure to construct stormwater harvesting facilities such as dams and water dams has significantly hindered stormwater harvesting. Second, there was a failure regarding institutional management of the few facilities set up during the colonial era. Uncontrolled land subdivisions had affected land sizes, thus making it difficult to have land available for stormwater harvesting facilities. Allocation of the land to private ownership did the hill a disservice compared to other hills like Iveti and Kiima Kimwe, which are gazetted forest lands. Finally, unregulated agricultural activities upstream had resulted in soil erosion into the rivers and siltation of the few available dams. The resulting pollution of the available surface water sources limited the ability residents to rely only on related groundwater sources – boreholes.

Findings on evaluating the potential for stormwater harvesting in augmenting RWS in Mua Hill settlement

The multi-criteria decision-making (MCDA) techniques were used to evaluate the potential for stormwater harvesting in the Mua Hills settlement (Figs. 8-11). The criteria used included slope, cadastral analysis, and land cover analysis.

The terrain of the Mua hills greatly supported stormwater harvesting. The Mua hill was the catchment for most local tributaries of the Athi River. Before these tributaries drained their water to the Athi River, dams and water pans could be constructed down the hill to help collect and store water that could serve the settlement during dry seasons. The runoff collected could be

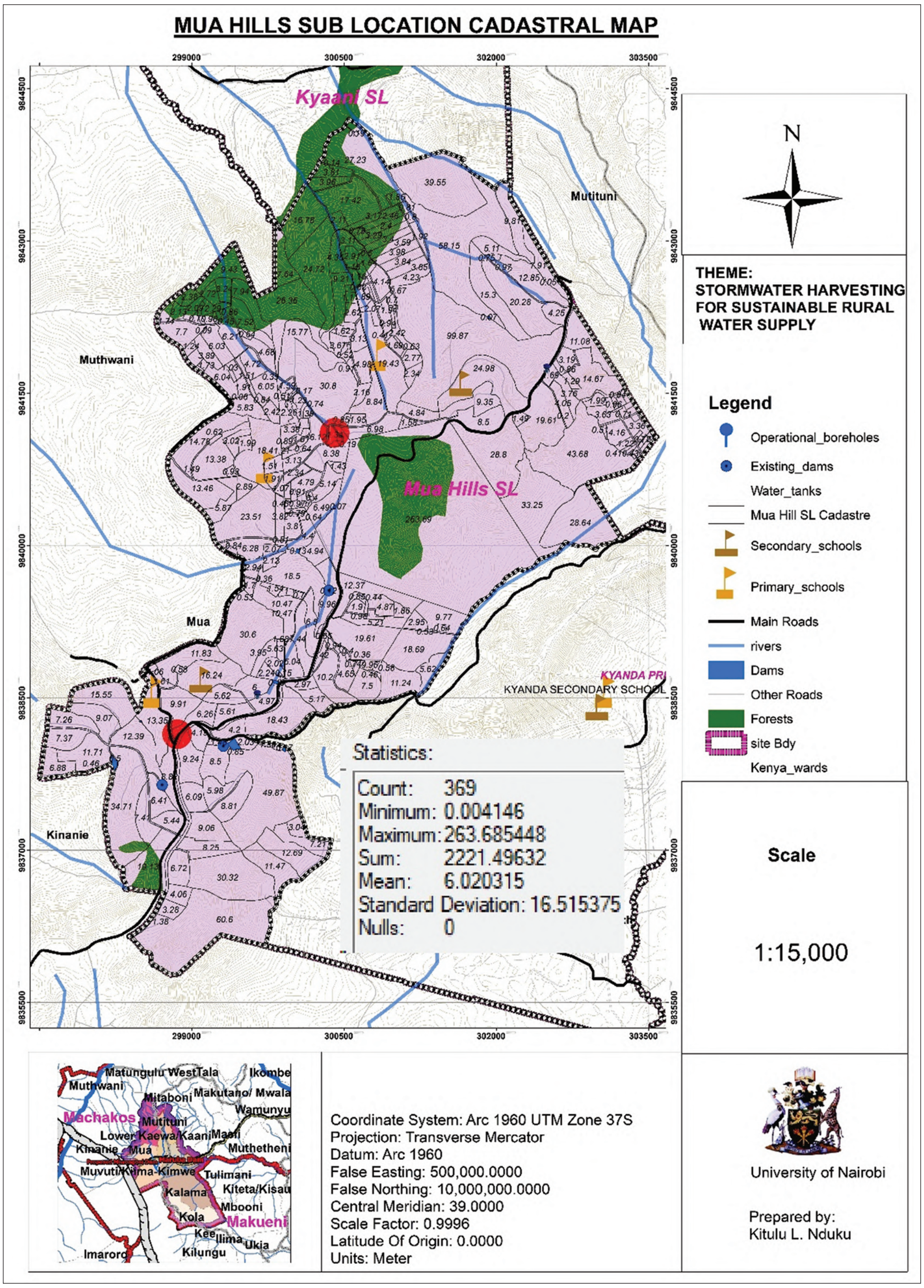

Fig. 9: Cadastral map of Mua Hills sub-location

Source: Sacco *et al.*, 2021, adapted using GIS from records of the Survey of Kenya

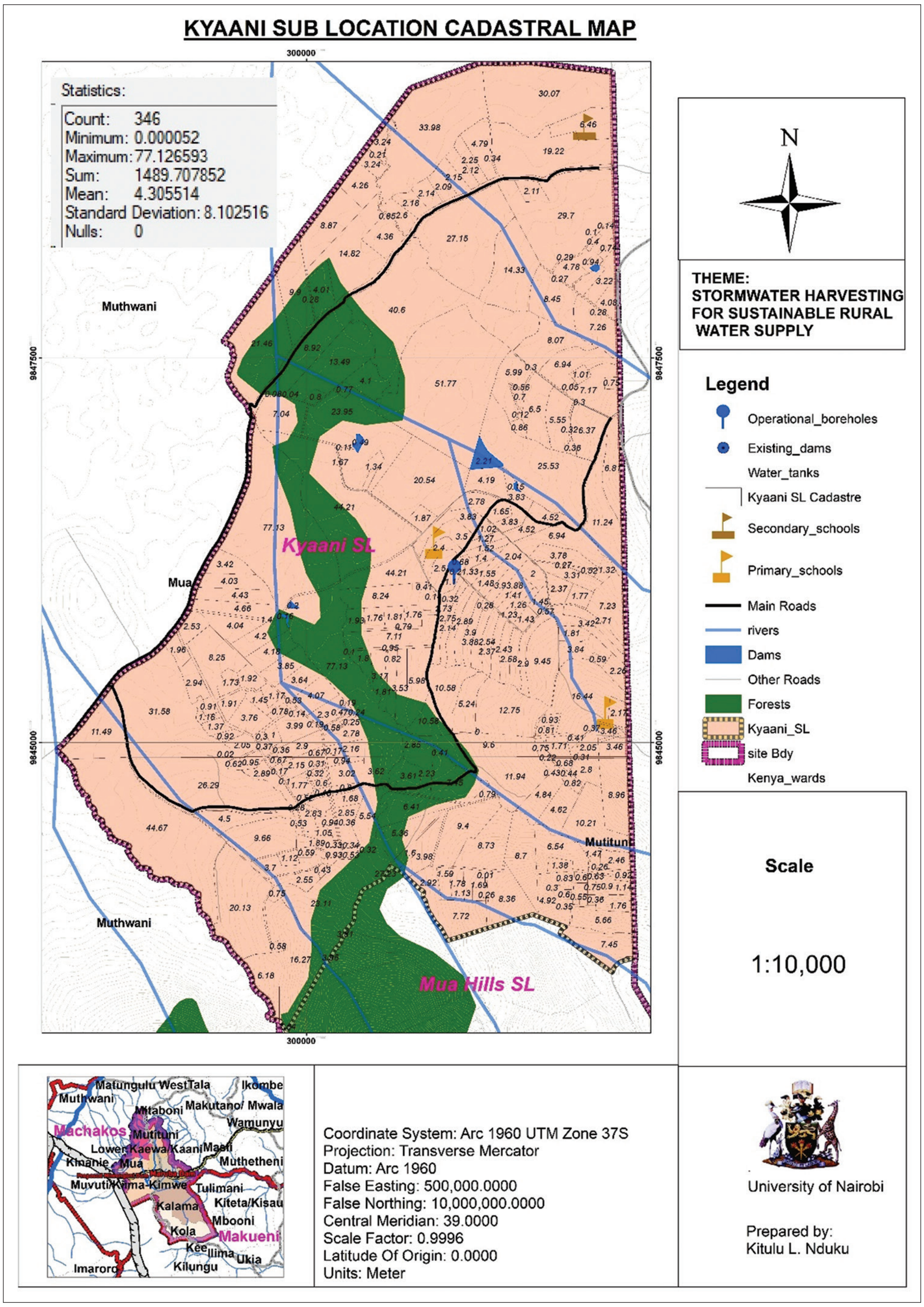

Fig. 10: Cadastral map of Kyaani sub-location
Source: Sacco *et al.*, 2021, adapted using GIS from records of the Survey of Kenya

filtered, stored, and utilized in different ways or be used directly for recharge.

According to the Mua hill settlement cadaster, there were designated dams and water pans. A number were constructed, but they were all silted up due to a lack of proper management. The rest that were not built had their land encroached on by private dwellers. In 2023, the Machakos Water and Sewerage Company decided to construct a new Miwongoni dam, whose catchment is the Mua hills, to supply water to Machakos town. There remains a dire need to conserve the land and flora on the hill. Overlaying the cadaster on the terrain data guided the analysis to determine whether the areas previously marked for boreholes were suitable (Figs. 8-11).

Findings on strategies that can be employed to ensure stormwater harvesting for sustainable RWS

The first step in the Mua Hills settlement, which is a catchment by itself, should be to address the land tenure issue. The hill was under freehold tenure, which permitted the residents full mandate to carry out any activity on the land. In consequence, uncontrolled land successions were witnessed in the area, leading to many subdivisions resulting in uneconomical plot sizes.

A land use policy could be developed to guide or regulate the activities that could be practiced on the catchment. For example, each plot owner could be required to dedicate at least 20% of their land to forestry. Public lands such as schools, hospitals, and chief's camps could reserve up to

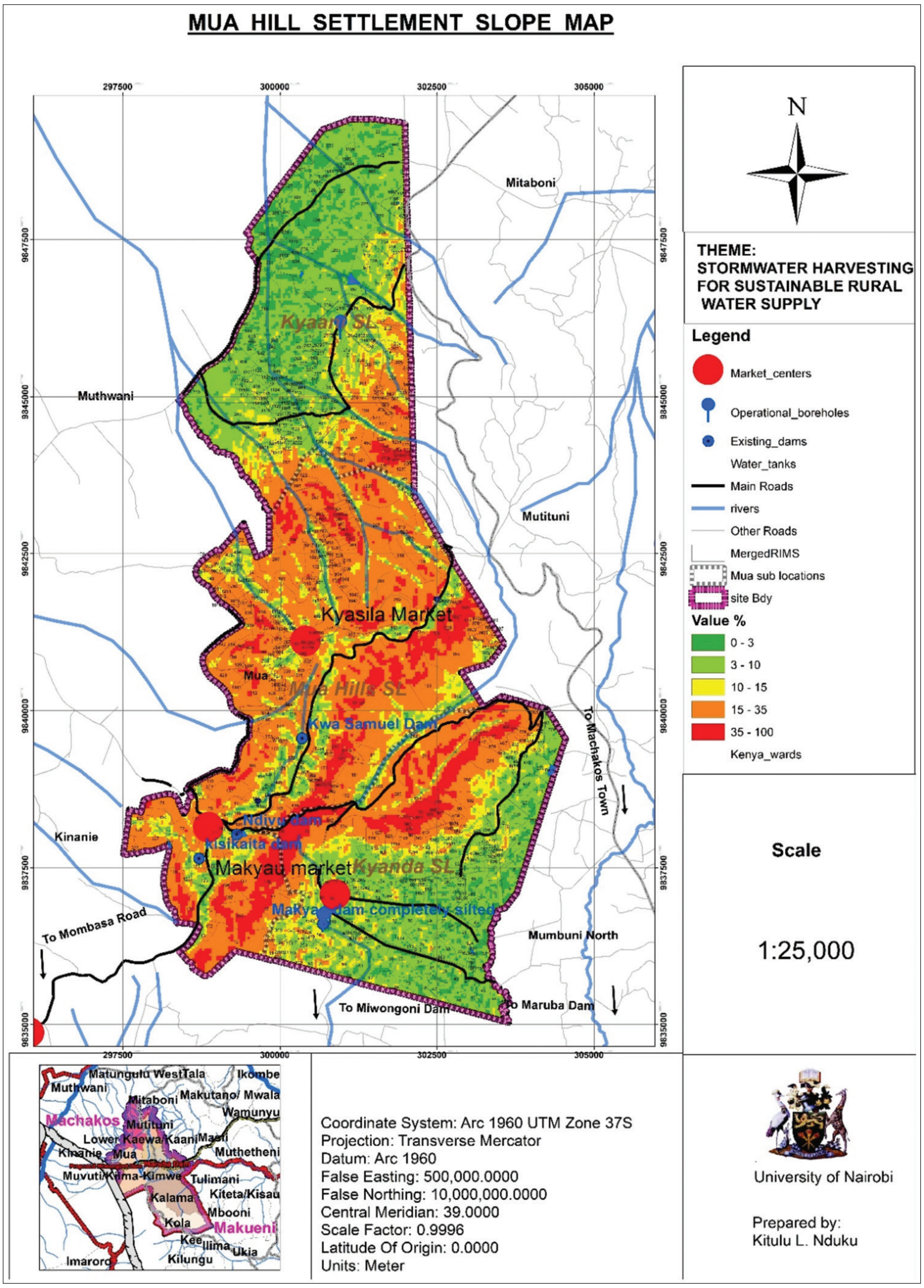

Fig. 11: Slope map of Mua Hills Settlement
Source: Sacco *et al.*, 2021, adapted using GIS from records of the Survey of Kenya

40% of their land for forestry. The policy could also look into repossessing the initial dam sites, then have the small dams done first and the silted dams desilted and protected. On the other hand, the MACHWASCO could delineate the area as a catchment that needed to be conserved. In the eventuality, a resettlement action plan should be prepared to relocate all the current Mua hill settlers to the lower parts of Machakos County. This could be most effective as the whole hill would then be left for conservation, and an ensuing maximum quality stormwater for harvesting.

In addition to that, a Catchment Management Strategy could be formed to achieve the overall goals of protecting local biodiversity, promoting sustainable use and conservation of the land and water resources by optimizing their utilization on a sustainable basis. Further, a catchment management unit (CMU) could be established with the mandate to implement the catchment management strategy. The roles of the units will include coordination of all management activities in the catchment, monitoring of all water resources in the catchment, developing and coordinating memoranda of understanding with all stakeholders, and coordinating and reviewing environmental impact assessment of development activities.

"The landscape that is portrayed in this schematic view displays the following components: (a) Protected existing native forests, reflecting either old or second growth, where natural seeds are collected; (b) restored riparian forest creating a biological corridor connecting remaining forest patches; (c) a naturally regenerating area, adjacent to an existing natural forest that provides seed rain for regeneration of natural flora; (d) restored or livelihood natural forest, which might include non-invasive exotic useful species for timber and none timber forest products, where people monitor biomass and biodiversity

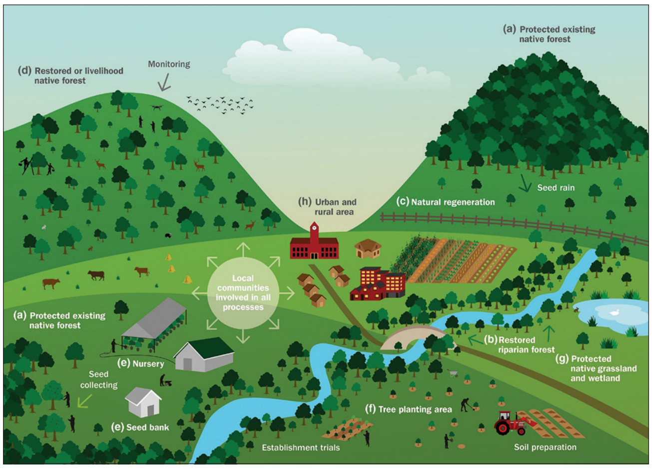

Fig. 12: Schematic view of a successful reforestation program
Source: Sacco *et al.*, 2021

recovery; (e) tree nursery and seed bank where natural flora seeds are stored and propagated; (f) tree planting area, with a section dedicated to establishment trials; (g) protected natural non-forest ecosystems, such as grassland and wetland; and (h) urban and rural areas, with sustainable agriculture and livestock" (Sacco *et al.*, 2021).

Testing hypotheses of the Study

1. The null hypothesis (H_0) that existing water supply does not meet the water demand in the Mua Hills Settlement though not tested statistically was found not to apply here as the study established that the existing water demand surpassed the water supply by 8.7 m^3/day.
2. The alternate hypothesis (H_1) that stormwater harvesting has great potential for water supply in the Mua settlement was also not tested statistically, but still found to merit consideration here as the study confirmed an over 29.64% potential for storm water harvesting in Mua Hill Settlement.

CONCLUSIONS

The study concluded that stormwater harvesting can augment RWS. It can be used directly for agricultural purposes or treated and used for primary domestic uses. Alternatively, it can be used to recharge groundwater sources. The following conclusions for the specific objectives emerged.

Analysis of existing water supply vis-a-vis water demand in Mua hill settlement

Like other rural and urban areas, the Mua Hill settlement had a water demand that surpassed the water supply. This state manifested itself more and more over time when the population kept growing while no specific measures were taken to ensure the available resources like water were still sufficient. In most societies, the supply of such utilities remains constant, while the sources get polluted, thus leading to a deficiency. For any rural area, just as in urban areas, it is necessary to take note of the implications of economic expansion, technological advancements, land use and urbanization, environmental degradation rates, government initiatives, and climate change on water demand and supply in an area.

Factors affecting the use of stormwater in RWS in Mua Hill settlement

Stormwater harvesting was rarely practiced in the Mua Hills settlement. Although a few people harvested rainwater from rooftops, it was inadequate for households, especially during dry seasons due to low rainfall and a low storage capacity. Stormwater harvesting in Mua Hill was greatly hindered by the private land tenure that allowed residents to farm upstream, thus polluting any dams built. Finally, the government failed to construct all delineated dams, leaving them to be encroached into and converted to agricultural lands.

Evaluation of the potential for stormwater harvesting in augmenting RWS in Mua Hill settlement

Based on the three criteria used for analysis, slope, cadaster analysis, and land cover analysis, there was potential for stormwater harvesting. Small dams and water pans could be constructed upstream to supply water to the settlers up the hill. On the other hand, increasing vegetation cover upstream would increase the amount of rainfall received and directed down for ground seepage as well as for runoff to streams, thus increasing the amount of stormwater that would eventually be collected at the Miwongoni dam and supplied to the larger Machakos town. However, there was a need to control development and agricultural activities upstream to avoid polluting the dams.

Strategies that can be employed to ensure storm water harvesting for sustainable RWS

With much potential for stormwater harvesting in Mua and other urban and rural areas across the world, there still lacked a catchment-based approach in water resource to guide in conservation and protection of these areas. This research therefore concluded that an important point to begin with was the demarcation and gazettement of catchment areas as protected areas that service surface water resources. On catchments that were already settled and on freehold land tenure like Mua, a land use policy could be developed to regulate what activities could be carried out on such areas, control agricultural activities, and probably require the residents and public institutions to set aside around 20% and 40% of the lands for forestry, respectively. Alternatively, the people settled on the catchment areas could be resettled to other lower areas that were suitable for settlement and other human activities.

RECOMMENDATIONS

Analysis of existing water supply vis-a-vis water demand in Mua hill settlement

The study recommended that periodic mapping, monitoring, and evaluation of water projects in relation to population, land use, and water regimes dynamics be done after every 3 – 5 years. This would help to ensure that water supply was upgraded with increasing water demands and where need be, proper management and conservation of catchment areas for water sources be done well.

Factors affecting use of stormwater in RWS in Mua Hill settlement

The study recommended that all lands set aside for construction of dams, water pans, and other stormwater facilities ought to be conserved and protected from encroachment. Second, all catchments should be delineated and gazetted as protected areas away from human activities. Where catchment areas had been allocated to private owners, a land use policy could be developed to regulate what activities could be undertaken. Finally, control of agricultural activities upstream was essential to avoid pollution of surface water sources downstream.

Evaluation of the potential for stormwater harvesting in augmenting RWS in Mua hill settlement

It was necessary to harness the potential for stormwater harvesting to be done for every area using the MCDA analysis techniques. Consideration of criteria such as slope analysis, cadaster analysis, and land use and land cover analysis was important. Hilly areas that were catchment areas or even potential catchment areas ought to be conserved. There was a need to implement the recommendation by the Physical Planning handbook that areas above a 35% gradient were not suitable for human settlement. Implementation of this would help reclaim all such catchments that were settled and thus help address water supply issues in areas downstream.

Strategies that could be employed to ensure stormwater harvesting for sustainable RWS

There was a need to develop a policy on catchment planning and management. In addition, land, land use, and water resource management needed to be integrated. It was also necessary to formulate a Catchment Management Strategy to guide in achieving the overall goals of protecting local biodiversity. This would promote sustainable use and conservation of land and water resources by optimizing their utilization on a sustainable basis. Finally, there was a need to form a CMU that would implement the Catchment Management Strategy.

ETHICAL COMMITTEE CONSIDERATION STATEMENT

The study aligned with the basic ethical considerations of participant rights. It, therefore, embraced the five principles of informed consent, voluntary participation, confidentiality and anonymity, transparency, and accountability.

a. *Informed Consent:* All participants were engaged first to ensure that they understood and were satisfied with the purposes, and procedures adapted for use in interviews and observations that involved them. It was made clear that the inquiry supported a self-funded academic research, with no other benefit to the researcher other than of a scholarly nature.
b. *Voluntary participation:* Participants were also afforded free choice to participate and to exit the exercise unobtrusively at any time they chose to and therefore with dignity and no stigma.
c. *Confidentiality and Anonymity:* The inquiry steered clear of personally identifiable data, anonymizing all participant identities by coding rather than registering identities of respondents. The study adopted a data management approach deliberately sought to store all data securely. It restricted access of the data solely to the researcher, supervisors and any other authorized individuals.
d. *Transparency:* Results, outcomes, and implications of the study were made available to the respondents in an accessible and transparent manner, using their own internal community management hierarchies. Similar information was shared with the relevant institutions from where key informants obtained.
e. *Accountability: Power Imbalances:* The study relied on neutral, non-coercive language while respecting the autonomy of all participants put effort. In this way, it afforded the research and the respondents parity and minimized out bias or prejudice in the observation or interview processes.

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AUTHORS' CONTRIBUTIONS

Loise Kitulu conceived the study, collected data, analyzed the data, and wrote the research report under the supervision and guidance of Silas Muketha and Mwangi Maringa. Isaac Mwendwa Muasya, Jackson Muange Kanyasya, and John Muthama Wambua of Mua Hill settlement helped in data collection. Loise Kitulu abstracted the paper from her research report under the guidance of Mwangi Maringa, who also carried out a thorough editorial work on it. All authors read and approved the final draft of the paper

CONFLICTS OF INTEREST

The study was alert to identify and disclose any conflicts of interest that could emerge in the course of the research. It was also poised to provide mitigations to resolve or manage any such conflicts in order to safeguard the integrity of the study. As it transpired, no conflicts of interest were encountered.

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