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Review article

# GIS-based multi-criteria decision analysis model for utility water demand: The case of Lodwar Municipality, Turkana County, Kenya

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ABSTRACT

Water scarcity is a global issue resulting from rapid urbanization, increasing population growth, industrial development and expansion of human activities over time and space. Water shortage affects every continent and is listed as one of the largest global risks hence the need for proper management of water resources. Municipalities and cities worldwide are struggling to maintain a steady supply of water to meet the increasing water demand. The study used Geographic Information System (GIS) techniques and Multi-Criteria Decision Analysis (MCDA) to develop a decision support model that can be applied to improve the utility water demand management for the Lodwar Municipality in Turkana Kenya. The data comprised remotely sensed data, population density, spatial plans, utility infrastructure maps and metered water connections data. The AHP pairwise comparison matrix was applied to assign weights for the 8 criteria influencing water demand in the area. The population density, proximity to water network facilities and land use criteria were equivalent to 30 %, 25 %, and 23 % respectively whereas 22 % of other criteria were dependent on each other. The analysis of satellite images showed the expansion of built-up areas and emerging human activities in regions towards the South and Western of Lodwar Town. The resulting model outcome identified the potential demand priority sites within the region of which some are underserved. The model efficiency was assessed through the application of statistical indicators as well as graphical and map presentations. Consequently, the addition of more input variables affecting demand is likely to improve the results over changing aspects within the zones. Municipality water utility managers and decision-makers can therefore employ the model information to highlight suitable areas for network expansion as well as infrastructure management planning within the municipality. This method offers an alternative hybrid technique for mapping potential utility water demand in rural municipalities with inadequate data.

## 1. Introduction

Global water demand is increasing due to changing consumption patterns, rapid population growth, and economic development [1]. Besides, global water use has increased by a factor of six for the past 100 years [2]. The water demand is projected to exceed supply by more than 40 % by 2030, especially in developing countries of sub-Saharan Africa where it may go up by 50 % [3]. Accelerating urbanization has intensified water management challenges for many large cities worldwide with Asia and Africa experiencing rapid urbanization rates of 1.5 % and 1.1 % per year, respectively [4]. Water scarcity is affecting every continent and is listed as one of the

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largest risks globally in terms of potential impact in the next decade by the World Economic Forum 2019 [5]. In Africa, water scarcity affects one in three persons, the WHO/UNICEF JMP report [6], further notes that 411 million people in Africa still lack sufficient access to basic drinking water services, 779 million have inadequate access to basic sanitation services while 839 million lack access to basic hygiene. Water insecurity and drought risks caused by climate change have led to projected water scarcity for close to 230 million Africans. Similarly, an estimated 460 million people living in high-water demand areas will exceed the available water supply by 2025. This situation is already impacting food and energy security as the continent's population continues to grow steadily. Water access remains a matter of concern and efficiency in water use is now a crucial issue [7]. As African countries continue to rapidly urbanize, the effects of climate change have also led to shifting rain patterns impacting freshwater supplies. In late 2022, an estimated 226 million people in Eastern and Southern Africa had inadequate access to basic water services, and another 381 million people lacked access to basic sanitation services [8]. The Sub-Saharan water shortage has intensified amid climate change and related drought risks leading to decreased water levels in reservoir sources as well as other storages and supplies of fresh water. Consequently, the water security due to scarcity has been exacerbated by the rising drought situation [9,10] (see Fig. 4).

Kenya has been facing water management challenges for decades. The water shortage is experienced in rural areas and more pronounced in the Arid and Semi-Arid Lands which have less developed water infrastructure [11]. The water resources within the country are unevenly distributed where catchments account for over 75 % of the national surface water resources [12]. Kenya has been as classified as a water scare country with a water per capita of 647 $m^3$ of freshwater per year [13], 41 % of its over 50 million people rely on unimproved water sources such as shallow wells, ponds, and rivers while 71 % use unimproved sanitation solutions [14]. The water demand in the agricultural and industrial sectors is rising as well as the increased domestic water use which is a combined result of rapid population growth. The urban population are faced with inadequate access to clean water. Rapid urbanization has negatively impacted access to a sufficient supply of water due to high water demand in urban areas [15]. The development of most upcoming towns serving different areas in Kenya relies on water. These towns in counties have accumulated huge deficits in the provision of basic services, a situation that has been escalated by their related unplanned growth and informal developments [16]. The Kenya Towns Sustainable Water Supply and Sanitation Program projects started in Kenya have improved the quality of life for beneficiaries in several towns. These projects guaranteed access to clean, safe, and reliable water supply in 28 small towns in Kenya [7].

Lodwar is such a small town in Northern Kenya facing a rising water demand. The main water service provider for Lodwar town is Lodwar Water and Sanitation Company (LOWASCO), which relies on solar/electric-powered boreholes situated along the Turkwel River. Although the aquifer system which is tapped by the LOWASCO boreholes has sufficient water to supply the town [17,18] a larger urban population faces problems such as the inadequate and unreliable supply of water due to low pressure, frequent pipe bursts, and excessive leakages due to a dilapidated supply network [19]. The large-scale irrigation schemes to be implemented along the Turkwel River and increasing water demand as a result of the growing urban population, and commercial and emerging oil activities within the region are presenting an anticipated demand for huge supplies of water in Lodwar town and the nearby regions [20]. Water resources management in urban areas has changed in recent times and there is a need to develop sustainable and efficient urban water systems to adapt to these changes [21]. The managing of water demand in these urban areas is thus becoming a challenge with increasing water consumption levels. Establishing the spatial dimensions of water demand is essential in the planning and development of water distribution systems at water utility companies.

Multidisciplinary modelling approaches involving hydrology, economy, ecology, and socio-politics have been applied widely as tools for selecting proper measures to solve water-related problems [22]. These methods use geographic information systems mapping and simulation models to provide decision-makers and water managers with interactive analysis tools. Geoinformation methods and Multi-criteria Decision Analysis (MCDA) are computational approaches that integrate multiple criteria and order of preference to select the best option [23]. It applies to diverse fields to obtain an optimum solution to a problem wherever several parameters are considered with the least user experience. The GIS-MCDA considers geospatial data models, and spatial dimensions of the valuation conditions as well as results in alternatives in the whole criteria evaluation [23,24]. Over 500 studies have published MCDA methodologies for infrastructure management from the mid-1990s to the present [25,26]. A preview and classification analysis by Ref. [27] and subsequent studies by Refs. [28–33] applied different MCDA methods such as AHP, PROMETHEE and ELECTRE respectively to demonstrate the applicability in solving water demand management, some did not address the problem in its entirety. In the analysis of water demand for the Mytilene town of Lesvos Island in Greece [34], applied GIS-based multicriteria to estimate the present and near future water demands of the town. The AHP method used to cross-relate the factors and weights derivation classified about 33 % of the area in high and very high priority zones of the potential urban water demands. Similarly, in the selection of new water supply infrastructure in the city of Santa Marta Columbia [35], integrated a hierarchy of non-economic benefits and the future expected costs into a global index alongside geoinformation methods. The multicriteria analysis treated economic criteria separately from non-economic criteria which had been previously proposed to address the same problem. The theory enabled various stakeholders to systematically evaluate alternatives to the multifaceted water supply problem. The analysis of the literature indicates the Analytical Hierarchy Process (AHP), a pair-wise comparison method is one of the widely used MCDA in studies due to its simple nature of application [36]. The method considers all factors where decision-making is very complex and requires the involvement of actors from different fields with extensive experience. The proliferation of artificial intelligence machine learning and predictive analytics application strategies have been employed in integrated water resources management in many regions. According to Ref. [37], the basic applications are categorized into three main groups, prediction, clustering, and reinforcement learning. These extensive applications are projected to accelerate the formation of sustainable water resource management plans over the next decade. The machine learning algorithms are categorized into three key groups: supervised, unsupervised, and reinforced learning [38]. The algorithms are applied to determine hidden patterns and or data groupings devoid of human intervention and in some cases (supervised and reinforced learning), inputs and outputs are mapped whereby the agent is informed of the best strategy to undertake for task completion. In a study by Ref. [39], data-driven models were applied to evaluate groundwater quality parameters prediction in the

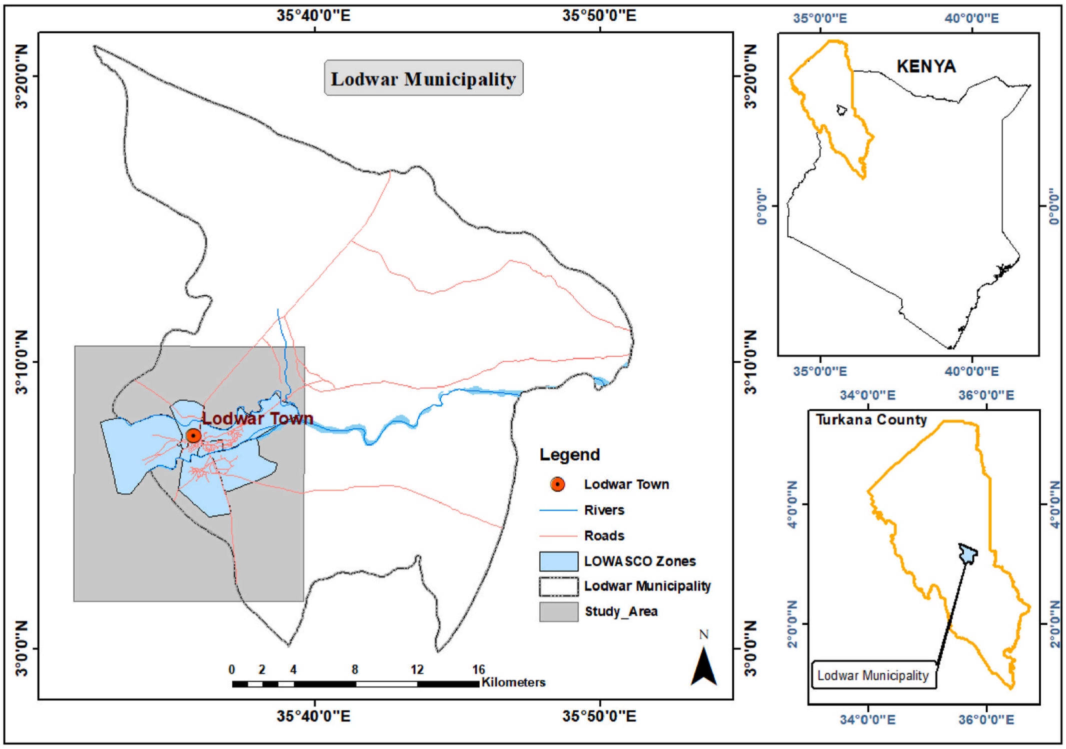


**Fig. 1.** Location of Lodwar Town

**Table 1**
Data and sources.

| Data | Sources |
|---|---|
| Demographic | Kenya National Bureau of Statistics (KNBS) |
| Land use and Land cover (LULC) and Slope data from Landsat 8 & STRM | USGS Earth Explorer/Glovis website http://glovis.usgs.gov; http://earthexplorer.usgs.gov. |
| Annual Water Consumption Records (2017–2019), Metered connections | Lodwar Water and Sanitation Company (LOWASCO) Data office. |
| LOWASCO Infrastructure map 2014 (CAD format) | Oxfam Turkana Programme and Director of Water Services, Turkana County. |
| Municipal boundaries, roads, and drainage shapefiles | ILRI shapefiles, Google Earth, Ministry of Lands and Physical Planning County Government of Turkana, |
| Urban spatial plans/Municipality Physical plans | Town Manager/Ministry of Lands and Physical Planning departments, Turkana County Government |
| Topographic map for Lodwar Area, Kenya. Sheet: Lodwar. No: 25, Scale 1:100,000. | Survey of Kenya |
| Other non-spatial/attribute data | Fieldwork, Observation, Key Informant Interviews. |

Alnekheeb basin, Iraq to obtain a sustainable water source. The study investigated the effect of input parameters on the performance of the proposed models. Several water quality parameters were used for the development modelling. The evaluation results noted that adding more input variables to the can occasionally increase the effectiveness of the proposed models in regards to prediction accuracy. Besides, some models provided a capable performance in forecasting the groundwater parameters compared to other models. In Kenya, while modelling the supply and forecasting the water demand for the Nairobi West area and Athi River town using GIS [40,41], both employed a GIS-based regression model to estimate the future water demand of the two towns. A comparison of the studies concluded that spatial effects have greater importance in influencing water demand among other variables. A review of water demand studies in Kenya indicates that most of the models applied and variations are a result of different factors influencing the demand for water in the respective urban areas and on a short-term basis. Further analysis of the literature reveals much focus on Kenya's major towns and cities with limited studies on upcoming small towns in ASAL regions.

In this context where the GIS-MCDA methodology studies in ASAL regions of Kenya are limited, the research focused on Lodwar municipality, a fragile town in Northern Kenya [42] to investigate the utility water demand. Whereas water utility managers are attempting to understand the general patterns associated with water use in the supply region, the suppliers are not able to curtail the rising demand by mapping potential expansion areas in advance. The study therefore is attempting to apply the methodology in this area where little application has been done as a result of limited reliable data. The paper proposes a method that can be applied which utilizes GIS-based multicriteria and empirical data in the analysis of spatial water demand as well as delineating potential demand priority areas within

**Table 2**
Annual water consumption records (source: LOWASCO data office & KNBS).

| Zone | Zone Name | 2017 | | | 2018 | | | *2019* | | | *2020* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Active Connections | Consumption ($M^3$) | Estimated Population | Active Connection | Consumption ($M^3$) | Estimated Population | *Active Connections* | *Consumption ($M^3$)* | *KNBS Population Census* | *Active Connections* | *Consumption ($M^3$)* | *Projected Population* |
| 1 | D.C area | 295 | 135,420 | 1652 | 311 | 155,745 | 1829 | 311 | 125,485 | 2006 | 253 | 136,755 | 2183 |
| 2 | Town A | 429 | 102,505 | 2401 | 439 | 124,750 | 2658 | 439 | 114,780 | 2915 | 421 | 123,670 | 3172 |
| 3 | Town B | 287 | 131,460 | 1934 | 287 | 152,664 | 2141 | 287 | 163,225 | 2348 | 268 | 157,680 | 2555 |
| 4 | California | 534 | 181,450 | 8465 | 602 | 289,450 | 9344 | 602 | 285,980 | 9994 | 560 | 301,230 | 10,644 |
| 5 | Nakwamekwi | 984 | 54,750 | 15,186 | 1232 | 68,520 | 16,764 | 1232 | 54,750 | 17,929 | 1356 | 232,450 | 19,094 |
| 6 | Nawoitorong | 1144 | 120,140 | 15,435 | 1144 | 227,420 | 17,039 | 1332 | 213,664 | 18,224 | 1175 | 243,565 | 19,409 |
| 7 | Napetet | 874 | 251,980 | 6619 | 981 | 249,656 | 7307 | 981 | 258,440 | 7815 | 933 | 245,600 | 8323 |
| 8 | Kanamkemer | 2836 | 388,825 | 20,917 | 3130 | 840,427 | 23,090 | 3230 | 659,043 | 24,695 | 3301 | 789,700 | 26,300 |
| | **Total** | **7383** | **1,366,530** | **72,609** | **8126** | **2,108,632** | **80,172** | **8414** | **1,875,367** | **85,926** | **8267** | **2,230,650** | **91,680** |

utility zones for future expansion. The data on water demand and social economic surveys gathered through the REACH Programme [42] field activities from 2015 in the Lodwar Municipality were key in selecting the town as the choice of study over others.

The main objective was to develop a GIS-based multicriteria model to identify potential demand priority areas. Other objectives included: mapping the spatial water demand within the utility zones in the municipality; and mapping the main water demand factors in the area. The application of this model in a real case within the area can improve the water utility to develop a proper network expansion plan to cater for the increasing demand management challenges thus ensuring an even distributed supply of water services. The next section describes the materials and methods followed by a discussion of the results.

## 2. Materials and methods

### 2.1. Study area

Lodwar Town, located in the Turkana Central Sub-County of Turkana County (3.2072° N, 35.6970° E, has a population of about 82,970 people and a population density of 14 people per square kilometre, with an average household size of 6 persons [43]. Its geology includes Holocene alluvial deposits, pebble sheets along the Turkwel River as well as basalt and phonolites [20]. The average elevation of the town is about 477m above sea level and the area receives about 217 mm of mean annual rainfall [44] The Town is part of the recently upgraded Lodwar Municipality which covers 706 km$^2$. Political and socio-economic changes in recent times have led to rapid growth, making it a major commercial centre in the North-Western region [45]. The study area is illustrated in Fig. 1 and focuses on a suitable area of interest in the Lodwar Municipality, including past town boundaries, the LOWASCO water infrastructure network map and designated areas for network expansion.

### 2.2. Data and software

The study used data (outlined in Tables 1 and 2) from the relevant sources and fieldwork done in 2020 and 2021, including the collection of both spatial and non-spatial data for the study area. The field visits were conducted by visiting several organizations and government agencies in both Turkana and Nairobi Counties, Kenya. GIS software Arc GIS 10.8 and ENVI 5.3 were used for pre-processing and land cover analysis of the Landsat 8 satellite imagery, while Arc GIS 10.8 was used for other GIS data processing and analyses.

### 2.3. Methodology

The adoption of a specific MCDA method over others is dependent on the features of the decision problem as well as the preferences of the decision-makers. In this study, the main procedure of GIS-MCDA [23,24] was adopted. Multi-criteria Decision Analysis for water demand zoning involves unlimited criteria to identify objectives, allowing water utility managers to influence decision-making on generating priority sites. The AHP is the most applied MCDA method in decision-making since it is the simplest and the most flexible in contrast to other MCDA methodologies [29].

The factors affecting water distribution and access include proximity to water pipelines, storage tanks, road networks, and business centers. Other factors include slope, land use/land cover as well as population density. The reliability of these factors is dependent on the absence/inconvenience of one factor within the infrastructure network. The raw data obtained from the water company was based on the annual zonal consumption in M$^3$ for the selected years. The number of people living in a given spatial area and the water volume consumed can be used to obtain the annual demand. The annual water volume available per person is calculated in M$^3$/year [46]. Using the population data from KNBS for each zone was used to determine the individual user consumption per year. The annual per capita demand values were computed through the division of the annual consumption over the population for each respective zone in consecutive years. The resultant values are detailed in Table 4. The annual minimum Basic Water Requirement (BWR) of 18.25 M$^3$ used in the comparison was computed based on daily recommended basic water requirements for human needs of 50 L [47]. Subsequently, the annual per capita demand values for each zone over the years were used in comparison to identify which zones are sufficiently supplied with water.

The study employed AHP [28,36,48] to compute the relative weights of factors within MCDA guidelines, assigning priority vectors. The AHP captures uncertainty in the judgments through the principal eigenvalue as well as the Consistency Index (CI). A measure of consistency (CI) is calculated using equation (2.1).

$$CI = \frac{\lambda_{max} - 1}{n - 1} \qquad \text{Equation 2:1}$$

Where: $\lambda_{\max}$ = the largest eigenvalue of the pairwise comparison matrix evaluation.

n is the number of classes and or criteria used in the analysis.

A Consistency Ratio (CR) is then calculated (according to equation (2.2)) to assess the reliability of the findings compared to random judgments [49]. Where the CR is above 0.1, the judgments are considered to be unreliable creating the need to revise the subjective judgment.

$$CR = \frac{CI}{RI} \qquad \text{Equation 2:2}$$

The value of RI (Ratio Index) is for different ‘n’ values that are obtained in the analysis.

**Table 3**
AHP comparison matrix framework and principal Eigen vector.

| | Criteria | *($X_1$)* | *($X_2$)* | *($X_3$)* | *($X_4$)* | *($X_5$)* | *($X_6$)* | *($X_7$)* | *($X_8$)* | *Eigen Vector* |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Population Density($\mathbf{X_1}$) | 1 | 2 | 1.8571 | 2.8333 | 3.125 | 2.7779 | 5.375 | 3.2222 | **26.50 %** |
| 2 | LU/LC Classes ($\mathbf{X_2}$) | 0.5 | 1 | 2.7779 | 2.7143 | 3.7143 | 3.5 | 5.1429 | 2.5 | **23.70 %** |
| 3 | Slope ($\mathbf{X_3}$) | 0.5 | 0.3333 | 1 | 0.8333 | 1.5 | 1 | 3.5 | 0.6667 | **9.70 %** |
| 4 | Distance from Water Pipeline ($\mathbf{X_4}$) | 0.3333 | 0.375 | 1.2 | 1 | 0.6 | 0.6667 | 3 | 1 | **8.50 %** |
| 5 | Distance from Storage Facilities ($\mathbf{X_5}$) | 0.3333 | 0.25 | 0.8333 | 1.6667 | 1 | 1.4 | 3.4 | 0.8333 | **9.60 %** |
| 6 | Distance from Boreholes ($\mathbf{X_6}$) | 0.3333 | 0.2857 | 1 | 1.5714 | 0.7143 | 1 | 1.6667 | 1.2 | **8.70 %** |
| 7 | Distance from Road Network ($\mathbf{X_7}$) | 0.2 | 0.2 | 0.2857 | 0.3333 | 0.2857 | 0.6 | 1 | 0.6667 | **4 %** |
| 8 | Distance from Business Centre ($\mathbf{X_8}$) | 0.3333 | 0.4444 | 1.5714 | 1 | 1.2 | 0.8333 | 1.5714 | 1 | **9.30 %** |

**Table 4**
Computed zones annual per capita demand.

| | Zone | Annual per capita ($M^{3)}$ | | | | *Average* |
|---|---|---|---|---|---|---|
| | | *2017* | *2018* | *2019* | *2020* | |
| 1 | D.C Area | 81.973 | 85.153 | 62.555 | 62.645 | 73.082 |
| 2 | Town A | 42.693 | 46.934 | 39.376 | 38.988 | 41.998 |
| 3 | Town B | 67.973 | 71.305 | 69.517 | 61.714 | 67.627 |
| 4 | California | 21.435 | 30.977 | 28.615 | 28.3 | 27.331 |
| 5 | Nakwamekwi | 3.605 | 4.087 | 3.054 | 12.174 | 5.73 |
| 6 | Nawoitorong | 7.784 | 13.347 | 11.724 | 12.549 | 11.351 |
| 7 | Napetet | 38.069 | 34.167 | 33.07 | 29.509 | 33.704 |
| 8 | Kanamkemer | 18.589 | 36.398 | 26.687 | 30.027 | 27.925 |

An AHP comparison matrix was created as shown in Table 3 to enable the separation of various and complex criteria into components that are hierarchically related to one another, utilising RI values for various “n” values.

## *2.4. GIS data processing and analysis*

Water demand maps were generated by linking consumption data obtained from the metered connections to the zone’s shapefile through a Spatial join tool in Arc GIS 10.8. The resultant layer of the combination was displayed as a bar chart for the years selected. The bar chart was applied to show the differences in annual per capita demand values.

The identified 8 criteria/factors influencing water demand in the area which were used in generating criteria maps. The slope data used was generated from the Shuttle Radar Topography Mission (STRM) Digital Elevation Model (DEM) 30m for Kenya. Using ArcGIS 10.8, the DEM was projected to WGS UTM Zone 36N and using the Spatial Analyst *(Masking Tool),* clipped the DEM to the study area boundaries. The slope percentage rise was then computed through the Spatial Analyst Surface Tools (*Slope Tool)*. The 8 slope percentage categories of the area were generated. The percentage rise was further reclassified to 5 categories using the *Reclassify Tool* in the Spatial Analyst Tool before integration into the final model.

The Landsat imagery with a spatial resolution of 30m is suitable for studying land cover changes in urban areas and was preferred in this study. The Land use/land cover maps were generated using pre-processed Landsat 8 images for the years 2016 and 2021 in ArcGIS 10.8 software. The Landsat images were projected to WGS UTM Zone 36N and using the Raster Processing *(Clip Tool)* of the Data Management Tools clipped the area boundaries. Composite bands for each image were created. An interactive supervised image classification and interpretation were performed on each of the two images. The results generated 6 land use/land cover classes for both the 2016 and 2021 images. The 2021 image was then used in the subsequent processes after reclassification into 5 classes.

The population data obtained from KNBS for the area was a shapefile of enumeration units for the 2019 census. The population density was categorized into seven classes to represent the distribution of the enumeration units in the area (Fig. 7). The vector shapefile was then converted into raster format and population classes were reclassified into four categories before use in the weighted overlay model.

For the remaining factors (Pipeline, Storage facilities, Boreholes Road network, and Business centers), the Arc GIS 10.8 Euclidean Distance Tool (a geoprocessing tool that calculates the distance to the closest source for each cell or points of reference) was applied. Criteria maps similar to (Fig. 8) indicating the closest distances from the factors influencing demand were generated with a maximum of 8 distance categories. The distances were further reclassified to 5 before integrating into the Weighted Overlay Model for analysis.

All 8 criteria maps generated were converted to raster format under data Conversion tools in ArcGIS 10.8 before the overlay analysis was performed. The process unifies the units and the scores lose their dimension along with their measurement unit [23,24].

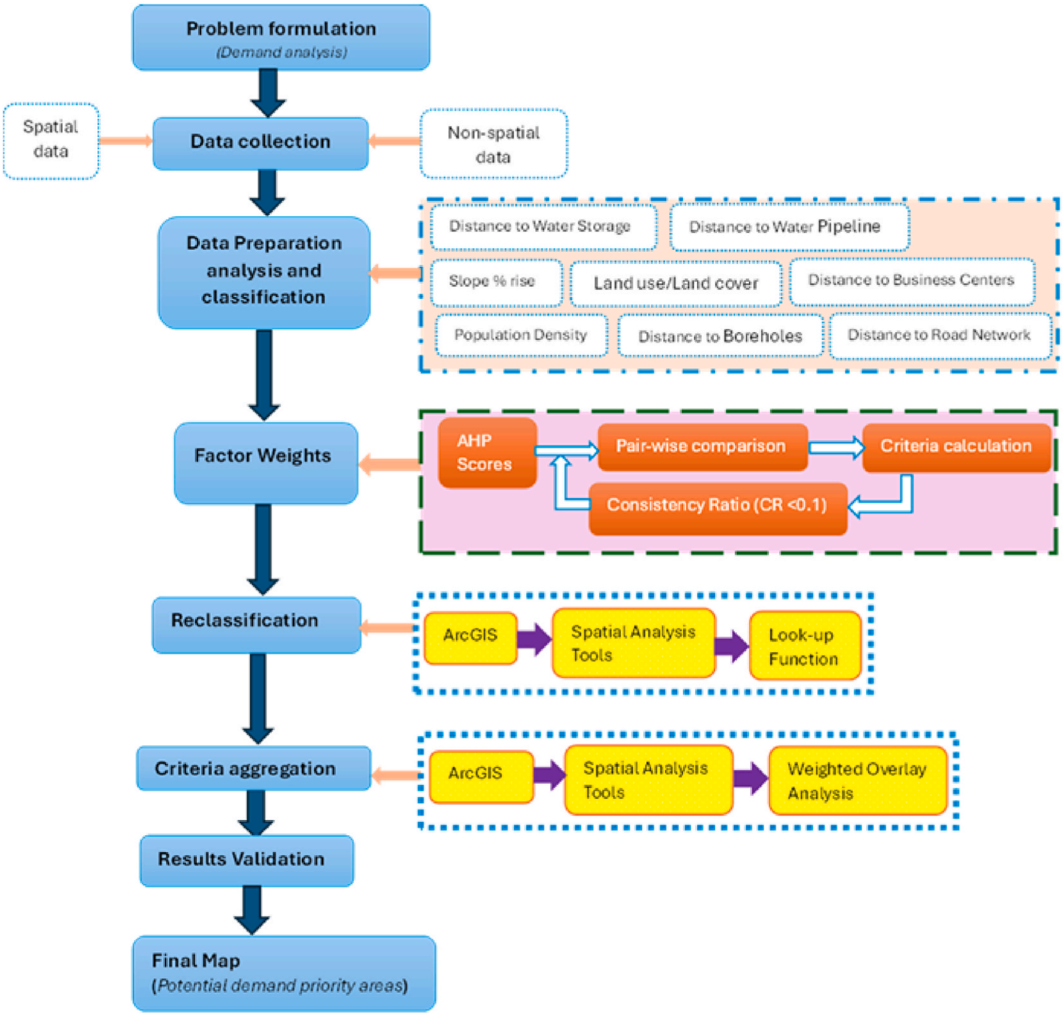


**Fig. 2.** Methodology flowchart.

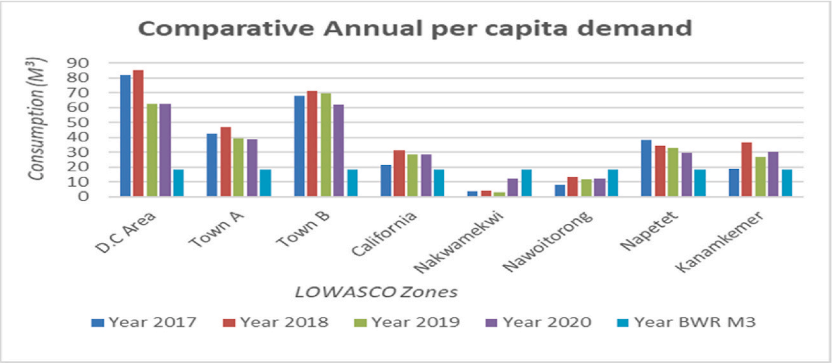


**Fig. 3.** Comparative annual percapita demand.

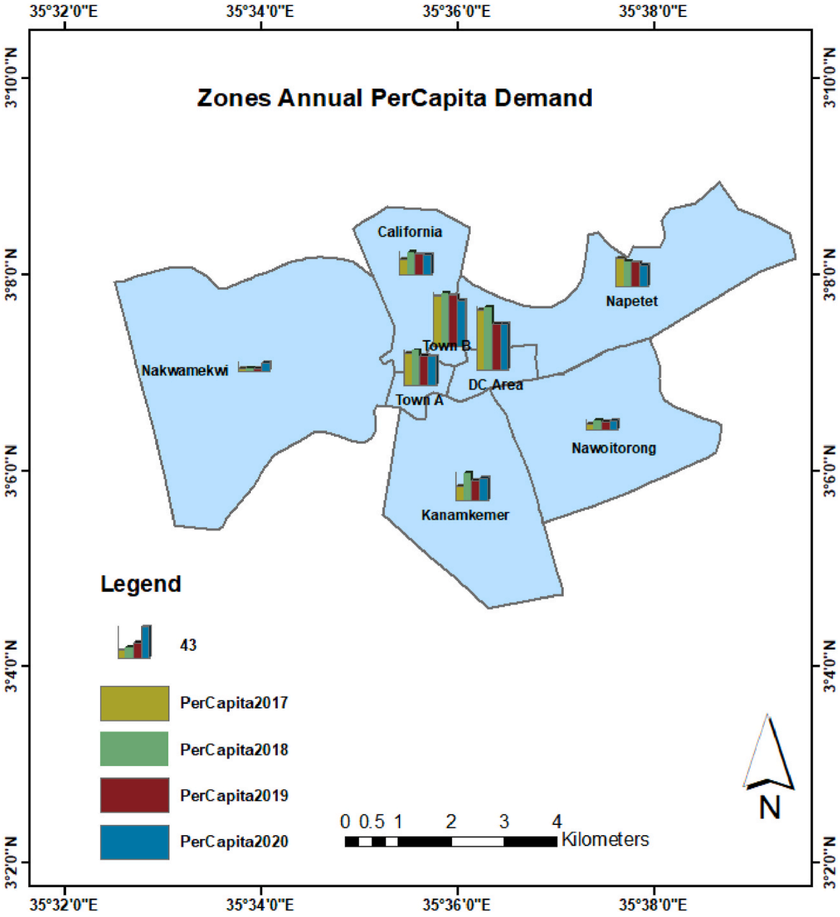


**Fig. 4.** LOWASCO zones Per-capita demand 2017 to 2020.

Each raster factor was reclassified to five classes with different rankings assigned to each of the four categories based on the influence as in Table 8. The Weighted Overlay Tool for raster data analysis in ArcGIS 10.8 was applied to combine all 8 factors with each assigned class weight via AHP as indicated in the matrix in Table 6 to generate potential demand areas. The GIS-based methodology in Fig. 2 used a Weighted Overlay to generate a thematic map to show priority areas [50] (see Fig. 3).

## 3. Results and discussion

### 3.1. Water per capita demand

The water consumption data records for 2017, 2018, 2019, and 2020 for the respective LOWASCO zones were analyzed and the annual per capita demand was computed.

The analysis of consumption data for LOWASCO zones from 2017 to 2020 (Figs. 3 and 4) shows that the DC area zone had the highest average annual per capita demand of 73.082 $M^3$, while the Nakwamekwi and Nawoitorong have the lowest. Other zones like Kanamkemer, California, and Napetet, have a medium to high range average per capita demand despite an increasing number of metered connections. The Town A and Town B zones have medium to high range average annual per capita demand. The zones are located within the township (Town A, Town B, and DC Area) and are associated with high population density, service industries, wholesale shops, hotel facilities, county and national government agencies, social amenities, public institutions, and commercial investments. The concentration of these activities leads to increased water consumption and a slight increase in metered connections.

Nakwamekwi zone has fewer business investments, service industries and few county government offices compared to other areas. Its location in the peri-urban areas attracts medium business activities but has low consumption (mostly for domestic purposes). Frequent water-pipe leakages, dilapidated water infrastructure networks, fewer storage facilities, and frequent borehole breakdowns contribute to inadequate and unreliable water supply, resulting in the lowest annual per capita demand.

The Basic Water Requirement (BWR) index developed by Ref. [47], measures the ability to meet basic human water needs. A

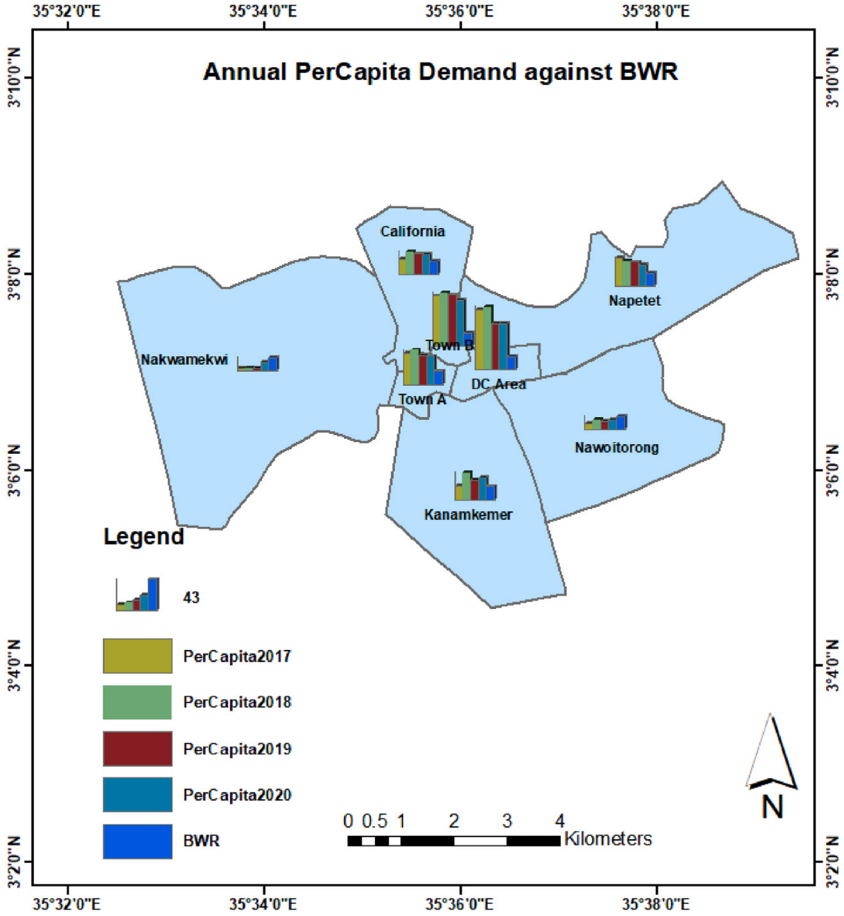


**Fig. 5.** Annual Per-capita demand against Basic Water Requirements (BMR).

comparison against the Basic Water Requirements (BWR) indicates most zones have a moderate to high demand, while Nakwamekwi and Nawoitorong have annual water supply below the required minimum Basic Water Requirement (BWR) of about 18.25 $M^3$. This low demand is attributed to the inability of the utility company to equitably supply water in the respective zones.

### 3.2. Factor maps

Factor maps were created based on the identified factors affecting water supply, including land use land cover, slope, population density, distance from boreholes, water pipeline, water storage facilities, road network and business centers as summarized in Table 6 and illustrated in Figs. 6, 7, 8 and 9).

### 3.3. Standardization of criteria

Each of the factors map layers was further reclassified into 5 classes with each class level assigned weights based on its suitability. The standardized 8 layers are presented in Fig. 10.

### 3.4. Weighted overlay analysis

The Weighted Overlay was used to combine the standardized layers for final analysis, generating a map with potential demand areas. The influence on demand, as well as layer interval (AHP) ranking, is detailed in Table 7. The influence and interval ranking for each class layer were based on the seven suitability ranks listed in Table 6.

Kenya is facing a water crisis with minimal renewable freshwater per capita predicted to decrease to 235 $M^3$/yr per capita by 2025 [51]. The present and future water demand sustainability of an urban area is reliant on water management models which can estimate demands for proper planning development and management of available water resources. The final model was revised with ground

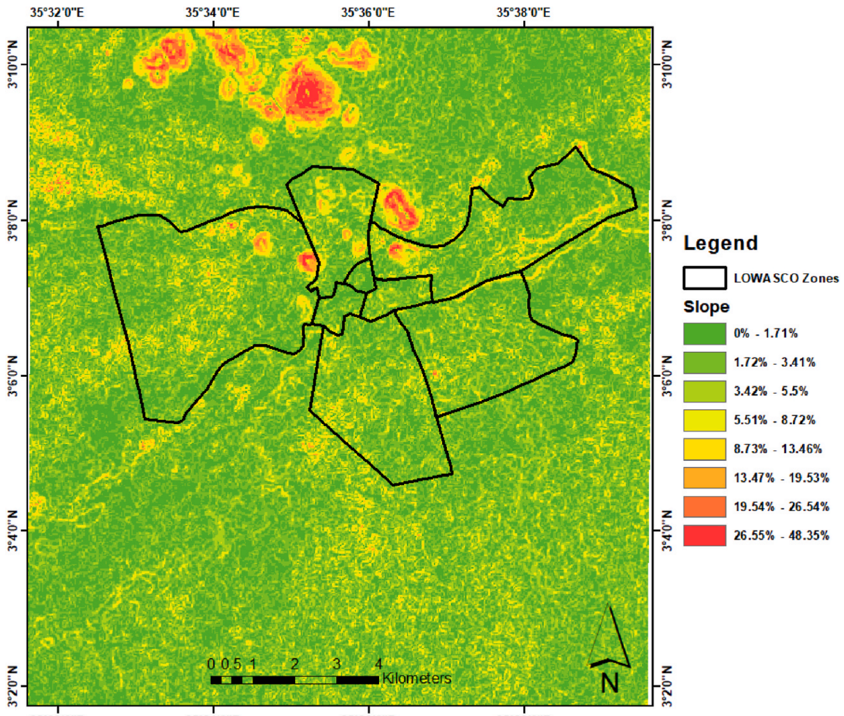


**Fig. 6.** Area slope.

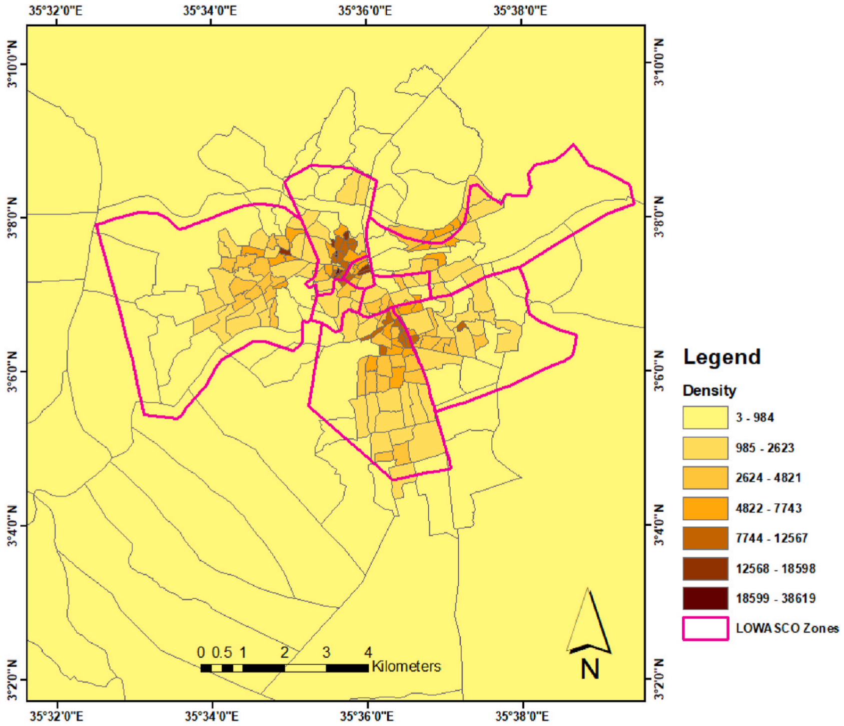


**Fig. 7.** Population density.

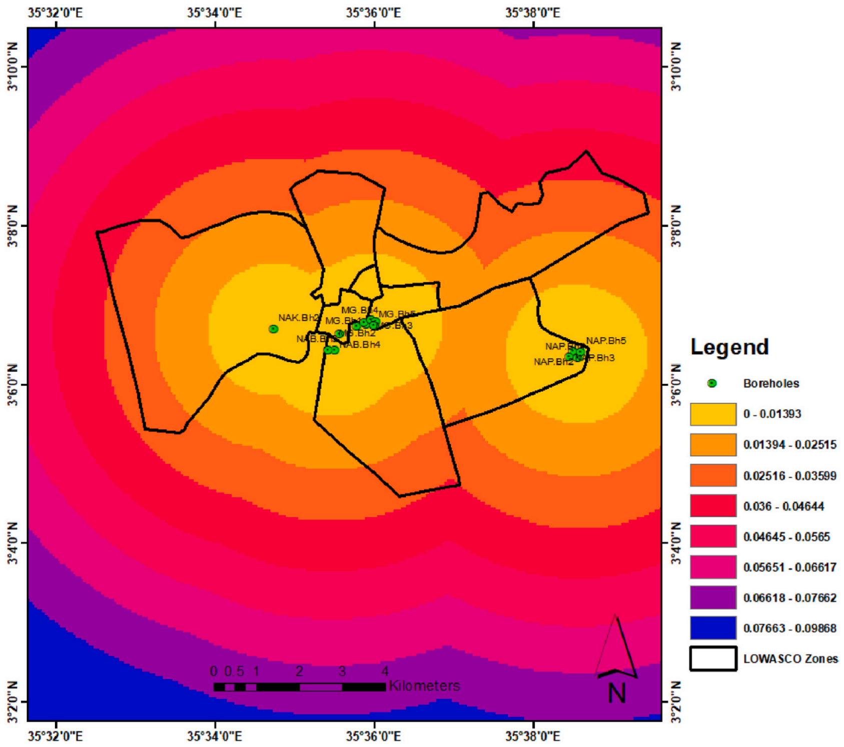


**Fig. 8.** Distance from LOWASCO boreholes.

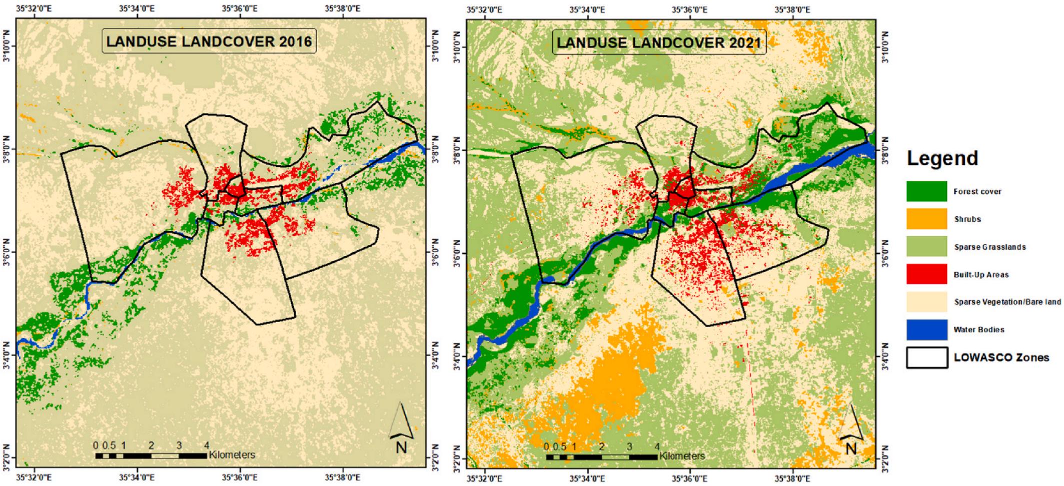


**Fig. 9.** Land Use/Land Cover change classes for 2016 and 2021.

data random GPS points of actual demand and supply status in different zones in comparison to the model leading to some adjustments of population density from 26 to 30 %. The modification resulted in a potential water demand priority map classified into four areas presented in Fig. 11.

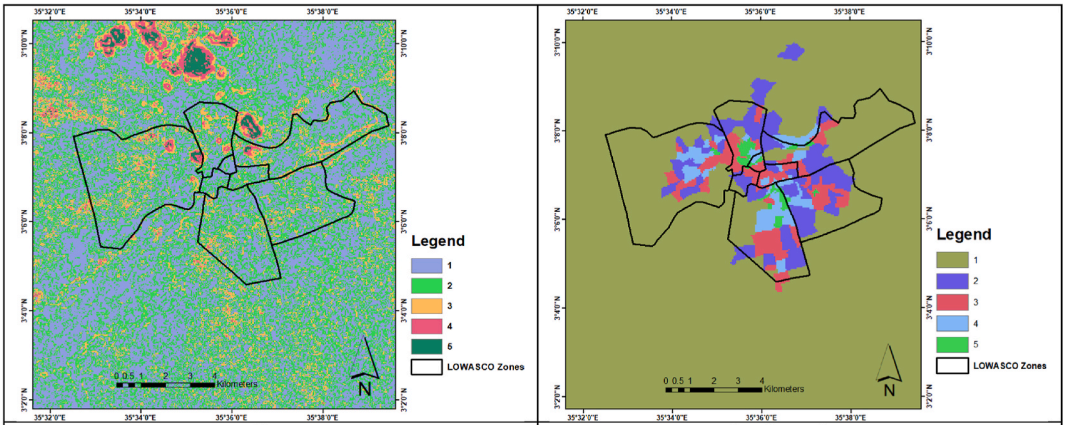
The three factors namely; population density, proximity to water network facilities and land use had the highest overall weights respectively (30 %,25 %, and 23 %) whereas the rest of the factors dependable on each other had a combined influence of 22 %.

The utility areas with “High” potential demand are driven by population density and proximity to reliable water storage facilities and distribution networks. This has led to increased built-up areas in the south and Western region primarily involving emerging business establishments and new settlements. The town’s upgraded status as a municipality in 2018 attracted investments in the northwestern region [45]. A combination of these factors thus makes the central areas have a potentially high demand.

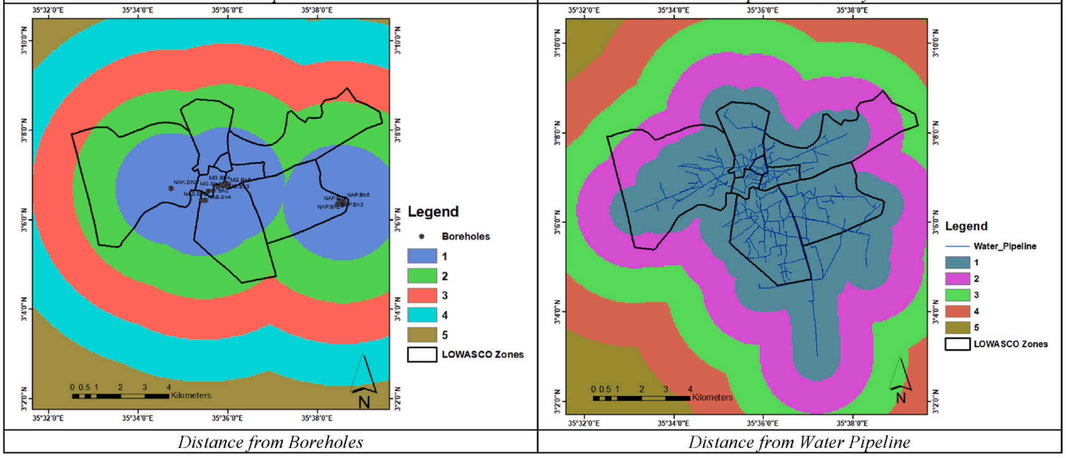
The moderate areas are currently experiencing the expansion of land use/human activities resulting from increasing population growth trends. Whereas relocation to these areas is rapid, taking advantage of the already established business services, there is a strain on the available water resources to cope with the population bulge and new human/economic activity setups. The potential demand priority sites within the area are thus underserved. This observation was evident in the metered consumption data analyzed which mapped out areas with per capita demand below basic water requirements. Subsequently, a 2020 study by Ref. [52] concluded that effective management of the existing water utility infrastructure especially the water sources can equitably support many zones. However, in areas with high demand as a result of losses within the network and operation inefficiencies, most customers are not fully served. Besides, it was noted that existing water sources can support network expansion when effective loss control and with the model result the expansion areas are mapped out to facilitate the extension process.

The unsuitable areas exist away from the established water network and with inadequate factors to influence demand. The areas are constrained by physical barriers and, poor road network thus limiting the expansion of the water network. However, current utility zones do not fully cover high-priority areas, and frequent water shortages affect the demand leading to few business activities and human settlements. Private water trucking has been used to compensate for the low supply.

Regions where development is needed are often those where information/data to inform long-term policy decisions is inadequate [53]. The expansion of land use and or human activities over space and time as evident in the satellite imagery analysis has impacted the water demand straining the current distribution system. The model parameters therefore present a simulated environment where the identification of growth patterns in terms of population density, human settlements as well and the demands of the different zones in the municipality can be visualized and predicted on time. The resultant demand model efficiency can be assessed through the application of statistical indicators as well as graphical presentations and maps. Consequently, further analysis of the model indicates that the addition of more input variables and or factors affecting demand is likely to improve the results thus identifying potential demand areas in the midst of changing demand factors within the zones.

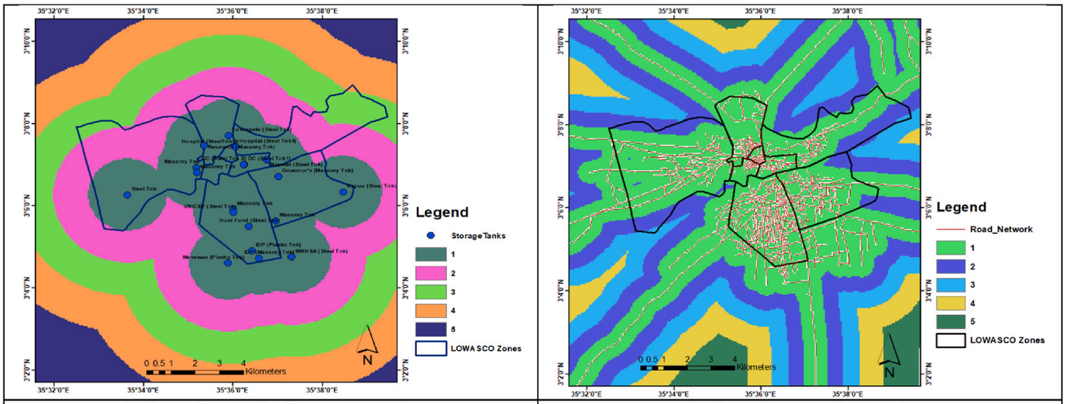


*Slope* *Population Density*



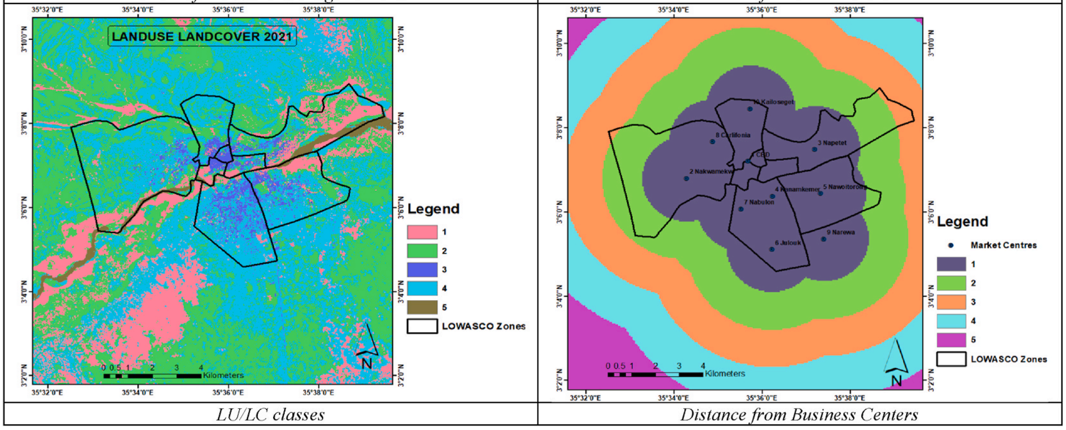
*Distance from Boreholes* *Distance from Water Pipeline*

**Fig. 10.** Standardized factor map layers



*Distance from Water Storage Facilities*

*Distance from Road Network*



*LU/LC classes*

*Distance from Business Centers*

**Fig. 10.** (*continued*).

**Table 5**
Land cover/land use area changes.

| | *LU/LC Category* | *Area (km2)* | | |
|---|---|---|---|---|
| | | 2016 | 2021 | *Change* |
| 1 | Forest/Agriculture Lands | *11.3344* | *16.0249* | *4.6905* |
| 2 | Shrubs | *0.993* | *19.2392* | *18.2462* |
| 3 | Sparse Grasslands | *155.074* | *100.568* | *−54.506* |
| 4 | Built up Areas | *4.4058* | *6.6525* | *2.2467* |
| 5 | Sparse Vegetation | *71.7962* | *98.7637* | *26.9675* |
| 6 | Water Bodies | *1.3831* | *3.778* | *2.3949* |

## 4. Conclusion and future outlook

Municipality utility water demand is influenced by interconnected factors, including population density, water pipeline network, boreholes and storage facilities. Water access within the municipality is directly linked to factors such as the proximity to water network infrastructure, road network and business investments. Low water demand is prevalent in areas with poor access to existing reliable water infrastructure forcing residents to use unreliable means to access water services. Population density influences 30 % of the decision-making on the water supply expansion, while land use accounts for 23 %.

Land use is also influenced by population density whereby densely populated areas have increased human activities which impacts the water demand. The proximity to water network facilities accounts for 25 % whereas 13 % is covered by the proximity to existing road networks and established business centers. The state of water network water facilities differs in the zones based on quality. The constant water supply is dependent on the quality of the network infrastructure. Geophysical factors such as slope morphology have a 9 % influence on water demand. Although utility water demand mapping allows for the identification of priority investment sites, interventions need to be aligned with the critical demand factors implying the need for a closer look at the individual water demand units within the municipality. Nonetheless, other areas may be included for establishing new zones or expanding the utility zones with

**Table 6**
Summary description of factor maps.

| Factor | Criteria |
|---|---|
| *slope* | Slope affects the access and distribution of water resources, with steeper slopes (25 %–48 %) having low population and business establishments, while gentle rolling (1 %–13.46 %) slopes have more households and established business centers and human operations which necessitate the need for water. Most of the water storage facilities such as tanks are constructed on elevated grounds. |
| *Population Density* | The population is concentrated in the central part of the township which requires increased water consumption for service industries, households, and business operations. The higher population density necessitates additional infrastructure and resources to meet demand. Improved water infrastructure services are needed to cater to the growing population. Other areas away from the township have less population density and reduced human activities. The population density decreases as one moves away from the township area, while peri-urban have low population densities and fewer human activities that require significant water consumption. |
| *Distance from Boreholes* | The distance from boreholes significantly affects water supply in towns, particularly in areas where boreholes and or groundwater are the primary sources of water. The distance impacts pumping costs, storage facilities and pipeline network thus influencing water prices. The water demand depends on proximity to boreholes and factors like quantity, reliability of storage facilities and pipeline network also influence the relationship. As the distance increases, the relationship diminishes. |
| *Distance from the Water Pipeline* | The pipeline in Lodwar Municipality connects storage facilities and boreholes to supply water to different utility zones. Households and businesses situated further away from the main distribution pipeline experience high costs for delivery and connection, affecting demand and user connection |
| *Distance from Water Storage Facilities* | Storage facilities on the LOWASCO network are important for water supply and demand. The proximity of these facilities to consumers improves access to reliable water supply and reduces connection costs. The accessibility of water reduces as the distance from storage facilities increases. |
| *Distance from the Road network* | The distance from the road network impacts access to water if the water distribution system runs parallel to the road network. Road network patterns affect pipe networks leading to unreliable access to water and increased costs due to water connections. The convenience of water connection diminishes with distance from the road network. |
| *Land use/Landcover Change* | Different land uses (Table 5) have varying levels of water demand based on their activities and water usage patterns. The relationship between land use/land cover in the area to water demand is complex and or multifaceted. Satellite images from 2016 to 2021 show a 51 % increase in built-up areas mainly in the southern Kanamkemer Ward and Township areas. This growth is attributed to huge investments in the real estate sector as well as the town's historical status as the county headquarters. |
| *Distance from Business Centers* | Established business centers in the area have access to water attracting alternative businesses and residents. New establishments/households benefit from proximity to water connections from existing business centers and access diminishes with distance. |

**Table 7**
Scale of AHP ranking method.

| Scale | Definition |
|---|---|
| 1 | Extremely Low |
| 2 | Very Low |
| 3 | Low |
| 4 | Moderate |
| 5 | High |
| 6 | Very High |
| 7 | Extremely High |

moderate demand as identified by the model results. The overall demand patterns are also affected by the operational status of the water sources(boreholes) which are constantly threatened by natural forces such as severe floods.

The suitability of this methodology incorporates the views of water utility managers which makes it applicable in rural municipalities with inadequate/reliable data on water uses. The stakeholders can systematically evaluate alternatives to the multifaceted water demand problem by making significant contributions to the final GIS model developed. The study results epitomized the potential of GIS-based multi-criteria analysis in mapping priority areas for network expansion. However, the reliability of valuation results depends on several factors ranging from dataset qualities as well as the possible errors in the GIS processes applied. Meanwhile, the weights applied to factors are also significant to the modelling results obtained in the end.

The study was limited by inadequate demographic data, future studies should focus on smaller geographic units like the individual utility zones, to improve water supply inequalities. Detailed mapping of water demand factors at smaller scales such as in the individual utility zones is required for clear identification of investment areas as well as overall water infrastructure planning. Other water uses within the network such as water kiosks and water trucking which partly influence the water demand in the municipality regions should be captured in a reliable database for easy integration into the spatial models. It is recommended that enough data should be collected in the development of the tool for water demand management in line with the objectives. Besides, the AHP, other MCDA

**Table 8**
Weight matrix for demand parameters.

| | Demand Factor | % Influence | Class Interval | Scale Value |
|---|---|---|---|---|
| 1 | Population Density | 26.50 % | <2184 | 3 |
| | | | 2185–5757 | 4 |
| | | | 5758–10158 | 5 |
| | | | 10159–18598 | 6 |
| | | | ≥18599 | 7 |
| 2 | LU/LC Classes | 23.70 % | Agric. & shrublands | 2 |
| | | | Sparse Grasslands | 4 |
| | | | Built-up areas | 7 |
| | | | Sparse vegetation and bare land | 5 |
| | | | Waterbodies | 1 |
| 3 | Slope | 9.70 % | <2.46 % | 7 |
| | | | 2.47 %–5.12 % | 6 |
| | | | 5.13 %–10.62 % | 3 |
| | | | 10.63 %–19.72 % | 2 |
| | | | >19.73 % | 1 |
| 4 | Distance from Water Pipeline | 8.50 % | <2 km | 7 |
| | | | 2–4 km | 6 |
| | | | 4–6 km | 5 |
| | | | 6–8 km | 3 |
| | | | >8 km | 2 |
| 5 | Distance from Storage Facilities | 9.60 % | <2 km | 7 |
| | | | 2–4 km | 6 |
| | | | 4–6 km | 5 |
| | | | 6–8 km | 4 |
| | | | >8 km | 3 |
| 6 | Distance from Boreholes | 8.70 % | <2 km | 6 |
| | | | 2–4 km | 5 |
| | | | 4–6 km | 4 |
| | | | 6–8 km | 3 |
| | | | ≥8 km | 1 |
| 7 | Distance from Road Network | 4 % | <2 km | 6 |
| | | | 2–4 km | 5 |
| | | | 4–6 km | 4 |
| | | | 6–8 km | 2 |
| | | | ≥8 km | 1 |
| 8 | Distance from Business Centers | 9.30 % | <2 km | 7 |
| | | | 2–4 km | 6 |
| | | | 4–6 km | 5 |
| | | | 6–8 km | 4 |
| | | | ≥8 km | 3 |

techniques (PROMETHEE, ELECTRE) can be applied with the addition and or modification of criteria based on the goals of the researchers. Additionally, the other studies within the MCDA Framework should incorporate supplementary data such as socio-demographic factors in the municipality which may include employment classes in the respective zones, education and income levels as well as cultural aspects concerning water conservation that affect water use. This may help the utility managers to properly plan infrastructure expansion that promotes social equity and the water needs of marginalized communities such as the internally displaced people in the municipality zones of Kanamkemer and Nakwamekwi.

## Data availability

Data will be made available upon request.

## CRediT authorship contribution statement

**Bonface Wanguba:** Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **David N. Siriba:** Writing – review & editing, Supervision. **Benson O. Okumu:** Supervision.

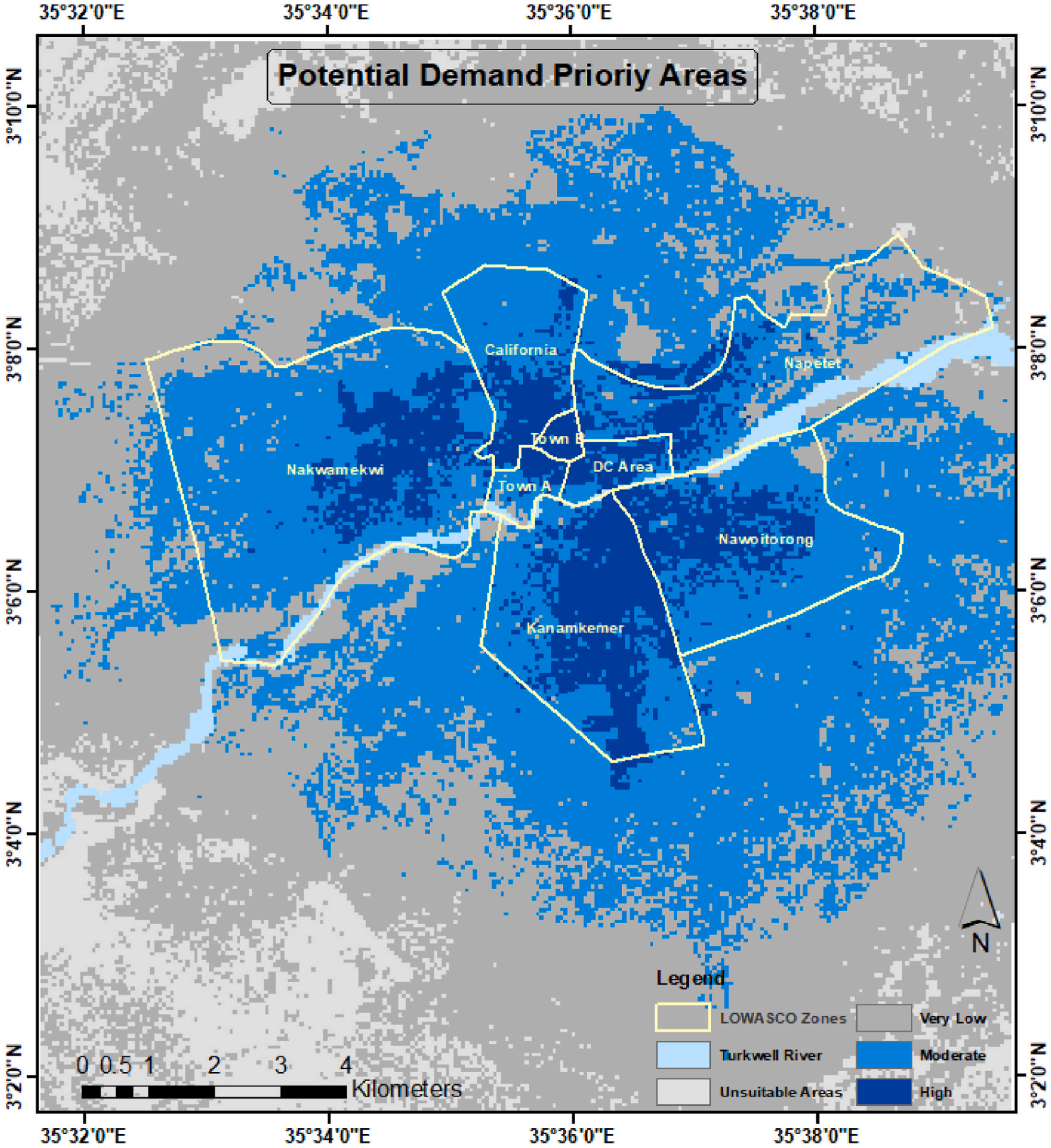


**Fig. 11.** Potential Demand priority map.

## Declaration of competing interest

The authors declare no personal relationships or conflicts of interest regarding the publication of this paper.

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## References

[1] UNESCO, Nature-based solutions for water 2018: the united nations World water development report 2018 [Online]. Available: https://wedocs.unep.org/20.500.11822/32857, 2018. (Accessed 4 March 2022).

[2] Y. Wada, M. Florke, N. Hanasaki, S. Eisner, G. Fischer, S. Tramberend, Y. Satoh, M.T.H. Van Vliet, P. Yillia, C. Ringler, P. Burek, D. Wiberg, "Modelling global water use for the 21st century: The Water Futures and Solutions (WFaS) initiative and its approaches.," 9 (1) (2016) 175–222, https://doi.org/10.5194/gmd-9-175-2016.

[3] G.A. Tobin, "Water, peace, and war, Confronting the Global Water Crisis by Brahma Chellaney (2014) (review),", https://muse.jhu.edu/article/556256/pdf. (Accessed 4 May 2023).

[4] UNDESA, World population prospects:: the 2017Revision, key findings and adance Tables, UN DESA Population Division (2017) [Online]. Available: https://population.un.org/wpp/Pulications/Files/WPP2017_KeyFindings.pdf. (Accessed 12 June 2022).

[5] report"The Global Risks Report 2019 14th Edition Insight Report," World Economic Forum, 115 January 20119. [Online]. Available: https://www3.weforum.org/docs/WEF_Global_Risks_Report_2019.pdf. [Accessed 17 May 2022].

[6] UNICEF & WHO, Progress on drinking water, sanitation and hygiene in Africa 2000-2020: five years into the SDGs. United Nations Children's Fund (UNICEF), World Health Organization (WHO), 2022 [Online]. Available: https://www.unicef.org/documents/progress-drinking-water-sanitation-and-hygiene-africa-2000-2020-5-years-sdgs. (Accessed 3 November 2022).

[7] World water day 2023: accelerating change in solving africa's water and sanitation crises [Online]. Available: https://www.afdb.org/en/news-and-events/world-water-day-2023-accelerating-change-solving-africas-water-and-sanitation-crises-59935, 2023. (Accessed 20 January 2023).

[8] Water in Eastern and Southern Africa, World Bank, 2023 [Online]. Available: https://www.worldbank.org/en/region/afr/brief/water-in-afe-eastern-southern-africa. (Accessed 12 November 2023).

[9] K.N. Pradeep, Water crisis in Africa: myth or reality? Int. J. Water Resour. Dev. 33 (2) (2016) 326–339, https://doi.org/10.1080/07900627.2016.1188266.

[10] C. Mora, A.G. Frazier, R.J. Longman, R.S. Dacks, M. Maya, E.J. Walton, J.J. Tong, L.K. Sanchez, S.O. Yuko, A.M. James, C.M. Ambrosino, F.-S. Iria, L.M. Giuseffi, T.W. Giambelluca, The projected timing of climate departure from recent variability, Nature 502 (7470) (2013) 183–187, https://doi.org/10.1038/nature12540.

[11] F. Mulwa, Z. Li, F.F. Fangninou, Water scarcity in Kenya: current status, challenges and future solutions, Open Access Library Journal 8 (1) (2021) 1–15. https://www.scirp.org/journal/paperinformation?paperid=106638.

[12] Africa defense Forum [Online]. Available:, ADF, 2019 https://adf-magazine.com/2019/10/kenyas-environmental-warriors/. (Accessed 21 March 2023).

[13] H. Mogaka, S. Gichere, R. Davis, R. Hirji, Climate Variability and Water Resources Degradation in Kenya Improving Water Resources Development and Management, 2006. World Bank Working Paper Series, No. 69, Report No. 34854, Washington DC, http://documents1.worldbank.org/curated/en/990211468283546915/pdf.

[14] Kenya's water and sanitation crisis, Water.org (2019) [Online]. Available: https://water.org/our-impact/kenya/. (Accessed 20 January 2023).

[15] Republic of Kenya, Ministry of water and sanitation, strategic plan 2018-2022 final draft [Online]. Available: https://africacheck.org/sites/default/files/Ministry-of-Water-Kenya-Strategic-Plan-2018-2022-Final-Version-Dec2018.pdf, 2018. (Accessed 10 February 2023).

[16] UN Habitat, Urban planning in Kenya: a survey of urban planning practices in the counties [Online]. Available: https://unhabitat.org/sites/default/files/download-manager-files/Urban_Planning_in_Kenya_webInside.pdf, 2019. (Accessed 3 February 2023).

[17] F. Tanui, D. Olago, S. Dulo, G. Ouma, Z. Kuria, Hydro geochemistry of a strategic alluvial aquifer system in a semi-arid setting and its implications for potable urban water supply: the Lodwar Alluvial Aquifer System (LAAS), Groundwater for Sustainable Development 11 (2020) 100451, https://doi.org/10.1016/j.gsd.2020.100451.

[18] D. Olago, F. Tanui, R. Hope, Protecting Groundwater for Climate Resilience and Water Security in Turkana, Smith School of Enterprise and the Environment, 2022 [Online]. Available: https://www.smithschool.ox.ac.uk/sites/default/files/2023-12/Protecting-groundwater-for-climate-resilience-and-water-security-in-Turkana.pdf. Accessed 19 Februay 2023.

[19] REACH, Country diagnostic report, Kenya [Online]. Available: https://reachwater.uk/resource/country-diagnostic-report-kenya/, 2015. (Accessed 19 February 2023).

[20] D. Olago, Constraints and solutions for groundwater development, supply, and governance in urban areas in Kenya, Hydrogeol. J. 27 (3) (2018) 1034, https://doi.org/10.1007/s10040-018-1895-y.

[21] M.A. Arfanuzzaman, A. Rahman, Sustainable water demand management in the face of rapid urbanization and groundwater depletion for socio-ecological resilience building, Global Ecology and Conservation 10 (2017) 9–22, https://doi.org/10.1016/j.gecco.2017.01.005.

[22] F. Bouraoui, B. Grizzetti, Modelling mitigation options to reduce diffuse nitrogen water pollution from agriculture, Sci. Total Environ. 468–469 (2014) 1267–1277, https://doi.org/10.1016/j.scitotenv.2013.07.066.

[23] L. Eastman, J. Weigen, P.K. Apos, J. Toledano, Raster procedure for multicriteria/multi-objective decisions, Photogramm. Eng. Rem. Sens. 61 (5) (1995) 539–547. https://www.asprs.org/wp-content/uploads/pers/1995journal/may/1995_may_539-547.pdf.

[24] J. Malczewski, GIS and Multicriteria Decision Analysis, John Wiley & Sons, New York, 1999. https://www.wiley.com/en-us/GIS+and+Multicriteria+Decision+Analysis-p-9780471329442.

[25] S. Greco, M. Ehrgott, J.R. Figueira, Multiple Criteria Decision Analysis: State-Of-The-Art Surveys, Kluwer Academic Publishers, London, 2019. https://www.semanticscholar.org/paper/Multiple-criteria-decision-analysis%3A-state-of-the-Greco-Ehrgott/860c8022c62675158eef21a8a4e36119d081408a.

[26] J. Malczewski, GIS-based multicriteria decision analysis: a survey of the literature, Int. J. Geogr. Inf. Sci. 20 (7) (2006) 703–726. https://www.tandfonline.com/doi/full/10.1080/13658810600661508.

[27] J.R. Figueira, S. Greco, M. Ehrgott, Multiple criteria decision analysis: state of art surveys, International Series in Operations Research and Management Science (2016), https://doi.org/10.1007/978-1-4939-3094-4.

[28] N.N. Hassoun, Y. Djebbar, L. Djemili, Application of the analytical hierarchy process for planning the rehabilitation of water distribution networks, Arab Gulf J. Sci. Res. 41 (2023) 518–538, https://doi.org/10.1108/AGJSR-07-2022-0110.

[29] J.M.B. dos Santos Amorim, M.S.d.T. Bezerra, M.M. Silva, L.C.O. De Sousa, Multicriteria decision support for selection of alternatives directed to integrated urban water management, Water Resour. Manag. 34 (2020) 4253–4269, https://doi.org/10.1007/s11269-020-02671-9.

[30] I.-A.E. Amilkar, J. Benítez, J.S. Izquierdo, R. Pérez-García, Multi-criteria optimization of supply schedules in intermittent water supply systems, J. Comput. Appl. Math. 309 (2017) 695–703, https://doi.org/10.1016/j.cam.2016.05.009.

[31] M.E. Fontana, D.C. Morais, Water distribution network segmentation based on group multi-criteria decision approach, Production 27 (0) (2017), https://doi.org/10.1590/0103-6513.208316.

[32] V. Kumar, L.D. Vasto-Terrientes, A. Valls, M. Schuhmacher, Adaptation strategies for water supply management in a drought-prone Mediterranean river basin: application of outranking method, Sci. Total Environ. 540 (2016) 344–357, https://doi.org/10.1016/j.scitotenv.2015.06.062.

[33] A.T. de Almeida-Filho, M.B.S. Monte, D.C. Morais, A voting approach applied to preventive maintenance management of a water supply system, Group Decis. Negot. 26 (3) (2017) 523–546, https://doi.org/10.1007/s10726-016-9512-8.

[34] G.P. Panagopoulos, G.D. Bathrellos, H.D. Skilodimou, F.A. Matsouka, Mapping urban water demands using multi-criteria analysis and GIS, Water Resour. Manag. 26 (5) (11 January 2012) 1347–1363, https://doi.org/10.1007/s11269-011-9962-3.

[35] H. Amorocho-Daza, S. Cabrales, R. Santos, J. Saldarriaga, A new multi-criteria decision analysis methodology for the selection of new water supply infrastructure Santa Marta city, Columbia, Water 11 (4) (2019) 805, https://doi.org/10.3390/w11040805.

[36] P.H. Dos Santos, S.M. Neves, D.O. Sant'Anna, C.H. de Oliveira, H.D. Carvalho, The analytic hierarchy process supporting decision making for sustainable development: an overview of applications, J. Clean. Prod. 212 (1) (2019) 119–138, https://doi.org/10.1016/j.jclepro.2018.11.270.

[37] G. Fatemeh, D. Kaan, "Application of machine learning in water resources management: a systematic literature review", Water 15 (4) (2023) 620, https://doi.org/10.3390/w15040620, 620.

[38] H. Mosaffa, M. Sadeghi, I. Mallakpour, M. Naghdyzadegan, H.R. Pourghasemi, Application of machine learning algorithms in hydrology, Computers in Earth and Environmental Sciences (2022) 585–591, https://doi.org/10.1016/B978-0-323-89861-4.00027-0.

[39] M.F. Allawi, Y. Al-Ani, A.D. Jalal, Z.M. Ismael, M. Sherif, A. El-Shafie, Groundwater quality parameters prediction based on data-driven models, Engineering Applications of Computational Fluid Mechanics 18 (1) (June 2024), https://doi.org/10.1080/19942060.2024.2364749.

[40] P.N. Wafula, T.G. Ngigi, Gis based analysis of supply and forecasting piped water, International Journal of Engineering Science Invention 4 (2) (February 2015) 1–10. http://www.ijesi.org/papers/Vol(4)2/Version-1/A042101011.pdf.

[41] W.M. Manetu, F. Mutua, B.K. Kenduiywo, Spatial modelling of current and future piped domestic water demand in Athi River town, Kenya, J. Geogr. Inf. Syst. 11 (2) (April 2019) 196–211, https://doi.org/10.4236/jgis.2019.112014.

[42] REACH, "Small Towns in Fragile Environments, University of, Oxford, Oxford, UK, 2015-2024 [Online]. Available: https://reachwater.uk/research/where-we-work/small-towns-fragile-environments/. (Accessed 18 May 2022).

[43] KNBS, Kenya Population and Housing Census Reports Volume II, Kenya National Bureau of Statistics, 2019, p. 241. https://www.knbs.or.ke/?wpdmpro=2019-kenya-population-and-housing-census-volume-ii-distribution-of-population-by-administrative-units. (Accessed 18 January 2023).

[44] F. Opiyo, M. Nyangito, P. Omondi, O.V. Wasonga, Trend analysis of rainfall and temperature variability in the arid environment of Turkana, Kenya, Environ. Res. J. 8 (2) (2014) 30–43. https://www.researchgate.net/publication/264458956.

[45] County Government of Turkana, Turkana county integrated development plan (CIDP II) [Online]. Available: https://repository.kippra.or.ke/handle/123456789/2832, 2018. (Accessed 19 February 2023).

[46] M. Falkenmark, J. Lundqvist, C. Widstrand, ") macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development,", Nat. Resour. Forum 13 (4) (1989) 258–268, https://doi.org/10.1111/j.1477-8947.1989.tb00348.x.

[47] P.H. Gleick, Basic water requirements for human activities: meeting basic needs, Water Int. 21 (2) (1996) 83–92, https://doi.org/10.1080/02508069608686494.

[48] R.W. Saaty, The analytic hierarchy process—what it is and how it is used, Mathematical Modeling 9 (3–5) (1987) 161–176, https://doi.org/10.1016/0270-0255(87)90473-8.

[49] S.H. Zyoud, H. Shaheen, S. Samhan, A. Rabi, F. Al-Wadi, D. Fuchs-Hanusch, Utilizing analytic hierarchy process (AHP) for decision making in water loss management of intermittent water supply systems, J. Water, Sanit. Hyg. Dev. 6 (4) (December 2016) 534–546, https://doi.org/10.2166/washdev.2016.123.

[50] A. Varade, D.Y. Khare, K.P. Dongre, S. Muley, G. Wasnick, Integrated geographical information system (GIS)-based decision support system (DSS) approach to identify the site-specific water conservation structures in a watershed of Nagpur district, Central India, Sustainable Water Resources Management 3 (2) (4 March 2017) 141–155, https://doi.org/10.1007/s40899-017-0085-8.

[51] M.O. Hassan, G.A. Tularam, Migration in sub-Saharan Africa (SSA)—the cases of the effects of climate change on rural-urban Democratic Republic of Congo, Kenya and Niger migration in sub-Saharan Africa (SSA)—the cases of Democratic Republic of Congo, Kenya and Niger, in: D. Malcangio (Ed.), Applications in Water Systems Management and Modeling, InTech, 2018, p. 140, https://doi.org/10.5772/intechopen.72226.

[52] M.C. Odira, S. Dulo, D.O. Olago, P.M. Odira, Water availability analysis of multiple source groundwater supply systems in water stressed urban Centers: case of lodwar municipality, Kenya, J. Civ. Environ. Eng. 10 (2) (2020), https://doi.org/10.37421/jcde.2020.10.339.

[53] F.A. Hirpa, E. Dyer, R. Hope, D.O. Olago, S.J. Dadson, Finding sustainable water futures in data-sparse regions under climate change: insights from the Turkwel River basin, Kenya, J. Hydrol.: Reg. Stud. 19 (October 2018) 124–135, https://doi.org/10.1016/j.ejrh.2018.08.005.