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Evaluate the Future Scenarios of Water Demand in the Middle Nzoia River Catchment

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Abstract Effective water allocation in river catchments experiencing rapid population growth, land-use change, and climatic variability remains a pressing global concern. This study evaluated the future scenarios of water demand within the Middle Nzoia Catchment in western Kenya using WEAP model. The study utilized a comprehensive dataset covering hydrological, water Quantity, and socio-economic variables from 1982 to 2022. Model calibration (2001-2010) and validation (2011-2020) were undertaken using observed streamflow data. Future demand scenarios to 2052, projected a potential increase to 45% from the base year under the High Growth scenario, reaching 260 million m³ annually. The agricultural and domestic sectors experienced the most significant increases, driven by population growth and intensified irrigation practices. Water allocation simulations demonstrated that during low-flow months, supply could meet only 69% - 72% of total demand, signaling potential water scarcity and inequitable distribution. Allocable water volumes were estimated at 240 million m³ annual but without integrated management strategies, unmet demand could increase to 31% to 2052. The study highlights the critical need for adaptive management approaches, including enhanced demand- side efficiency, investment in storage infrastructure, and strengthened institutional coordination. These results provide actionable guidance for policymakers, and water managers in similar hydrological contexts facing complex socio-environmental pressures.

Keywords Catchment; Water demand; Scenarios; WEAP model

1 Introduction

Water allocation and management are critical issues worldwide, particularly in regions experiencing rapid population growth, climate change, and competing demands for water resources (Amitaba et al., 2024). Water resources management refers to the planning, development, distribution, and management of water resources, to ensure their efficient and equitable use for various purposes such as domestic consumption, agriculture, industrial use, and environmental protection. Water allocation specifically focuses on determining the fair distribution of available water resources among different sectors, ensuring that all users, including ecosystems, have their needs met (Phung et al., 2023). Traditionally, water resources management has been approached through sector-specific plans, often developed at the national or regional level, but in many cases, this fragmented approach has led to inefficiencies and unsustainable practices. In response to these challenges, integrated water resources management (IWRM) has emerged as a more holistic approach, seeking to balance competing demands and promote sustainability through coordinated, science-based decision-making (Elshorbagy, 2006).

International organizations like the International Water Association (IWA) and the Global Water Partnership (GWP) play essential roles in advancing global water management practices. The IWA is focused on promoting the science and practice of water management through innovation, research, and technological development. It provides a platform for professionals to exchange knowledge, develop innovative solutions, and collaborate on various water-related challenges (Smith et al., 2023). The IWA's initiatives primarily target improvements in water treatment technologies, the optimization of water distribution systems, and the promotion of sustainable practices across different sectors (Group, 2016).

Africa as a whole faces significant water management challenges driven by climate variability, rapid population growth, and competing demands from agriculture, industry, and urbanization. In Nigeria, water stress is particularly evident in the northern regions, where frequent droughts, rapid population growth, and industrial contamination, including oil spills, exacerbate water scarcity (Chepyegon and Kamiya, 2018) Similarly, in South Africa's Western Cape, including Cape Town, the "Day Zero" crisis highlighted the severity of water shortages, which were worsened by drought and poor water management practices (Chepyegon and Kamiya, 2018).

East African nations, such as Uganda, Tanzania, Rwanda, and Burundi, face similar water allocation and management issues, each with unique challenges. In Uganda, despite vast water resources, equitable distribution is a challenge, particularly in the northern and eastern parts of the country, where infrastructure is lacking (Galema et al., 2024) The rapid population growth in urban areas like Kampala adds pressure to already limited water resources (Husain and Rhyme, 2020). Rwanda, with its abundant rainfall and numerous lakes, faces challenges related to urbanization and balancing agricultural water use with environmental sustainability. In cities like Kigali, increasing water demand has led to significant investments in water infrastructure, but the country must also address water quality and pollution issues (Chopra and Ramachandran, 2021).

Kenya is grappling with a complex set of challenges related to water supply and demand, influenced by its variable climate, rapid population growth, and the pressures of economic development. Water availability is unevenly distributed across the country, with arid and semi- arid regions facing significant water scarcity (Mulwa et al., 2021) This disparity is exacerbated by the country's dependence on erratic rainfall patterns, which often lead to water shortages, particularly in areas with low annual precipitation (Chepyegon and Kamiya, 2018). As the population grows and urbanizes, the demand for water continues to rise, placing additional strain on the already limited resources and infrastructure (Kou et al., 2025).

Kenya's Lake Victoria Basin serves as an essential water source, but rising populations around the lake, compounded by climate change, threaten the sustainability of water resources in the region. Efforts to regulate water use and prevent pollution face challenges, especially in managing cross-border water resources with neighboring Uganda and Tanzania (Robledo et al., 2024).

The current challenges are further exacerbated by a lack of robust scientific information on the hydrological dynamics of the catchment, including seasonal variability and long-term trends in water availability. Without detailed, accurate data and integrated planning mechanisms, it is difficult to predict the future impact of various water demands and allocations on the catchment's water resources. As a result, water management decisions are often based on unverified assumptions, which may lead to inefficient water use and increased competition for water resources, threatening both environmental sustainability and the livelihoods of local communities.

The study aimed at addressing key water management challenges in the Middle Nzoia Catchment, with a focus on Middle Nzoia. By evaluating current water availability and demand, simulating various scenarios using the WEAP model, and determining optimal water allocation strategies, the study provides a comprehensive understanding of the region's water dynamics (Agarwal et al., 2019). The ultimate goal of the study was to recommend actionable strategies for sustainable water resource management and policy-making. These recommendations, grounded in detailed assessments and scenario simulations, are intended to guide effective water management practices, ensuring that resources are utilized efficiently and sustainably, thereby addressing both current and future water challenges in the Middle Nzoia Catchment.

Parts of Kakamega, Bungoma and Siaya Counties where the Middle Nzoia River Catchment traverses each, have independent development plans, many of which fail to consider the cumulative water supply and demand needs of the entire region. This fragmented approach to water management exacerbates inequities in water allocation and increases the risk of unsustainable water use. The absence of a coordinated, scientific framework for water resource management further limits the region's ability to manage its water resources effectively (Groves et al., 2015). The current challenges are further exacerbated by a lack of robust scientific information on the hydrological dynamics of the catchment, including seasonal variability and long-term trends in water availability. Without detailed, accurate data and integrated planning mechanisms, it is difficult to predict the future impact of various water demands and allocations on the catchment's water resources. As a result, water management decisions are often based on unverified assumptions, which may lead to inefficient water use and increased competition for water resources, threatening both environmental sustainability and the livelihoods of local communities.

The main objective of the study was to evaluate water demand over the period 2022 - 2052, in the Middle Nzoia River Catchment. The study aimed to address the gaps using Water Evaluation and Planning (WEAP) model by simulating various future scenarios using the WEAP model, and determining optimal water allocation strategies within the Middle Nzoia River Catchment, the ultimate goal of the study was to recommend actionable strategies for sustainable water resource management and policy- making. These recommendations, grounded in detailed assessments and scenario simulations, are intended to guide effective water management practices, ensuring that resources are utilized efficiently and sustainably, thereby addressing the future water challenges in the Middle Nzoia Catchment.

This study aims to understand the implications of both current and future water abstraction on water availability in the catchment. By evaluating various scenarios, the study will provide a scientific basis for predicting future water shortages and help address the challenges of rising water demand. The study will generate essential knowledge on water distribution and demand across sectors, guiding effective water allocation strategies by the Water Resource Authority (WRA) and informing key government policies. Simulation models will help forecast future water needs and evaluate the potential impact of different allocation strategies, fostering discussions on equitable water distribution. Additionally, the study will enhance understanding of the relationship between water flow, ecological conditions, and water use in the catchment. The outcomes will provide critical insights for balancing water availability with demand, ensuring sustainable management of water resources in the Middle Nzoia River Catchment.

2 Materials and Methods

2.1 Description of the study area

This study was conducted in the Middle Nzoia River Catchment that traverses across Bungoma County, Kakamega County, and Siaya County. This study's boundaries was from upstream of the Bunyole water falls at the railway crossing bridge (UTM 67973.00 m N, 702154.00 m E) with an elevation of 1,516 m above sea level, and downstream at (UTM 27589.00 m N, 649276.00 m E) in Sigomere- masiro bridge in Siaya county, including all the major tributaries within that section, which are Lukusi, Surongai, Luandeti, Chebaiywa, Nambirima, Kuywa, Chwele, Maira, Mangango, Luji, Khalaba, and Lusumu (Figure 1).

The Nzoia River is about 257 km Long, the entire catchment traverses the six Counties of Elgeyo Marakwet, Trans Nzoia, Uasin, Gishu, Bungoma, Kakamega, and Siaya. River Nzoia is one of the largest rivers in Western Kenya. The main stream of the river flows from the western side of the Elgeyo Escarpment (Sergoi, Sosiani and Kipkelion Tributaries) the Cherangani Hills (Chepkotet and Kaisungur Tributaries) from an elevation of approximately 2,286 m above mean sea level. Its tributaries which flow from the high slopes of Mount Elgon, attain maximum elevation in the river’s basin and are estimated at about 4,300 m above mean sea level (Agnes, 2019). The river has a discharge of about 118 m^3/s or about $3.721 \times 10^9 m^3$ annually, making it the second biggest river in the country by discharge.

Nzoia River can be divided into three zones, the upper zone, the Middle zone, and the lower zone, the upper zone which is also known as mountain zone is forested, with natural vegetation covers consisting of high altitude forest and high altitude savannas, this zone but suffers severe land degradation. The middle zone also known as plateau zone is the major farming zone, also Kakamega forest, which is the only remnants of the equatorial Congolese/Guinean forest, is in this zone. The lower zone also known as low land zone is generally flat and is prone to flooding. The wider River Nzoia watershed, including the main water catchment (Figure 2).

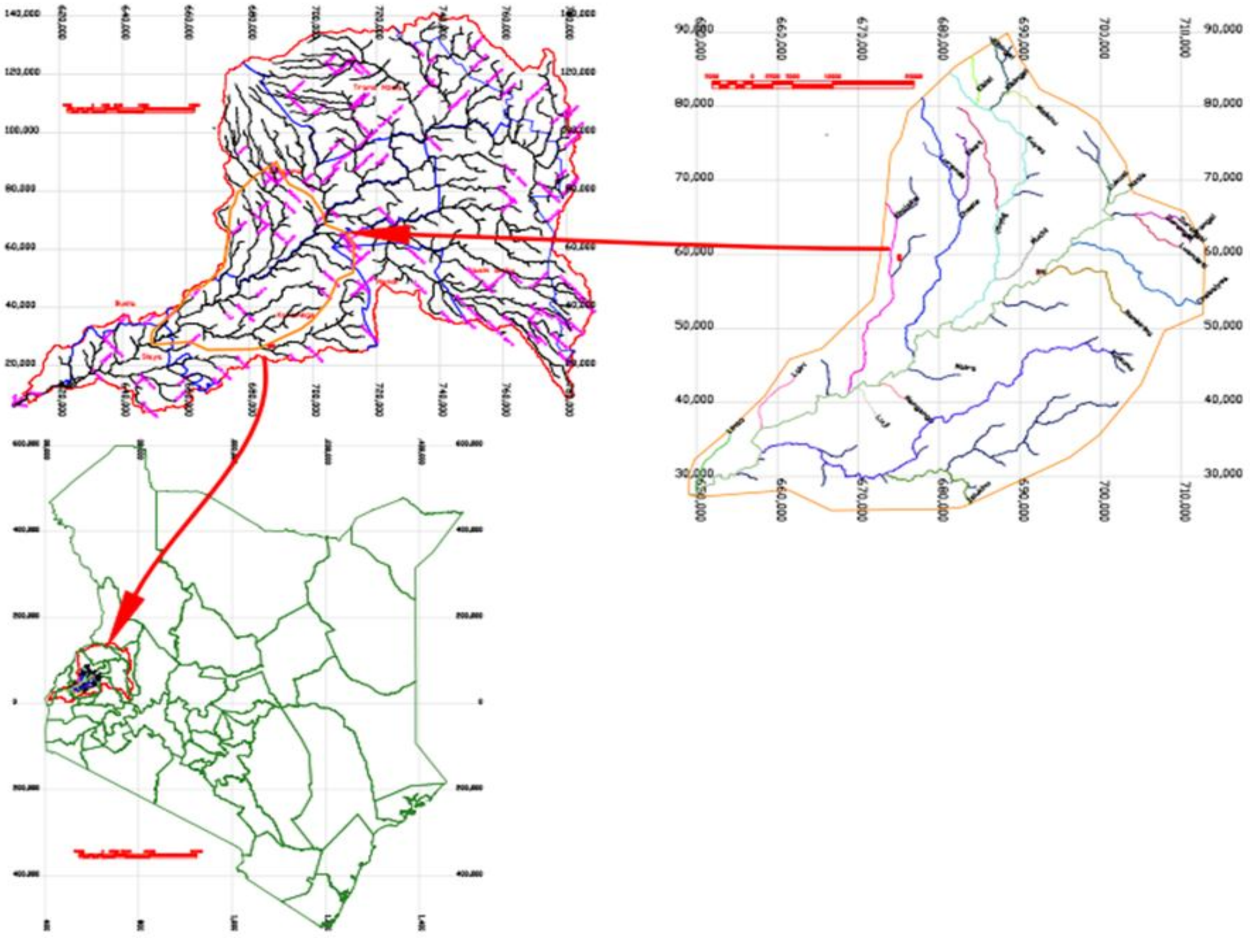


Figure 1 Location and layout of the Middle Nzoia River Catchment study area (source: Kenya waterways open street map export)

2.2 Assessment of the current water availability and demand

2.2.1 Hydrological data collection

To assess current water availability in the Middle Nzoia River Catchment, historical hydrological data were gathered from various gauging stations located along the river and its tributaries. This data consisted of daily or monthly discharge records spanning the past 40 years, which provided a comprehensive overview of river flow patterns and fluctuations. Additionally, historical and contemporary rainfall data were sourced from local meteorological stations within the catchment area to understand precipitation trends and their impact on surface water availability.

2.2.2 Water demand data

Water demand data were collected across the major sectors to provide a comprehensive understanding of current water use patterns within the Middle Nzoia River Catchment.

Agricultural sector: Data on irrigation practices, including crop types, irrigation methods, and seasonal water requirements, were collected through surveys and interviews with local farmers. These data were used to assess water consumption patterns in the agricultural sector, which is a major contributor to overall water demand in the catchment.

Domestic sector: Data on household water use, including daily or monthly consumption rates, water sources (e.g., piped water, wells, and surface water), and seasonal variations, were collected through household surveys, interviews, and utility records. This information provided a basis for assessing domestic water demand in the catchment.

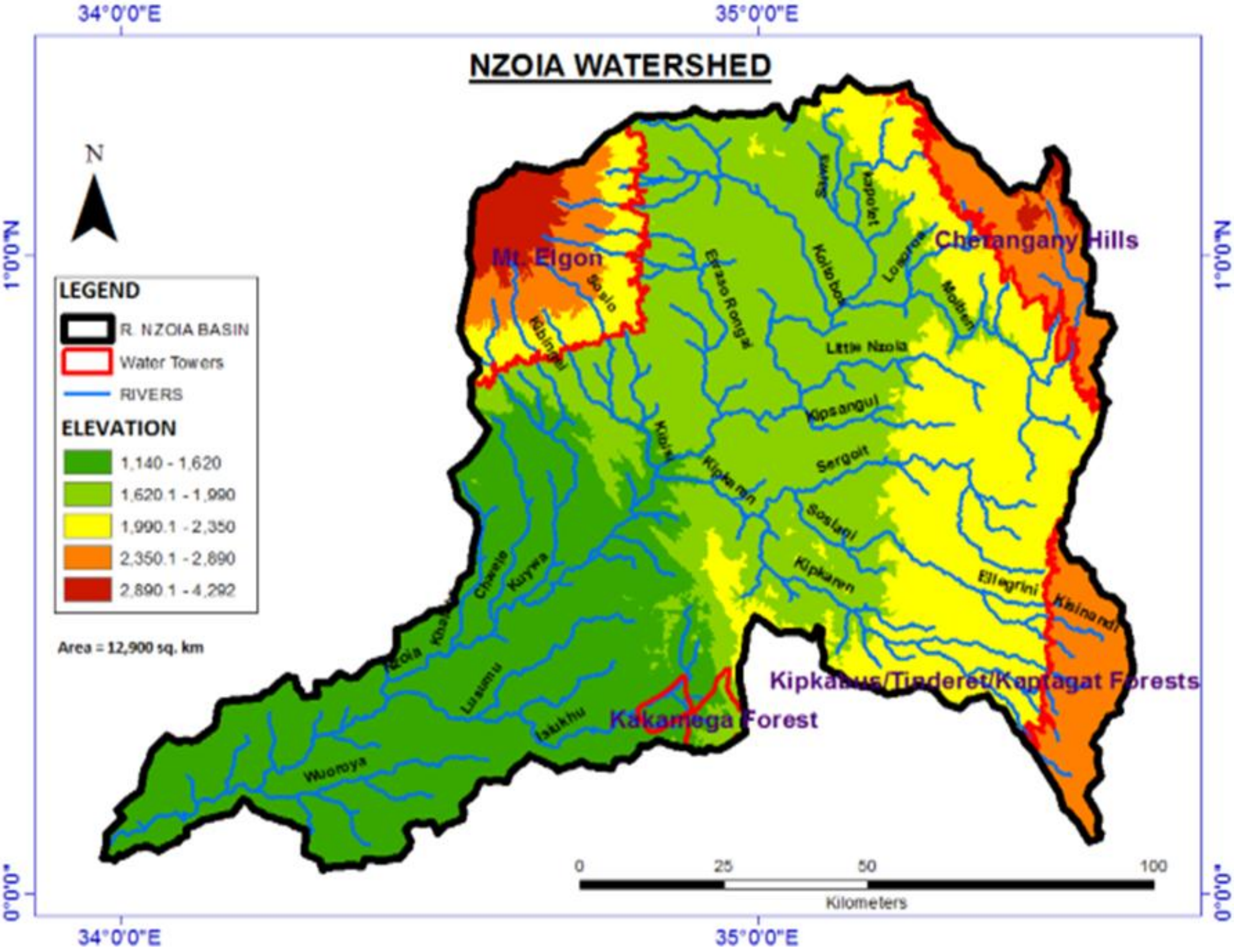


Figure 2 River Nzoia watershed and the main water catchment (Source LVBC 2023)

Industrial sector: Information on water consumption by industries and commercial establishments was collected through surveys, utility company records, and local government databases. These data were used to assess the contribution of the industrial sector to overall water demand.

Livestock sector: Data on livestock water requirements, including animal types, population sizes, and daily or seasonal water consumption, were collected through surveys and interviews with farmers and livestock owners. Information on water sources used for livestock, such as rivers, ponds, and dedicated water troughs, was also recorded to evaluate the sector's contribution to total water demand.

2.3 Simulating implications of various scenarios using the WEAP model

2.3.1 Model setup and calibration

The data gathered from hydrological, water quality, and demand sources were meticulously organized and formatted for compatibility with the WEAP model. This step ensured that the data could be effectively utilized within the modeling environment to simulate water resource dynamics. Subsequently, the WEAP model underwent a calibration process, where it was adjusted using historical data to match real-world observations of water availability and demand within the Middle Nzoia River Catchment (Fard and Sarjoughian, 2019). This calibration was essential to ensure that the model accurately reflected past hydrological conditions and provided reliable outputs for future scenario analysis.

2.3.2 Scenario development

Several future scenarios were developed in the WEAP model to assess the potential effects of different drivers on water resource management in the Middle Nzoia River Catchment. The scenarios were designed to evaluate how changes in land use, climate conditions, population growth, and related management factors could influence water availability and water demand over time.

The Reference Scenario was used as the baseline condition and assumed no major changes in land use, climate, or population growth. This scenario provided a benchmark against which the other scenarios were compared. The High Growth Scenario represented a situation of rapid population and economic growth, resulting in substantial increases in water demand across the major sectors. In contrast, the Medium Growth Scenario reflected moderate increases in population and water demand, together with less pronounced changes in land use and climate-related conditions. These scenarios provided a basis for examining possible future trends and for identifying appropriate water allocation and management strategies under different development pathways.

2.4 Determining water allocation

The WEAP model was executed under the predefined scenarios to simulate the outcomes of different water allocation strategies across the Middle Nzoia River Catchment. The model output provided insights into how water resources would be distributed under various conditions, considering both supply and demand factors.

Optimization: To enhance the efficiency and sustainability of water resource management, the WEAP model's optimization tools were employed. These tools were used to identify optimal water allocation strategies that would balance the competing demands for water within the catchment. By adjusting allocation parameters and testing different management options, the optimization process provided data-driven recommendations on how best to allocate available water resources, ensuring equitable distribution while maximizing the sustainability of the catchment’s water supply.

3 Data Analysis

3.1 Model development

3.1.1 Definition of the study area and time frame

The study area for this analysis was clearly defined as the Middle Nzoia River Catchment, including all its tributaries and the associated sectors that depend on water resources. The temporal scope of the analysis encompassed both historical and projected data. Historical data spanning the last 40 years was collected to establish a baseline understanding of water availability and demand, while projections of future scenarios accounted for anticipated changes in land use, climate patterns, and population growth, which could significantly impact water resources in the catchment.

3.1.2 Creation of the current accounts

Current accounts were developed by integrating the collected hydrological, water quality, and demand data into the WEAP model. This step involved inputting historical flow data, water quality parameters such as temperature and pH, and detailed information on water usage from key sectors: agriculture, domestic, industrial, and agricultural. These current accounts provided the model’s baseline representation, which was essential for evaluating the water availability and demand under present conditions. They served as the reference point for comparing future scenarios and assessing the model’s sensitivity to various factors influencing water resources.

3.1.3 Creation of scenarios

Several future scenarios were formulated to simulate potential changes in the catchment's water dynamics. These scenarios included shifts in land use patterns, climate variability, population growth projections, and potential policy interventions. Each scenario was constructed to explore the impacts of these changes on water supply and demand, offering a comprehensive view of how the catchment’s water resources may evolve under different conditions.

3.1.4 Evaluation of the scenarios

The developed scenarios were assessed using the WEAP model to determine their impacts on water availability and demand. This involved running simulations for each scenario to analyze changes in key indicators, including flow rates, water quality, and water allocation requirements. The simulation results were then compared to the current accounts to identify significant deviations from the baseline conditions. This comparison allowed for the identification of potential issues, such as water shortages or quality degradation, and highlighted critical trends or risks that may arise under different future scenarios.

3.1.5 Model calibration and validation

The WEAP (Water Evaluation and Planning) model was calibrated and validated to ensure it accurately simulated the hydrological and water use dynamics of the Middle Nzoia River Catchment. Calibration and validation were critical steps to confirm the reliability of the model before applying it to future water demand and allocation scenarios.

3.1.6 Calibration of the WEAP model

The objective of the calibration process was to align the model's simulated outputs with observed historical data, thereby ensuring that WEAP could reliably represent the catchment's water system behavior under past conditions. The calibration was conducted using a 10-year dataset covering the period 2001 to 2010.

3.1.7 Calibration process

1) Data Integration: Historical hydrological data—including river discharge measurements, rainfall records, and climate data—were integrated into the WEAP model. This data formed the basis for simulating water availability and distribution in the catchment.

2) Parameter Adjustment: Model parameters, particularly those related to surface runoff, infiltration, evapotranspiration, and sectoral water demand, were iteratively adjusted. Parameters such as runoff coefficients, root zone conductivity, and demand per capita were fine-tuned to achieve realistic simulations.

3) Historical Data Comparison: Simulated streamflow outputs were compared against observed discharge data from key gauging stations within the catchment. Discrepancies between simulated and observed data were addressed through continued refinement of model inputs and assumptions.

4) Sensitivity Analysis: Sensitivity analysis was carried out to identify which model parameters had the greatest influence on output accuracy. This step helped prioritize parameters for adjustment and improved model efficiency.

5) Calibration Metrics: The performance of the calibration process was evaluated using statistical indicators such as Nash-Sutcliffe Efficiency (NSE), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE).

These metrics quantified how closely the simulated results matched observed data and provided confidence in the model's reliability.

3.1.8 Validation process

1) Independent Data Collection: Observed hydrological data for the validation period— including river flows and other relevant catchment characteristics—were used to test the model. These datasets were independent of those used during calibration.

2) Simulation of Validation Period: The model was run using the calibrated parameters to simulate catchment behavior over the 2011–2020 period. No further parameter adjustments were made during this stage.

3) Performance Evaluation: The accuracy of the validation simulations was assessed using the same statistical metrics applied during calibration (NSE, MAE, and RMSE). High levels of agreement between observed and simulated data during this period further confirmed the model's predictive capacity.

4) Model Robustness Testing: The model's performance was evaluated under various conditions to test its stability. This included testing across wet and dry years to ensure the model's applicability under variable hydrological conditions.

5) Validation Results: The results demonstrated that the WEAP model could reliably simulate the water dynamics of the Middle Nzoia Catchment. The consistency of model performance across both calibration and validation periods affirmed its suitability for future scenario analysis and water resource planning.

3.1.9 Model performance metrics

Model performance was thoroughly assessed using key statistical metrics during the calibration phase. The Nash-Sutcliffe Efficiency (NSE) was employed to evaluate how well the WEAP model simulations matched observed data, with values nearing 1 indicating a good fit between simulated and real water dynamics. Additionally, the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were calculated to measure average deviations and squared differences between observed and simulated values, providing insight into the model's accuracy and precision in predicting river flow and water quality. During the validation phase, these metrics were recalculated using independent datasets not used in calibration, testing the model's robustness and ability to generalize to new data. The consistency of NSE, MAE, and RMSE across various time periods and scenarios was evaluated to confirm the model's reliability, ensuring that the WEAP model continued to provide accurate predictions and remained a trustworthy tool for future analysis. The mathematical expressions to compute the parameters mentioned above are:

Mean Absolute Error (MAE)…………………….……………………………………(i)

Root Mean Square Error (RMSE) ……………………………………….…………..….(ii)

NB: The mean absolute error (MAE) and root mean square error (RMSE) are used to measure the deviation between the model outputs and the observed flows. Values tend to be zero for perfect agreement between observed and simulated values.

Error in Volume (VE in %)……………………………………………..…….….(iii)

Nash-Sutcliffe Coefficient(R)……………………….…………………………..……(iv)

Index of Agreement (IA)……………………….…………………………..………..(v)

The Index of Agreement =1 indicates the best (perfect) performance of the model.

Where:

Qoi is the observed streamflow at time (m^3/s)

Qsi is the simulated streamflow at time (m^3/s)

Vo is the observed streamflow volume (million m^3/month)

Vo is the simulated streamflow volume (million m^3/month)

Q is the average streamflow (m^3/s)

3.2 Scenario analysis

3.2.1 Sensitivity analysis

The scenario analysis involved a comprehensive sensitivity analysis to examine how changes in model parameters influenced the simulation results. rates were adjusted to assess their impact on the model's predictions.

3.2.2 Scenario comparisons

Statistical methods were utilized to conduct a comparative analysis of outcomes across various scenarios, focusing on the effects of altered land use, climate conditions, and water management strategies. This analysis quantitatively assessed the impact of each scenario on water supply and demand, facilitating the evaluation of the effectiveness of different water management strategies. The results of this comprehensive analysis formed the basis for developing evidence-based recommendations for sustainable water resource management.

4 Results

4.1 Calibration

Monthly simulated and observed streamflow data for the calibration period (2001-2010) for selected control stations in the Middle Nzoia Catchment (Figure 3). The model's ability to reproduce observed values depicts the relationship between simulated and observed flows.

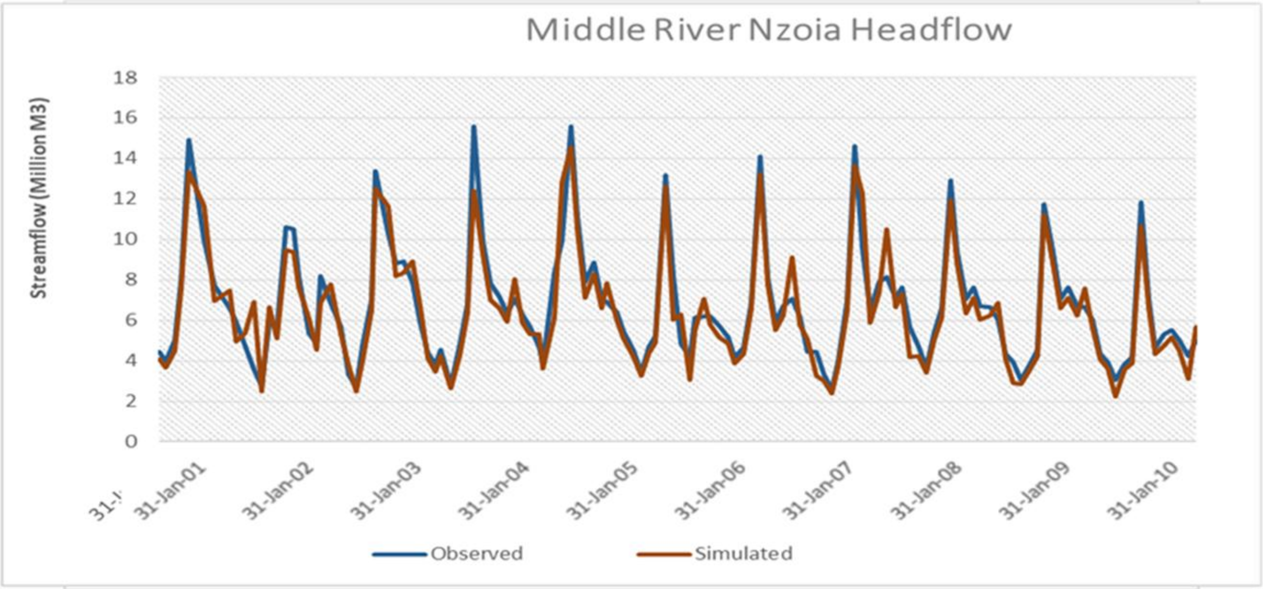


Figure 3 Calibration results showing observed and simulated monthly streamflows at selected stations in the Middle Nzoia Catchment (2001-2010) (Source: Researcher (2025))

This figure shows a time series plot of streamflow for the Middle River Nzoia Headflow. The time-series pattern for the Middle Nzoia Headflow indicates clear seasonal and interannual variability in streamflow between January 2000 and January 2010. Streamflow peaks generally occurred during the same periods each year, reflecting the influence of rainfall seasonality and catchment hydrological processes, whereas the lower flows corresponded to dry-season conditions. Overall, the simulated streamflow followed the observed pattern closely, indicating that the WEAP model was able to reproduce the temporal dynamics of streamflow reasonably well. The agreement between the two series was particularly strong during low-flow periods, where the simulated and observed values were nearly overlapping, suggesting that the model performed well under baseflow conditions. This close correspondence supports the suitability of the model for water resources assessment, planning, and forecasting in the Middle Nzoia Catchment.

The statistical fit indicators for the calibration period (2001-2010) are summarized in Table 1, which presents the performance of the WEAP model at Nzoia (IDD1) Gauging Station. The results show that the model achieved a Mean Absolute Error (MAE) of 5.552 m^3/s and a Root Mean Square Error (RMSE) of 11.921 m^3/s. In addition, the Nash–Sutcliffe Efficiency (NSE) was 0.712, the Index of Agreement (IA) was 0.913, and the Coefficient of Determination (R^2) was 0.757. These values fall within acceptable ranges for hydrological model evaluation and indicate good agreement between simulated and observed streamflow. A further comparison of observed and simulated monthly flows is presented in Figure 4, where the strong correlation between the two datasets ($r = 0.87009$) confirms that the model captured the observed streamflow trends satisfactorily.

Overall, the calibration results demonstrate that the WEAP model performed well in representing the hydrological behavior of the Middle Nzoia Catchment. The good model fit may be attributed to the ability of the model to capture the main physical characteristics of the basin, including the topographic variation between the middle and upper catchment, catchment size, and the seasonal response of runoff to rainfall. These findings provide confidence in the model's application for subsequent scenario analysis and water allocation assessment.

Table 1 Fit statistics of simulated data by WEAP and observed stream flow data for calibration

Fit Statistic	Range	Acceptable Range	Value
Mean Observed Flow (m³/s)			9.009
Mean Simulated Flow (m³/s)			7.760
Median Observed Flow (m³/s)			8.998
Median Simulated Flow (m³/s)			6.984
Standard Deviation (Observed) (m³/s)			3.764
Standard Deviation (Simulated) (m³/s)			5.001
Mean Absolute Error (MAE) (m³/s)	0 to ∞	Lower is better	5.552
Root Mean Square Error (RMSE) (m³/s)	0 to ∞	Lower is better	11.921
Nash-Sutcliffe Efficiency (NSE)	–∞ to 1	> 0.5	0.712
Index of Agreement (IA)	0 to 1	Closer to 1	0.913
Coefficient of Determination (R²)	0 to 1	> 0.6	0.757

Source: Researcher (2025)

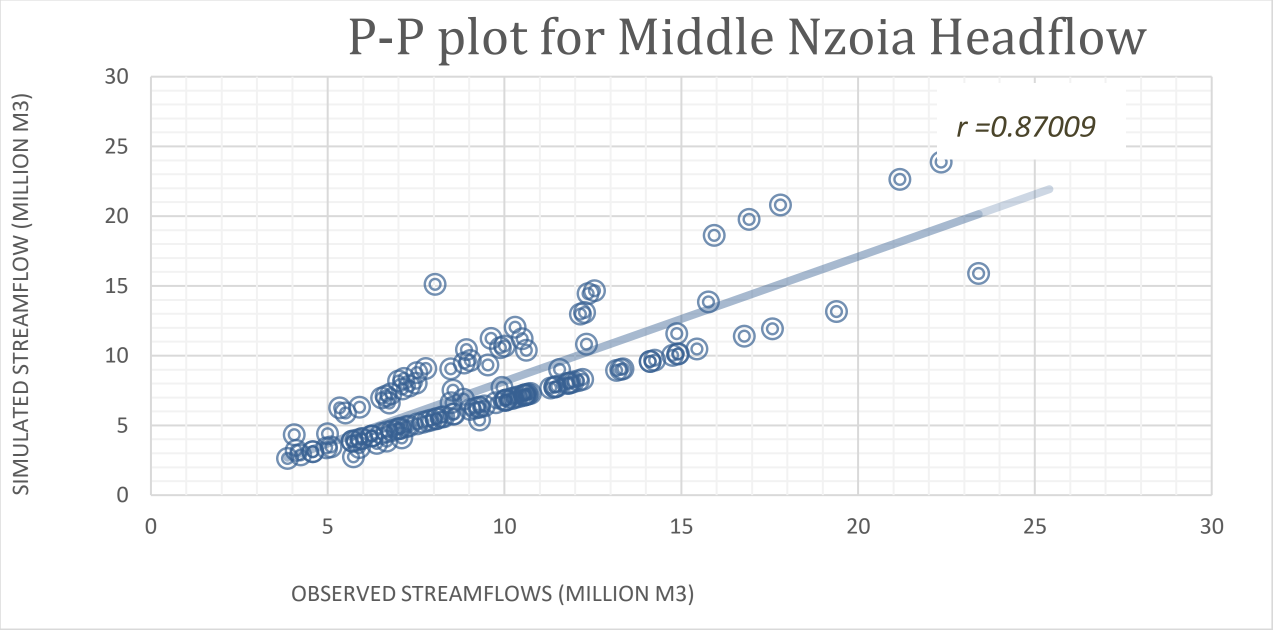


Figure 4 Calibration results showing Relationship between monthly observed and simulated streamflow in the Middle Nzoia Catchment (2001-2010) (Source: Researcher (2025))

Based on the performance metrics, the WEAP model demonstrates strong capability in simulating streamflow at Nzoia (IDD1) station during the 2001-2010 calibration period. The Nash-Sutcliffe Efficiency (0.712) which is above the acceptable range by 21%, R² (0.757) which is above the acceptable range by 16%, and IA (0.913) all reflect good agreement between simulated and observed values, confirming the model's reliability for use in future scenario analysis and water resource planning.

4.2 Validation

To assess the reliability and robustness of the calibrated hydrological model, a validation exercise was conducted using an independent dataset from Nabuyole gauge station covering the period 2011 to 2020. This period was selected to test the model's performance under different hydrological conditions from those used in calibration (which covered 2001-2010). The validation ensures that the model is not over fitted and can reliably simulate flows in varying conditions (Figure 5).

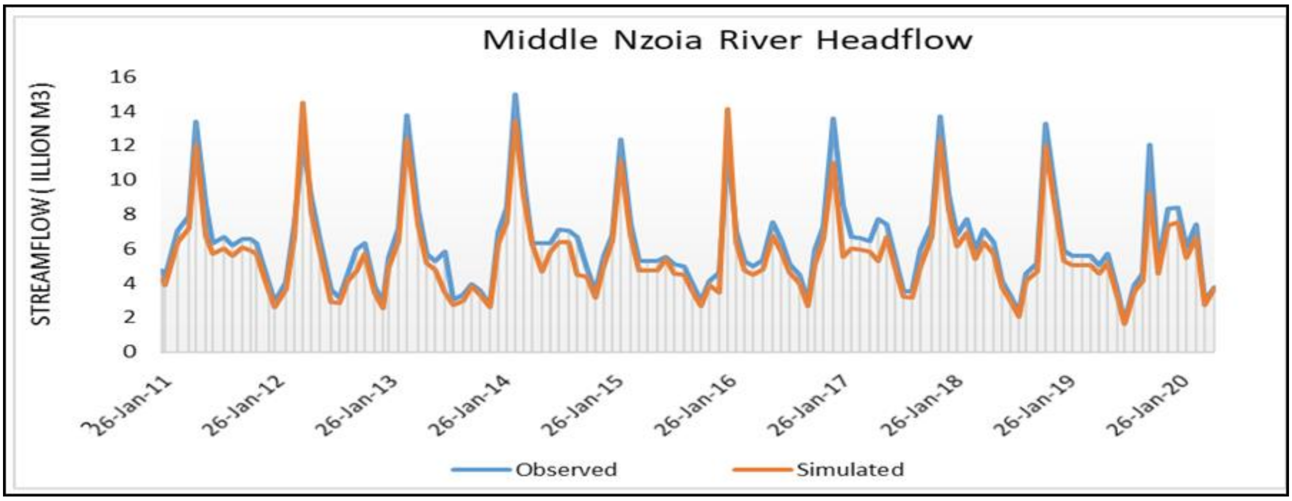


Figure 5 Validation results showing observed and simulated monthly streamflows at selected stations in the Middle Nzoia Catchment (2011-2020) (Source: Researcher (2025))

The above figure shows a time series plot of streamflow for the Middle River Nzoia Headflow. The y-axis represents streamflow (in Million cubic meters, M^3), and the x-axis represents the time period from 26-Jan-2011 to 26-Jan-2020. Two datasets are compared: Observed streamflow (blue line); Simulated streamflow (orange line).

The streamflow shows strong seasonal peaks almost every year, likely corresponding to rainy seasons in the catchment area. Peaks occur roughly once or twice a year, with values reaching 12×10^6 m^3 to 15×10^6 m^3. Dry-season flows drop significantly, sometimes below 4×10^6 m^3.

The Middle Nzoia River streamflow has strong seasonal variability driven by rainfall cycles. The hydrological model simulates the streamflow quite well, matching observed data closely over the 2011-2020 period. Minor discrepancies exist at extreme flows, but overall, the simulation is reliable for hydrological and water management applications.

Summary of annual and monthly fit statistics for the simulated validation data generated by the WEAP model and the observed streamflow data at selected gauging stations in the Middle Nzoia River Basin is presented in Table 2. The statistics cover the validation period from January 2011 to December 2020, and they provide a quantitative evaluation of the model's performance in simulating streamflows using independent data not applied during calibration.

The calibration and validation results affirm the robustness and predictive reliability of the WEAP model in simulating hydrological processes within the Middle Nzoia Catchment. During the calibration phase (2001-2010), the model exhibited strong hydrological fidelity, with statistical indices such as the Nash—Sutcliffe Efficiency (NSE = 0.712), coefficient of determination ($R^2 = 0.757$), and index of agreement (IA = 0.913) indicating a high degree of correspondence between simulated and observed streamflow data. The validation phase (2011- 2020) yielded even stronger performance metrics, with NSE = 0.807, R2 = 0.821, and Pearson's correlation coefficient (r = 0.888), suggesting that the calibrated model structure and parameters are transferable and generalizable under varying hydroclimatic conditions.

The low values of Mean Absolute Error (MAE = 5.886 m^3/s) and Root Mean Square Error (RMSE = 11.991 m^3/s) during validation further reinforce the model's capability in minimizing predictive uncertainty. The model's skill in reproducing both temporal dynamics and magnitude of observed flows across sub-catchments supports its applicability for scenario analysis, future water demand forecasting, and integrated water resource management. The performance metrics meet accepted hydrological modelling thresholds, validating the WEAP model as a reliable decision-support tool for simulating surface water availability and allocation under dynamic climatic influences within the basin.

Table 2 Fit statistics of simulated data by WEAP and observed stream flow data for validation

Fit Statistic	Range	Acceptable Range	Value
Mean Observed Flow (m^3/s)			9.111
Mean Simulated Flow (m^3/s)			8.621
Median Observed Flow (m^3/s)			9.010
Median Simulated Flow (m^3/s)			8.345
Standard Deviation (Observed) (m^3/s)			4.786
Standard Deviation (Simulated) (m^3/s)			3.767
Mean Absolute Error (MAE) (m^3/s)	0 to ∞	Lower is better	5.886
Root Mean Square Error (RMSE) (m^3/s)	0 to ∞	Lower is better	11.991
Nash-Sutcliffe Efficiency (NSE)	—∞ to 1	> 0.5	0.807
Index of Agreement (IA)	0 to 1	Closer to 1	0.819
Coefficient of Determination (R^2)	0 to 1	> 0.6	0.821

Source: Researcher (2025)

4.3 Scenario analysis and projected water demand (2022-2052)

4.3.1 Sectorial trends in water demand

Domestic water use follows a gradual upward trajectory, driven primarily by population growth. Demand increases from 11.6 × 10^6 m^3 annual in 2022 to nearly 36.8 × 10^6 m^3 annual by the year 2052, necessitating infrastructure upgrades. Industrial demand use, though Higher than domestic demand is expected to rise steadily, increasing from 14.9 × 10^6 m^3 annual in 2022 to 30.2 × 10^6 m^3 annual by the year 2052. The table below summarizes the projection of the demands from base flow year to projected year 2052 (Table 3).

Table 3 Overrow base year demand 2022 and projected year 2052

SUMMARY OF WATER DEMAND PROJECTION					
No.		Supplied demand 2019	Base year 2022	2032	2052
1	Domestic Water Demand	11,039,060	11,648,610	16,753,865	36,871,205
2	Commercial Demand	7,212,035	7,653,320	8,791,390	3,063,350
3	Agricultural Demand	7,943,860	8,430,040	9,683,450	14,389,395
4	School Demand	5,818,100	6,173,975	7,091,950	10,538,280
5	Health Facility Demand	2,813,055	2,968,180	3,590,140	5,993,665
6	Industrial Demand	14,162,000	14,943,465	18,074,070	30,175,280
	TOTAL WATER DEMAND	48,988,110	51,817,955	63,985,230	111,031,175

Total water demand across all sectors is projected to 111 × 10^6 m^3 annual, underscoring the importance of sustainable practices such as rainwater harvesting, wastewater recycling, and efficient irrigation. Policy actions must focus on seasonal conservation, infrastructure resilience, and equitable distribution to meet growing demand.

4.3.2 Comparison with 2022 baseline water demand

The 2022 baseline water demand under the current accounts scenario serves as a reference for assessing sectoral changes and planning needs. Total annual demand in 2022 was approximately 51.8 × 10^6 m^3 annual. Industrial use accounted for the largest share (14.9 × 10^6 m^3 annual) around 29%), followed by domestic (11.6 × 10^6 m^3 annual) agriculture (28.4 × 10^6 m^3 annual), commercial (7.6 × 10^6 m^3 annual), school (6.2 × 10^6 m^3 annual), and health sectors (2.9 × 10^6 m^3 annual) (Figure 6).

Two datasets are compared were: Base year (blue color); Projected year (orange color)

The figure above compares total water demand from the 2022 baseline to projections for 2052. Demand is expected to rise from 51.8 × 10^6 m^3 annual in 2022 to over 111 × 10^6 m^3 annual in 2052 with a 53% demand increment. This is driven by population growth, urbanization, agricultural expansion, and industrial development. These trends highlight the need for adaptive management strategies, including wastewater recycling, rainwater harvesting, and improvements in irrigation and industrial efficiency. Infrastructure investment and policy interventions are essential to ensure sustainable water allocation.

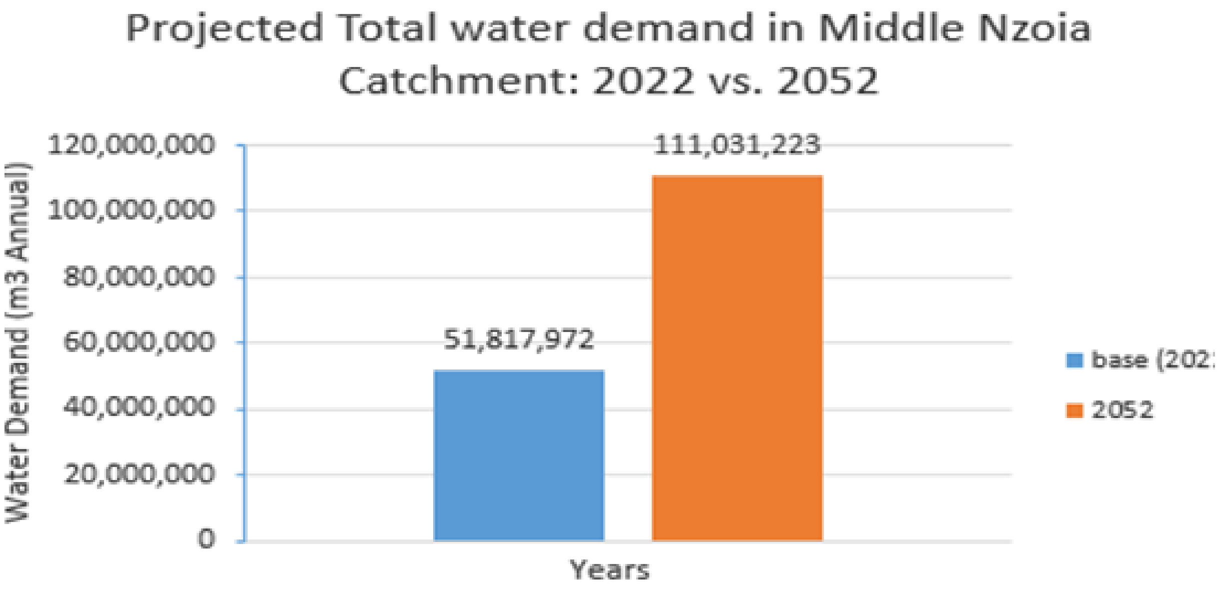
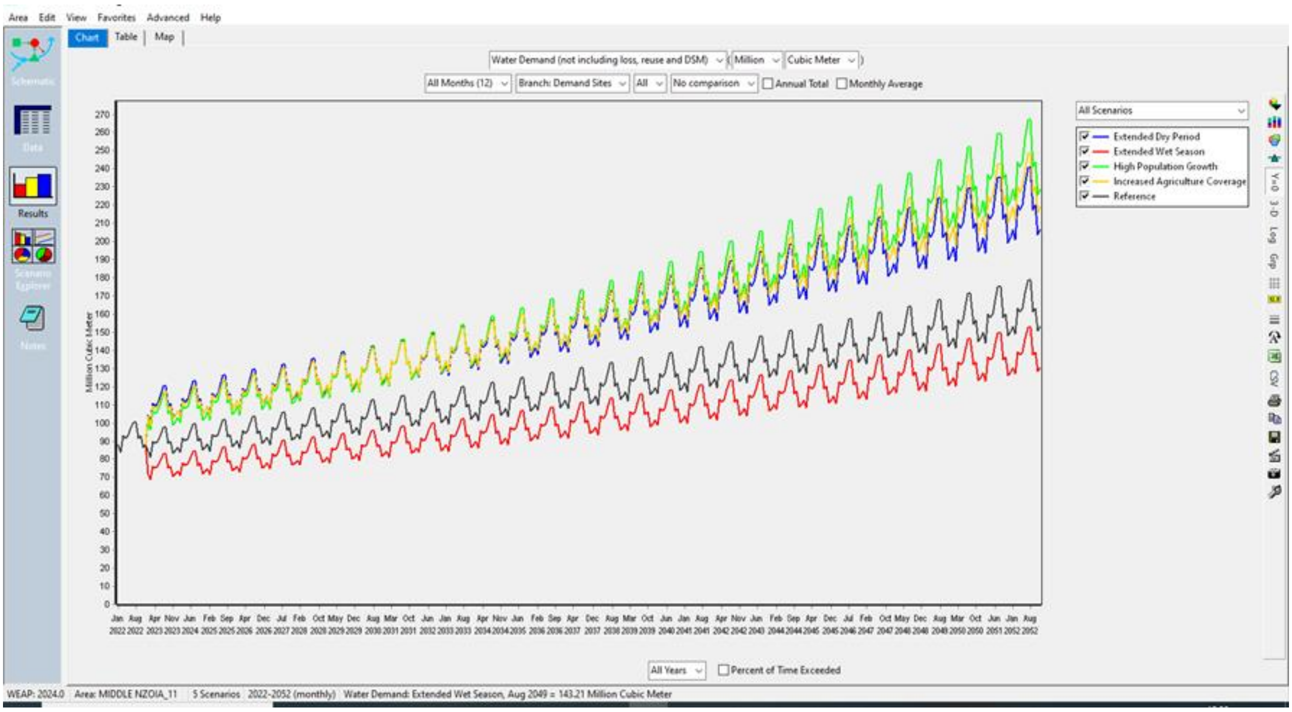


Figure 6 Projected total water demand in the Middle Nzoia Catchment (Source: Researcher (2025))

4.3.3 General water demand projections (2022-2052)

Seasonal and long-term inflow trends under the Reference Scenario between 2022 and 2052 (Figure 7).



Water Demand (not including loss, reuse and DSM) (Million Cubic Meter)

All Months (12) | Branch: Demand Sites | All | No comparison | ☐ Annual Total | ☐ Monthly Average

All Scenarios

☑ Extended Dry Period
☑ Extended Wet Season
☑ High Population Growth
☑ Increased Agriculture Coverage
☑ Reference

All Years | ☐ Percent of Time Exceeded

WEAP: 2024.0 | Area: MIDDLE NZOIA_11 | 5 Scenarios | 2022-2052 (monthly) | Water Demand: Extended Wet Season, Aug 2049 = 143.21 Million Cubic Meter

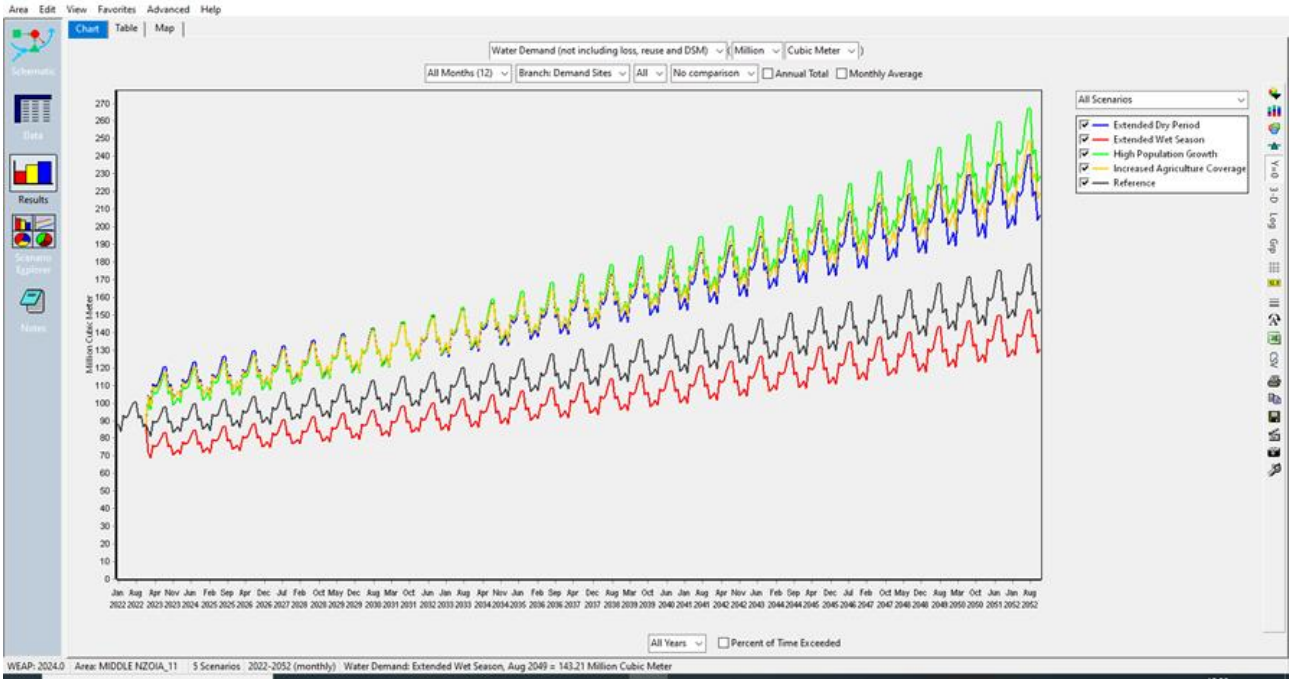
Figure 7 Monthly average inflows under the reference scenario (2022-2052) (Source: Researcher (2025))

Scenario-based analyses reveal varied demand patterns influenced by climate, population, and land use changes. The high population growth scenario shows the greatest increase, with peak demand reaching about 260 × 10^6 m³ to 50% rise over the base average (178 × 10^6 m³) in contrast, the extended wet season scenario shows reduced demand, peaking at around 152 × 10^6 m³ approximately 14% below the base average due to increased rainfall availability, reduced irrigation needs and higher soil moisture storage.

The increased agriculture coverage scenario shows a 39% rise, peaking at 248 × 10^6 m³ aligned with planting and harvesting periods. Among all scenarios, the extended dry period and high population growth show the highest increases in both volume and percentage. The extended wet season records the lowest demand and variability, while the extended dry period scenario shows moderate growth linked.

4.3.4 Domestic and institutional water demand relative to reference Scenario

Projected domestic water demand for high-potential and low-potential areas (Figure 8). Under the reference scenario, demand remains below 32 × 10^6 m³ by the year 2052.



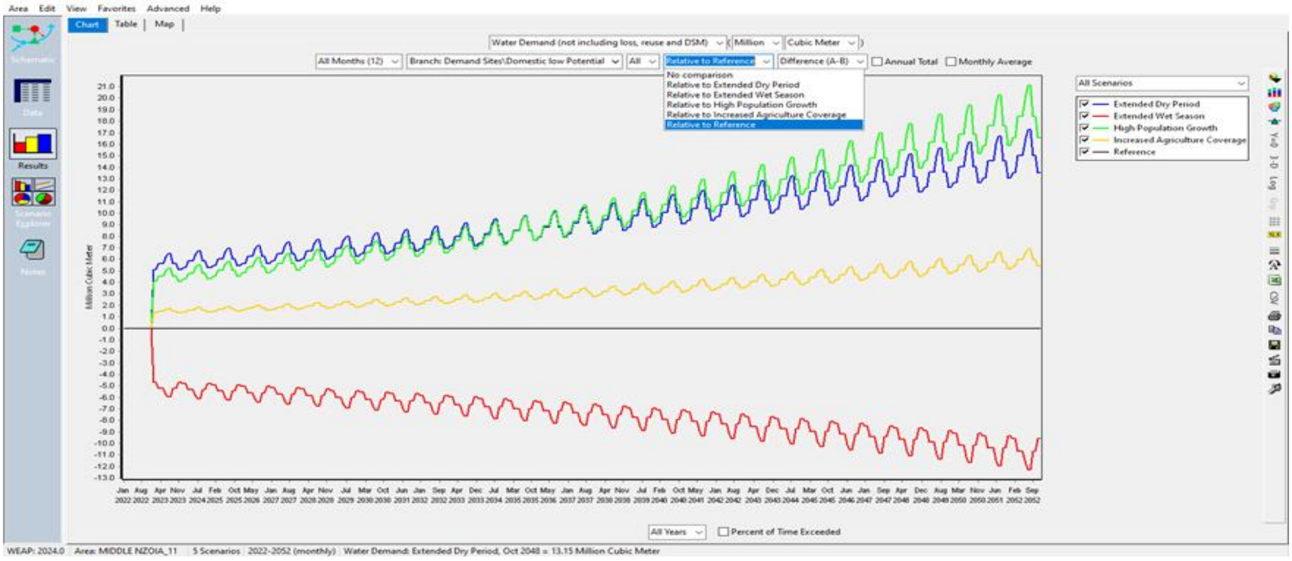
WEAP: 2024.0 Area: MIDDLE NZOIA_11 5 Scenarios 2022-2052 (monthly) Water Demand: Extended Wet Season, Aug 2049 = 143.21 Million Cubic Meter

Figure 8 Domestic water demand in high-potential areas relative to the reference (Source: Researcher (2025))

The above image shows a WEAP system interface with a chart output displaying water demand projections under different scenariosY-axis: Water demand (Million Cubic Meters). X-axis: Time (Years from 2022 to 2052, with monthly resolution). The saw-tooth pattern reflects seasonal variation in water demand (wet vs. dry months), Extended dry period (green): Produces the highest water demand, steadily increasing over time, peaking to 30 × 10^6 m³ by the year 2052. Seasonal spikes are the largest, Extended wet season (blue): Lower than dry period but still significantly higher than baseline, showing the effect of more water use during longer wet conditions, high population growth (yellow): Moderate but steadily increasing demand, reflecting population-driven domestic demand pressures, increased agriculture coverage (red): Shows a small but steady increase in demand compared to the reference, reference (black/near zero line): The baseline case, serving as a comparison point.

Climate factors (dry/wet periods) create the largest deviations in demand compared to population or agriculture changes, extended dry periods strain water demand most severely, likely due to irrigation and domestic supply needs, population growth has a significant long- term impact but less seasonal fluctuation, agricultural expansion adds demand but is relatively smaller in this analysis compared to climate-driven factors (Figure 9).

Reference (black line) - The baseline scenario, extended dry period (red) - Shows decreased demand relative to reference, extended wet season (yellow) – Near-zero difference, suggesting minimal impact, high population growth (green) - Significantly increases demand over time, increased agriculture coverage (blue) - Also shows rising demand, though less than high population growth.



Water Demand (not including loss, reuse and DSM) (Million Cubic Meter)

All Months (12) | Branch: Demand Sites\Domestic low Potential | All | Relative to Reference | Difference (A-B) | ☐ Annual Total | ☐ Monthly Average

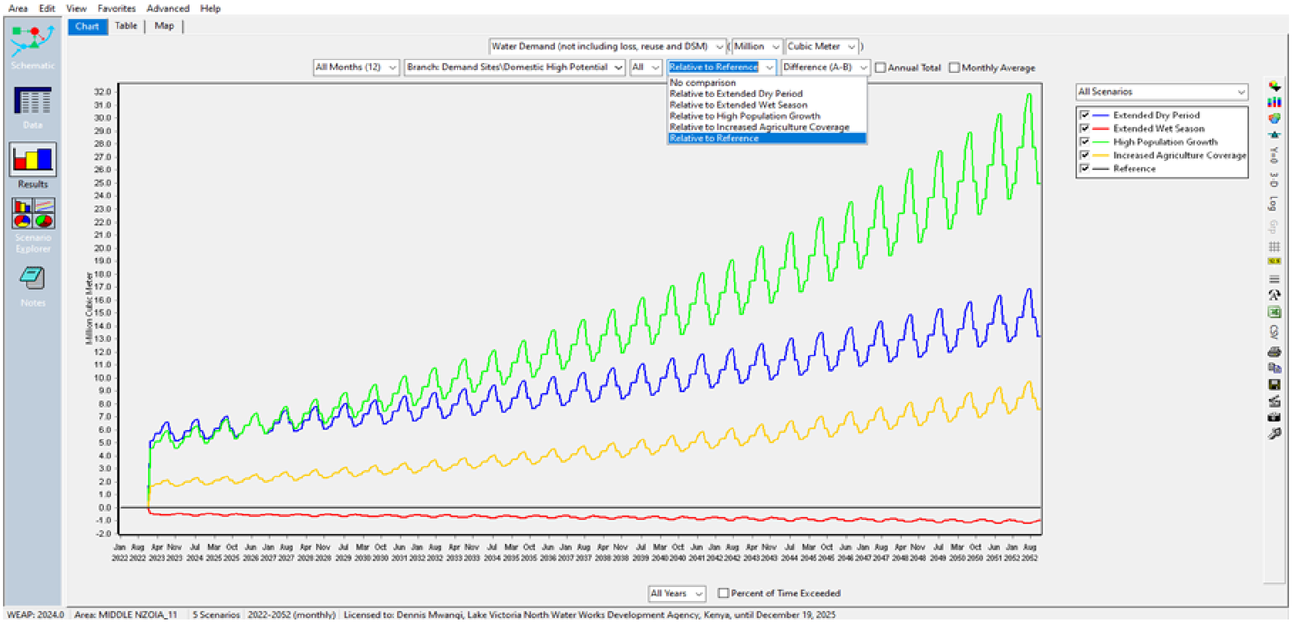
All Years | ☐ Percent of Time Exceeded

WEAP: 2024.0 | Area: MIDDLE NZOIA_11 | 5 Scenarios | 2022-2052 (monthly) | Water Demand: Extended Dry Period, Oct 2048 = 13.15 Million Cubic Meter

Figure 9 Domestic demand in low-potential areas relative to the reference scenario (Source: Researcher (2025))

The reference line is at zero, serving as the baseline, the red line (extended dry period) shows consistently negative values suggesting less water is available/demanded, the green line (high population growth) shows increasing positive deviation from the reference suggesting rising water demand due to population pressure. The blue line (increased agricultural coverage), similar upward trend to green but lower magnitude. The yellow line (extended wet season):

Close to the reference suggesting that wet conditions don't drastically affect domestic demand in high-potential areas, urbanization drives demand above 21 × 10^6 m^3 by the year 2052, requiring expanded infrastructure, efficiency improvements, and alternative water sources (Figure 10).



Water Demand (not including loss, reuse and DSM) (Million Cubic Meter)

All Months (12) | Branch: Demand Sites\Domestic High Potential | All | Relative to Reference | Difference (A-B) | ☐ Annual Total | ☐ Monthly Average

All Years | ☐ Percent of Time Exceeded

WEAP: 2024.0 | Area: MIDDLE NZOIA_11 | 5 Scenarios | 2022-2052 (monthly) | Licensed to: Dennis Mwangi, Lake Victoria North Water Works Development Agency, Kenya, until December 19, 2025

Figure 10 Institutional water demand relative to reference scenario (Source: Researcher (2025))

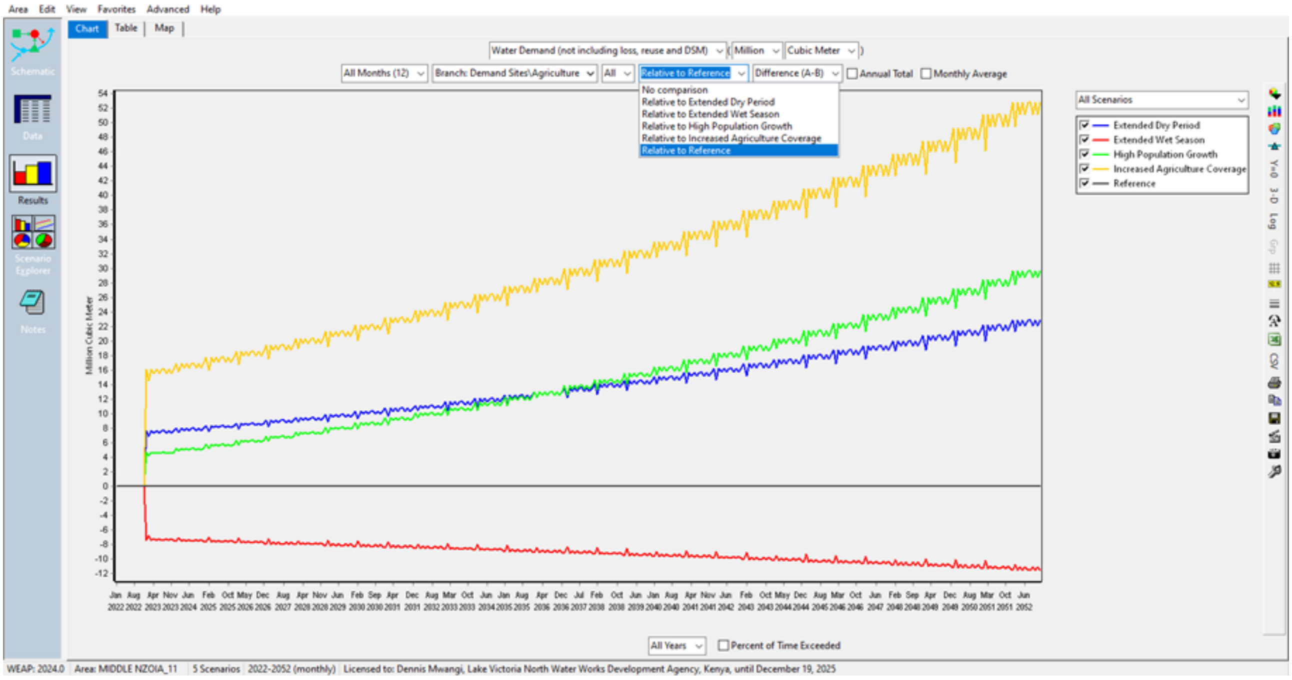
Each line shows how the institutional water demand in a given scenario deviates from the reference scenario. (black line) always at zero since other scenarios are being compared relative to it. High population growth (green line) shows a steady and sharp increase in institutional water demand over time, by the year 2052, demand is almost 4 million cubic meters higher than in the reference scenario. This scenario has the most significant impact on institutional demand. Increased agriculture coverage (blue line) also shows an upward trend, though lower than high population growth, suggesting increased institutional demand potentially due to support systems for agriculture (e.g., administration, irrigation management offices).

The extended wet season (yellow line) is slightly above zero and relatively stable over time. Suggesting minimal impact on institutional water use. Institutional water demand is likely not weather-dependent. The extended dry period (red line) stays below zero, indicating a slight reduction in water demand compared to the reference. This may imply either reduced availability, conservation measures, or lower usage due to reduced service delivery during droughts.

Institutional demand is highly sensitive to population growth but less affected by climate (wet or dry) conditions. The green scenario (high population growth) is a critical scenario to monitor for infrastructure planning. While agricultural expansion does affect institutional water use, its impact is moderate. Climate scenarios have a limited effect on institutional demand, possibly because such demand is more stable and less seasonal. This increase underscores the need for efficient technologies and wastewater reuse to support institutional expansion.

4.3.5 Agricultural and industrial water demand relative to reference scenario

Figure below presents agricultural demand under the increased agriculture coverage scenario. The demand needs increase significantly, especially during dry months. While dry-season shortfalls call for efficient irrigation, improved storage, and adaptive management (Figure 11).



Water Demand (not including loss, reuse and DSM) (Million Cubic Meter)

All Months (12) | Branch: Demand Sites\Agriculture | All | Relative to Reference | Difference (A-B) | ☐ Annual Total | ☐ Monthly Average

All Scenarios

- ☑ Extended Dry Period
- ☑ Extended Wet Season
- ☑ High Population Growth
- ☑ Increased Agriculture Coverage
- ☑ Reference

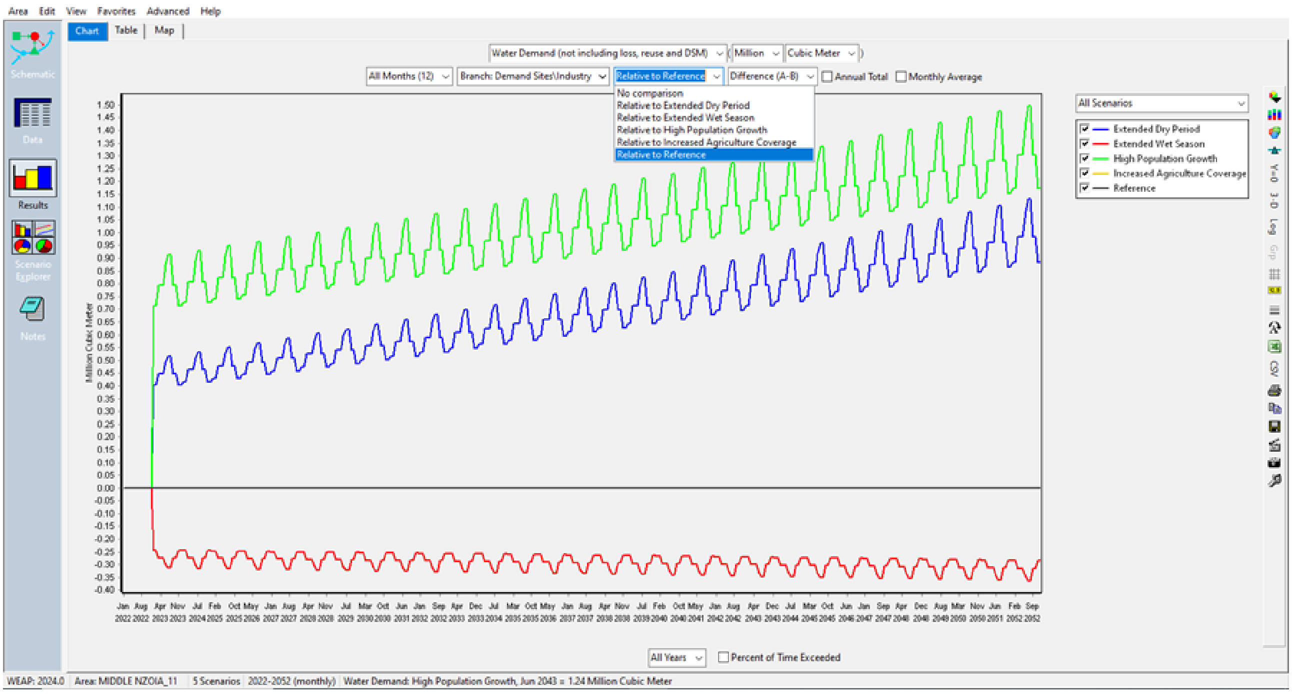
All Years | ☐ Percent of Time Exceeded

WEAP: 2024.0 | Area: MIDDLE NZOIA_11 | 5 Scenarios | 2022-2052 (monthly) | Licensed to: Dennis Mwangi, Lake Victoria North Water Works Development Agency, Kenya, until December 19, 2025

Figure 11 Agricultural water demand relative to reference scenario (Source: Researcher (2025))

Industrial demand, shown in Figure 4.19, rises steadily. The Industrial Growth Scenario surpasses 400 × 106 m^3 by the year 2052, compared to under 304 × 106 m^3 in the reference scenario.

The crisscrossing behavior between the extended dry period and high population growth scenarios is because of water demand composition difference ie. Extended dry Period affects agricultural water demand significantly, while high population growth impacts municipal and industrial demand more. As urban demand becomes more significant (due to exponential population growth), the high population growth scenario overtakes the dry period curve (Figure 12).



WEAP: 2024.0 | Area: MIDDLE NZOIA_11 | 5 Scenarios | 2022-2052 (monthly) | Water Demand: High Population Growth, Jun 2043 = 1.24 Million Cubic Meter

Figure 12 Industrial water demand relative to reference scenario (Source: Researcher (2025))

Industrial water demand relative to the reference scenario is presented in Figure 12. Overall, the results show that industrial water demand increases under both the high population growth and increased agriculture coverage scenarios, although the magnitude of increase differs between them. The high population growth scenario exhibits the greatest positive deviation from the reference scenario and continues to rise throughout the simulation period, indicating that industrial water demand is strongly influenced by demographic expansion and the associated growth in production activities, employment, and service needs. The increased agriculture coverage scenario also shows a positive upward trend, but its effect remains lower than that of population growth, suggesting a more moderate increase in industrial water demand, likely linked to the expansion of agro-processing activities and related infrastructure.

In contrast, the extended dry period scenario remains below the reference scenario over most of the simulation period, indicating reduced industrial water demand under prolonged dry conditions. This may be associated with limited water availability, operational constraints, water conservation measures, or reduced economic activity during drought periods. Seasonal fluctuations are evident across the scenarios; however, the long-term upward trends are more pronounced under the population growth and agricultural expansion scenarios. Overall, these results indicate that industrial water demand in the catchment is more sensitive to demographic and economic change than to seasonal wet conditions, and they highlight the need for improved water-use efficiency, recycling systems, and infrastructure upgrades to support sustainable industrial development.

4.3.6 Comparison between supply requirement, supply delivered, water demand and unmet demand

4.3.6.1 Supply requirement vs. supply delivered

Below is an integrated, technically detailed comparison which illustrates the water supply and demand dynamics in the Middle Nzoia Catchment from 2022 to 2052. This comparison addresses two key metrics: Supply requirement and supply delivered, while reflecting the influence of various scenarios such as high population growth, extended dry period, extended wet season, and increased agricultural coverage (Figure 13).

The left panel of Figure 13. Illustrates the supply requirement, an estimate that includes raw water demand adjusted for transmission losses, water reuse potential, and effects of demand- side management (DSM) interventions. This requirement consistently exceeds the supply delivered, as shown in the Figure 13 right panel.

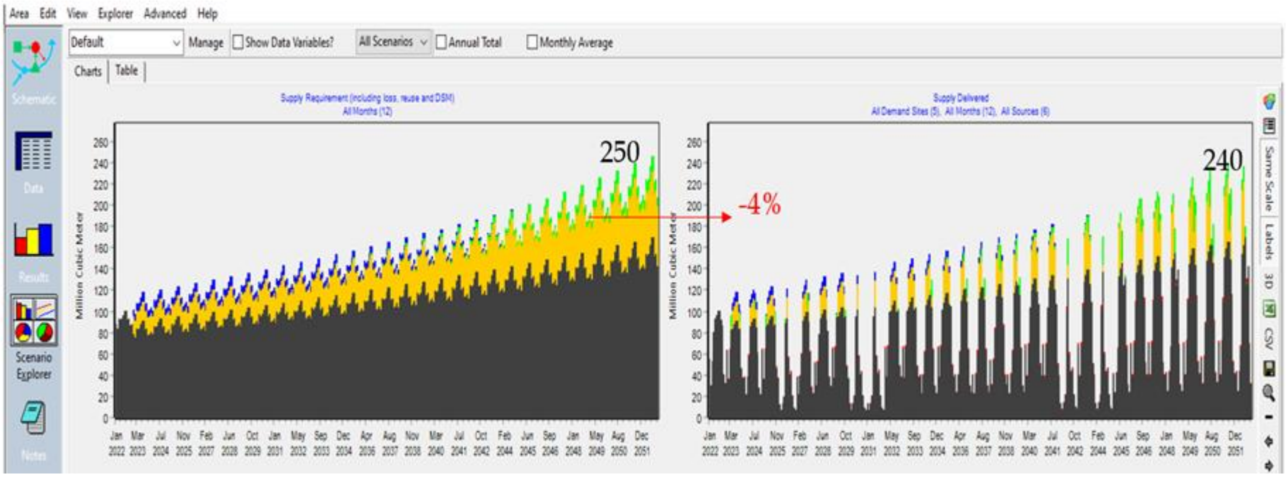


Figure 13 Comparative analysis of water supply and demand in the Middle Nzoia Catchment (2022-2052) (Source: Researcher (2025))

For instance, by the year 2052, the supply requirement was projected to reach approximately 250 × 10^6 m³, whereas the actual delivered supply lags behind at around 240 × 10^6 m³. This persistent supply deficit, averaging 4%, indicates chronic inefficiencies in distribution networks, water treatment capacities, and infrastructure operation.

This observation aligns with findings by Odwori (2021), who identified similar shortfalls in regional water utilities due to aging infrastructure and limited operational capacity.

4.3.6.2 Water demand vs. unmet demand

This comparison addresses two key metrics: water demand, and unmet demand, while reflecting the influence of various scenarios such as high population growth, extended dry period, extended wet season, and increased agricultural coverage (Figure 14).

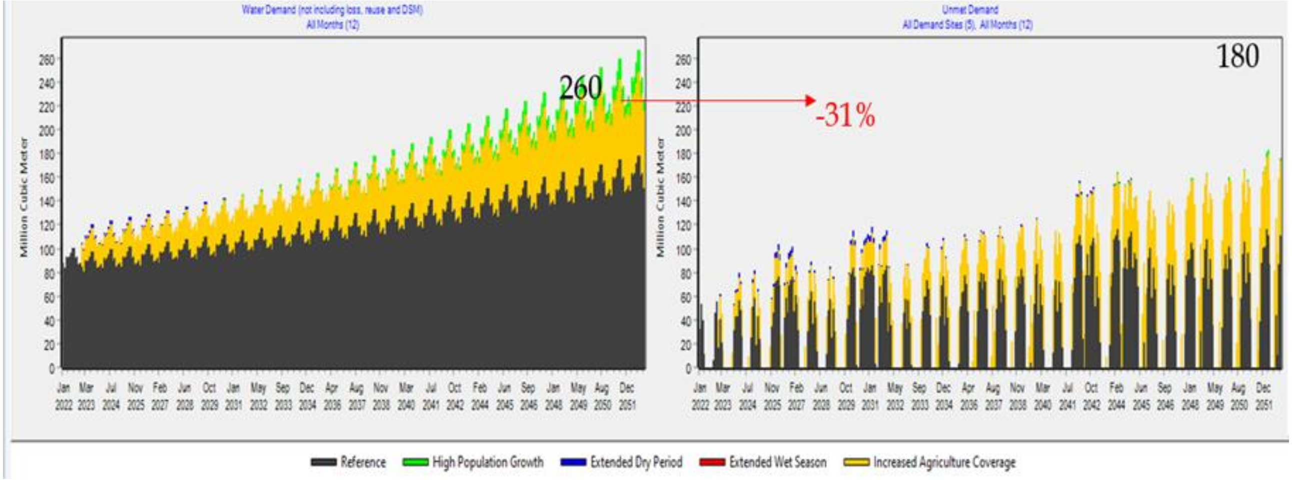


Figure 14 Comparative analysis of water supply and demand in the Middle Nzoia Catchment (2022-2052) (Researcher (2025))

The left panel of Figure 14 captures total water demand, which was projected to rise steadily from about 52 × 10^6 m³ in 2022 to nearly 260 × 10^6 m³ by the year 2052. This increase reflects growing population pressure, industrial expansion, and agricultural intensification.

In contrast, the unmet demand—shown in the lower right panel represents the volume of water required but not supplied. It starts at approximately 20 × 10^6 m³ in 2022 and was projected to climb to about 180 × 10^6 m³ by the year 2052, marking a 28% increase over the study period.

During extreme dry seasons and high-growth scenarios, unmet demand reaches to 31% of total demand on monthly average. These projections are consistent with studies by Odwori (2022) and Odaro, Obiri, and Masika (2025), which attribute rising deficits to climate variability, land use change, and inadequate water infrastructure.

4.3.6.3 Monthly average supply vs. unmet demand (2023-2052)

The monthly average supply delivered for all the demand sites from the year 2023 to the year 2052 reviewed that extended dry period, extended wet period, high population growth, increased agriculture coverage and reference scenario.

4.3.6.4 Supply delivered in all demand sites

The figure below shows the supply delivered in all demand sites, which include industrial demand, domestic demand, agricultural demand, commercial demand and institution demand. Subjected to; Extended dry period scenario, extended wet season scenario, high population growth scenario, increased agriculture coverage and the reference scenario (2023-2052).

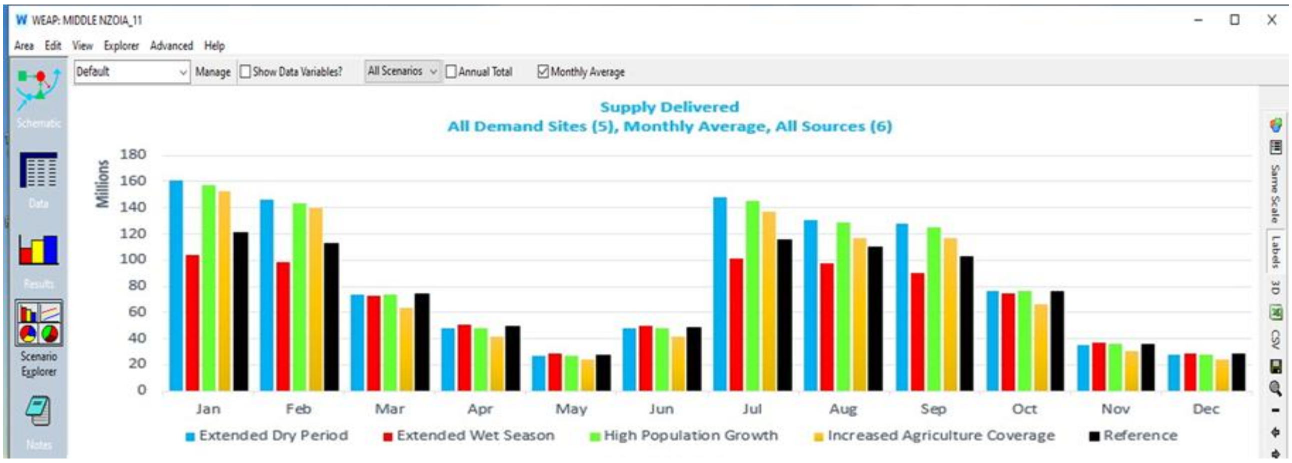


Figure 15 Supply delivered in all demand sites (Source: Researcher (2025))

January and February: Highest supply across all scenarios, particularly under the extended dry period and high population growth scenarios (160 × 10^6 m^3), March to May: Significant decline in supply across all scenarios, with May having the lowest supply (20 × 10^6 m^3 to 30 × 10^6 m^3). June and July: Gradual recovery begins; July sees a major rise again, especially under the extended dry period and high population growth. August and September: Supply remains relatively high but slightly lower than the January-February peak. October to December: Declining trend again, reaching minimal levels by November and December (20 x 10^6 m^3).

Supply delivery is highest at the start and middle of the year and lowest during late spring and end-year months. Extended dry period and high population growth scenarios often show higher supply deliveries, while extended wet season tends to have lower deliveries across most months.

4.3.6.5 Unmet demand in all demand site

The figure below shows the monthly average unmet water demand (in millions) for five demand sites under five different scenarios.

January-February very low unmet demand across all scenarios, almost negligible. March-June (Peak unmet demand period): Significant increase in unmet demand, peaking in April and May. The extended dry period and increased agriculture coverage have the highest unmet demand (110 × 10^6 m^3 to 115 × 10^6 m^3). Extended wet season consistently has the lowest unmet demand during this period. July-September: Notable drop in unmet demand across all scenarios. Still, increased agriculture coverage remains relatively higher. October-December: unmet demand rises again, peaking in December. High Population Growth and increased agriculture coverage show the highest unmet demand (120 × 10^6 m^3). Extended wet season has significantly lower unmet demand than others.

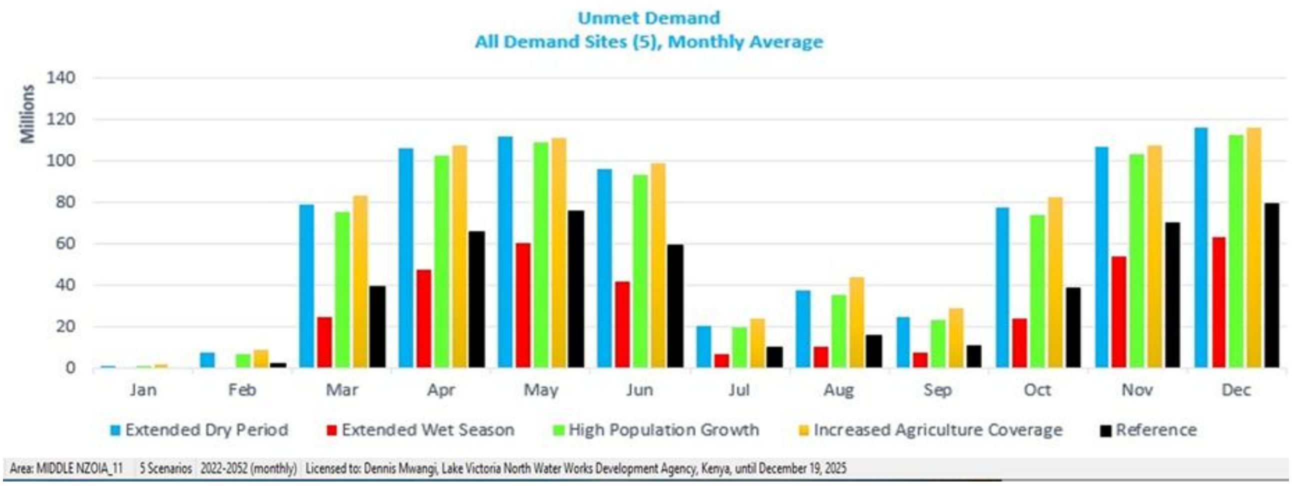


Figure 16 Unmet demand in all demand sites (Source: Researcher (2025))

5 Conclusion

Scenario simulations for the period 2023-2052 under varying assumptions (high population growth, extended dry season, extended wet season, and increased agricultural coverage) indicate a substantial rise in water demand, with projections exceeding 260 × 10^6 m^3 annual by the year 2052. Scenarios combining population growth and climate stress the unmet demand, the volume of water required but not supplied started at approximately 20 × 10^6 m^3 in 2022 and was projected to climb to about 180 × 10^6 m^3 by the year 2052, marking a 28% increase over the study period. During extreme dry seasons and high-growth scenarios, unmet demand reaches to 31% of total demand. This underscores the vulnerability of the catchment to both demographic and climatic drivers, and highlights the need for integrated planning and water-efficient technologies.

The total water demand, which was projected to rise steadily from about 52 × 10^6 m^3 in 2022 to nearly 260 × 10^6 m^3 by the year 2052. This increase reflects growing population pressure, industrial expansion, and agricultural intensification.

The catchment has an estimated allocable surface water potential of 240 × 10^6 m^3 annual, factoring in ecological flow requirements and infrastructure limitations. However, this potential is unevenly distributed and seasonally variable. Current allocation patterns disproportionately favor industrial and agricultural sectors, while essential domestic and institutional uses are under-prioritized. Without reforms, projected future demand will exceed sustainable supply. Therefore, equitable allocation mechanisms, demand management strategies, and resilience-building measures are critical for long-term sustainability.

The study advocates for the adoption of Integrated Water Resources Management (IWRM) to harmonize water allocation across domestic, agricultural, and industrial sectors. Emphasis should be placed on prioritizing essential water uses, particularly domestic and institutional demands, to ensure equitable access.

Enhancement of water storage capacity through construction and rehabilitation of reservoirs and small-scale storage systems is critical to buffer seasonal variability and drought periods. Additionally, promoting water-efficient irrigation techniques can significantly reduce agricultural water consumption while maintaining productivity.

Ecosystem-based management approaches, including catchment reforestation and wetland restoration, are recommended to improve natural water retention and baseflow sustainability. These interventions support both water availability and ecological resilience.

Furthermore, upgrading hydrological monitoring networks and data management systems is essential for real-time water resource assessment and adaptive management. Improved data collection will enhance the accuracy of modeling and decision-making processes.

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Conflict of Interest

The authors affirm that this research was conducted without any commercial or financial relationship that could be construed as a potential conflict of interest.

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