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Scenario Analysis of Water Supply and Demand Using WEAP Model: A Case of Yala Catchment, Kenya

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Abstract The counties traversed by Yala River Catchment in Kenya have been constrained by acute shortages of water resources because of the declining stream flows, which is occasioned by environmental changes, increasing population and changing land uses. This study applied Water Evaluation and Planning (WEAP) model to evaluate past trends and simulate current demand scenarios for the purposes of planning by authorities in regard to future use. The study used historical data (1970-2015) to assess water supply and demand in the catchment for the period 2016 to 2045 by simulation. Calibration and validation were each performed on 10-year streamflow datasets (1991-2000 and 2001-2010 respectively), drawn from 4 gauging stations. Simulations were then conducted for the scenarios namely: Reference (at 2.8% growth rate), High Growth (3.2%), High Growth (3.5%), and Moderated Growth (2.2%). The categories of water demand evaluated in WEAP included: Domestic-Institutional-Municipal, Agriculture, and Industry uses. In a 5-year time-step, WEAP demonstrated resultant increase in water demand for year 2020 by 7.46% from 2016 at Reference Scenario. WEAP further simulated a gradual increase in water demand during subsequent years. This trend would continue for the rest of the scenarios but with variations occasioned by adjustment of variables in WEAP such as population growth rates, monthly variations, annual activity levels, water use rates, water losses and reuse rates, industrial production units, agricultural acreages, and varied demand sites. In conclusion, there were demonstrated substantial increases in water demands within individual scenarios between 2016 to 2045, but these increases were significantly different scenario-by-scenario. The study recommends that supply and demand measures be employed with the aim of regulating activity levels, losses and consumptions so as to meet demands in case any of the studied scenarios would be applicable.

Keywords: *scenario analysis, water supply and demand, WEAP model, Yala catchment*

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1. Introduction

Yala Catchment is one of the several trans-national river basins in Kenya, releasing water into Lake Victoria. River Yala flows for a distance of 212 km before draining into Lake Victoria [1]. It has a gross catchment of 3,262 km^2 with an average annual flow of 30 m^3/sec. The Yala River Basin entails a catchment that traverses Nandi, Kakamega, Vihiga, and Siaya counties of the Kenyan western administrative region. There has been an accelerating growth of water consumption plus gradually deteriorating quantities water resource in the catchment. This has intensified unfair distribution of water resources, lack of proper management, hydropolitical tensions, unfeasible plans and unhealthy competitions within communities and across county trans-boundaries [2] (Figure 1).

The total water use by domestic and municipal sectors in the Yala Basin during the last decades is estimated to be 533.3 Mm^3/y [3]. Out of this, an estimated 32.3 Mm^3/y was being abstracted, treated and used for municipal, domestic, livestock, irrigation and industrial activities. Within the basin, the average water supply per capita is estimated to be 20 liter per day (l/d) and 50 l/d for rural and urban population respectively. This figure is not the real average of consumption because the losses of water are not considered [4].

There has been the disproportionate state of lack of water-sharing agreements and non-consolidation of planning and management frameworks among communities in the river network. This situation called for scenario analysis, which is a water planning and allocation attribute.

According to Mayol [5], scenario analysis is central to the management of water resources and has been conducted in several studies using a number of decision support systems. Several water resources-based models have been put to use in a number of studies with the aim of analyzing the water resources planning problems [6]. Examples of such models include AQUATOOL, MODSIM, MULti-sectoral and Integrated and Operational Decision Support System (MULINO – DSS). Others included River Basin Simulation Model (RIBASIM), Water Balance Model (WBalMo), and MIKE Basin [7,8]. However, these models have not been able to match the Water Evaluation and Planning (WEAP) model, which has been identified as a Decision Support Systems with capabilities of creating inclusive and integrated picture of water supply sources and uses through scenario analysis [8].

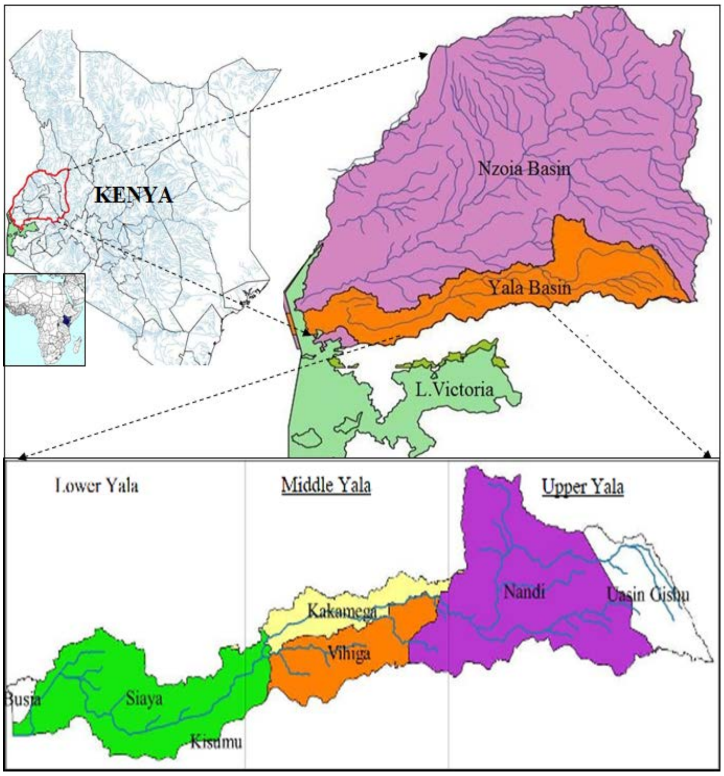

Figure 1. Kenyan River Basins and delineation for Yala Catchment

Sechi and Sulis [9] established that with WEAP, alternative baseline scenarios can be employed to examine vulnerability of water supplies to different demographic, technological, and climatologically/ hydrological futures. According to Droogers and Boer [10], WEAP exhibits unique approach for conducting assessments for integrated water resources planning and management. The tool's transparent structure makes possible the engagement of a multiplicity of stakeholders in a flexible process; its database has been found to be able to maintain information on water supply and demand [10].

Studies have confirmed that with the aid of scenario analysis, the WEAP can impel mass balance within a link-node architecture; and that it is able to calculate parameters such as water demand, supply, runoff, infiltration, crop requirements, flows, storage, pollution generation, treatment, discharge and in-stream water quality under a variety of policy and hydrologic scenarios [8,11,12,13,14].

The current study used the best available data on water supply, distribution and consumption in Yala River Catchment and applied them in WEAP model as base-line scenario (Current Accounts). The scenarios presented options that were projected for future water demand in Yala Catchment for the period 2016 to 2045. The scenarios presented assumptions and expected increases in the various indicators, and formed the core of the WEAP model. The remaining parts of this article are organized as material and methods, results and discussion, conclusion and recommendations and a list of references. The next section is material and methods.

2. Material and Methods

Population data for 2009 with projections for 2015 was obtained from Kenya Central Bureau of Statistics for the purpose of establishing water demand. This data was categorized by divisions, locations and sub-locations; and also by user categories [domestic (rural & urban), industrial, livestock, agriculture].

The per-capita water demand for the various demand categories were based on the Kenya's Ministry of Water and Irrigation Design Manual. Streamflow data was obtained from Water Resources Management Authority (WARMA) – the Western Kenya Sub-Regional Office for the years 1970-2015. A portion of this data was used for calibration (1990-2000) and validation (2001-2010) at control (gauging) stations (Edzawa, Yala, Zaaba and Mokong River headflows). Streamflow data was also used to select the appropriate year for simulation start up - current accounts scenario (the year 2015).

The gauging stations identified for this study were those from which tributaries joined main River Yala towards downstream counties from upstream catchment. They were: (i) 1FG03 (Kadenge), (ii) 1FG02 (Bondo), (iii) 1FG01 (Yala Falls), (iv) 1FE01 (Mushamgumbo), (v) 1FC01 (Kimondi) and (vi) 1FE02 (Tindinyo).

When categorized by counties under the study - beginning with upstream to downstream reaches of the Yala catchment, stream gauge measurements for Nandi, Vihiga, Kakamega and Siaya counties were determined by results from the gauge stations the stations 1FG03 (Siaya), 1FE01 (Kakamega), 1FE02 (Nandi) and 1FGFE01 (Vihiga) respectively. WEAP model was used to evaluate and analyze the surface water resources available in Yala Catchment based on the observed river flow levels of the gauging stations. From these stations, river gauging streamflow data was obtained from a monthly record between 1970 to 2015 (45 years).

The study area was defined and its boundary set by adding the vector layer of Yala Basin, which had been prepared using Q-GIS 2.6.1 in the WEAP software system.

A 30-year forecast period was set from 2016, with the last year of the scenario analysis being the year 2045. Monthly average head flow data at gauging stations was entered using the WEAP data tree. Such data included the minimum environmental flow requirement to meet the ecological needs, return flow, stream gauge, and transmission link for demand sites and supply source. Demand sites were entered at the schematic and demand priorities set based on the master plan of Yala River Basin counties plans for purposes of simulating water allocation priorities.

Water demand priorities represented levels of priority for allocation of constrained resources among multiple demand sites. Demand sites were prioritized into 1, 2 and 3 in the WEAP schematic platform, and those with first priorities were considered for supply before subsequent ones. For each demand site, the Annual Activity Level, Annual Water Use Rate and Consumption were entered to assist in calculating the water demand.

Different levels of disaggregation were created for each demand site, for example, (i) Domestic and Municipal Water Demand, (ii) Agriculture Water Demand, (iii) Industrial Water Demand and (iv) Environmental Flow Requirement (Figure 2).

At the WEAP's Data-View platform, water consumption of each demand site on current accounts scenario was calculated by multiplying the overall level of activity by water use rates, based on monthly variation of each demand site.

Reference Scenario (*Ref*) was created and used to incorporate currently identifiable trends in development, water supply availability, water-use efficiency and other aspects. The Reference Scenario was coded as "Reference" (also meant Business-as-usual Scenario) and was outlined based on the continuation of current patterns. This scenario was allocated a 2.8% growth rate based on population growth rate for Kenya.

Scenario I: High Growth Scenario (HG_1) was set to postulate *what-if* there would be High Population Growth (HG) but with Increased Domestic, Institutional and Municipal Demand, with controlled (minimum) Demand Measures. This Scenario was estimated to change demand from a population growth level of 2.8 to 3.2%.

Scenario II: High Growth Scenario (HG_2) was set to postulate *What-if* there would be High Population Growth (HG) but with Increased Domestic, Institutional and Municipal Demand, plus increased Industrial development (in Nandi, Vihiga, Kakamega and Siaya counties). This Scenario was estimated to change demand from the level of 2.8-3.5%.

Scenario III: Moderated Growth Scenario (MG_3) was set to postulate *What-if* there would be a Normal Population Growth (NG) but with Integrated (moderated) measures and controls of Supply & Demand. For instance, improvement of abstraction and storages along the Yala River and demand controls such as water saving initiatives and reduction of Un-Accounted-for Water. This Scenario was estimated to change demand at the level of 2.2% down from the rate of 2.8% given these assumptions.

Scenario IV: Normal Growth Scenario (NG_4) was set to postulate *What-if* there would be an expansion of irrigated Agricultural Acreage by 1.5% due to Consolidated Population Increase for the period in focus. The model was also developed with user-defined Key Assumptions that were added as new branches to the Data View Tree so as to guide scenario changes. The Key Assumptions developed were: (a) Monthly Variations for Domestic, Municipal, Agricultural, Industrial and Commercial aspects.

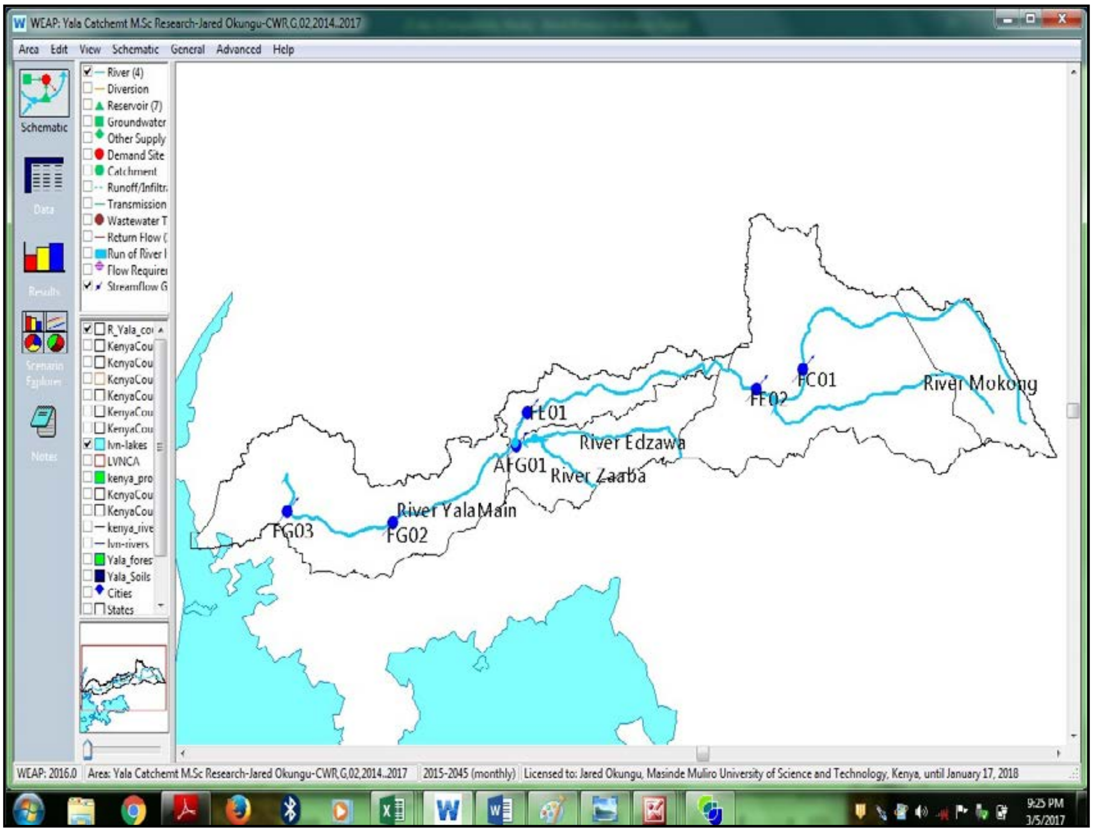

Figure 2. WEAP Schematic View of Demand sites in Yala catchment

The model was run for each scenario for the periods 2026-2045 and results recorded graphically for comparison purposes.

3. Results and Discussion

3.1. Current Accounts Scenario

In Figure 3, there was an observed demonstration of good calibration and validation performance of the WEAP model at significant correlations (r=0.85 to 0.95). Results demonstrate that the catchment outflow was the highest at Kadenge (FG03) and Bondo (FG02) at their downstream ends, followed distantly by Yala Falls (FG01), Mushamgumbo (FE01), Tindinyo (FE02) and Kimondi (FC01) on the upstream end of the catchment. This occurred between the years 1970 to 2015 across all the gauging stations.

Results further depict highest flows during the year 1978-79 and particularly year 1994. Lowest flows were experienced in the years 1980, 1985, 1987, 1997, 2000 and 2013 across all the gauging stations. The rest of the years experienced moderate flows across all the gauging stations. These results are indicated in Figure 3.

Results also show that under Current Accounts Scenario stream flow relative to gauges in Yala Catchment over the period under forecast between 2016 and 2045, exhibit higher flows in River Yala in the years 2016, 2019, 2023, 2020, 2026, 2027, 2029, 2030, 2037 and 2038 as detailed by Figure 4. The year 2027 is simulated to stand out with the highest flow compared to the rest of the years.

As illustrated in Figure 5, results demonstrated increase in water demands without following the orders of scenarios because conditions set under each scenario varied.

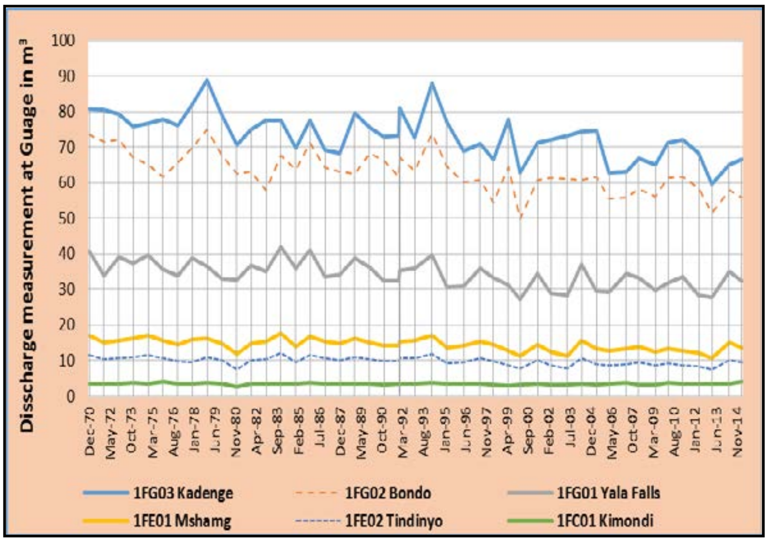

Figure 3. Graph showing yearly relationship from the six river gauging stations in Yala Catchment for the period 1970 - 2015

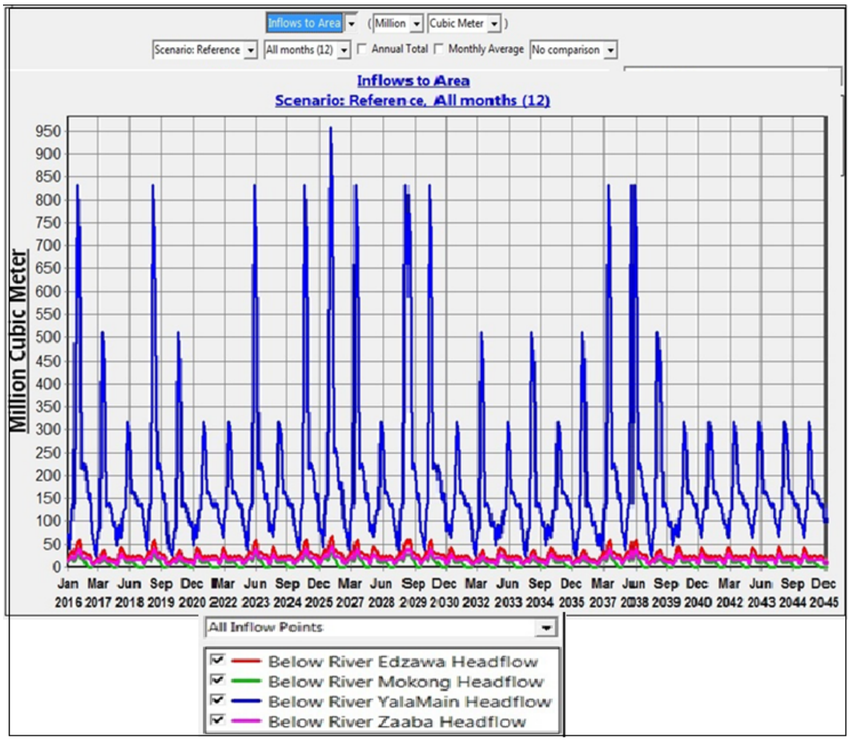

Figure 4. Streamflow under current Scenario relative to gauges in Yala Catchment Area

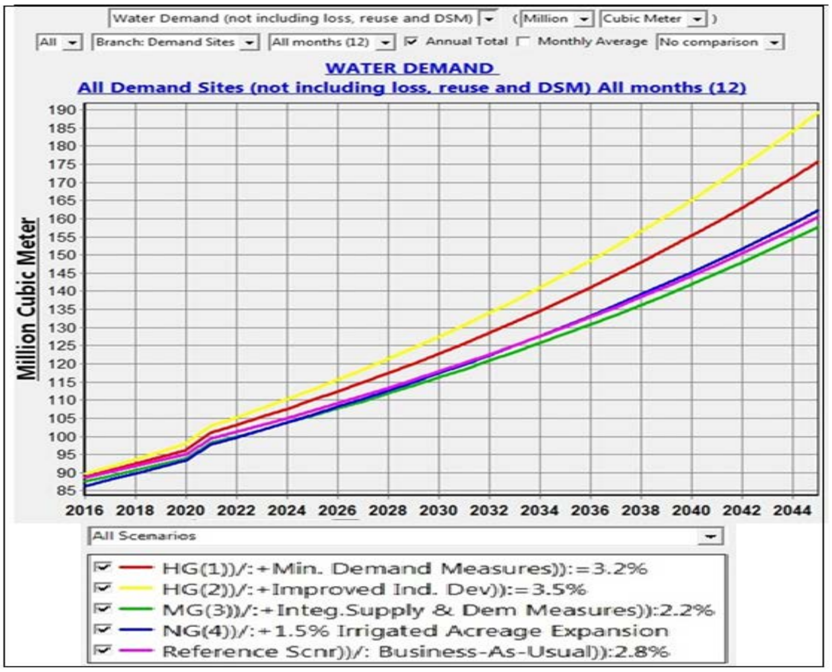

Figure 5. Progression of the Water Demand scenarios at in Yala River Catchment

Figure 5 illustrates that Scenario II [High Growth Scenario (HG_2)] with a focused demand increase from 2.8-3.5% and related conditions would require the highest amount of water from the entire catchment for the forecast period 2016-2045. This would be followed by Scenario I as Scenario IV and reference scenario would require almost similar water quantities, although Scenario IV would bypass Reference Scenario in water demanded in the year 2033. Scenario III would require least water demand due to control measures that were input in the WEAP for simulation.

3.2. Reference Scenario

Under Reference Scenario, for a five-year time step, WEAP simulated that in the year 2020, water demand would increase by 7.46% from previous year (2016) as at Reference Scenario. When similar comparison was made for the years 2025, 2030, 2035 and 2045, simulation demonstrated an increasing demand of 12.51%, 10.09%, 10.44%, 10.91% and 10.91% respectively for the reference scenario (Table 1). The sharp increase was witnessed from year 2022 because of the simulated pick-up of industrial demand for Siaya and Kakamega counties, which were dormant until the year 2021.

Table 1. Increasing water demand under Reference Scenario across entire Yala Catchment

YEAR	Water Demand (Mm^3) for Reference Scenario	% increase from previous year
Y2016	88.5	
Y2020	95.1	7.46%
Y2025	107.0	12.51%
Y2030	117.8	10.09%
Y2035	130.1	10.44%
Y2040	144.3	10.91%
Y2045	160.6	11.30%

A comparison of demand trends between the year 2016 and 2045 was observed to vary across the four counties in Yala Catchment. This is because of their variabilities in population, water use rates and future projections such as industrial growth.

As illustrated in Figure 6, Nandi County requires less streamflow quantities at 12.1Mm^3 and 23.1 Mm^3 of water respectively, in the years 2016 and 2045, with an increasing trend in between the years. This is an average of 13.7% of the total water that would be demanded. Kakamega County would follow with 21.7% of the total water demand, Vihiga county (26.9%) and Siaya county (37.7%).

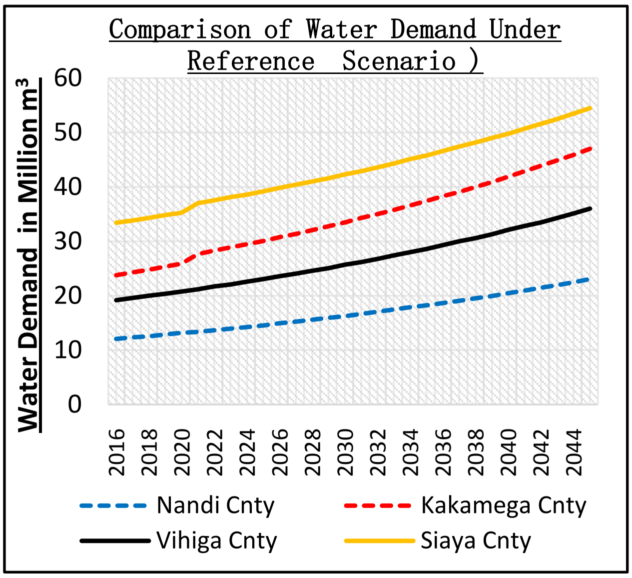

Figure 6. Water Demand under Referece Scenarios for counties across Yala Catchment.

These percentages were simulated as such in relation to population and water use rates from various demand categories.

Scenario I: High Growth Scenario (3.2%) with Minimal Demand Measures

In the year 2016, water demand under this scenario was simulated to depict a 0.34% increase from Reference Scenario. In a five-year time step, this progressed to 1.37%, 2.90%, 4.24%, 5.92%, 7.55% and 9.46% from the years 2020, 2025, 2030, 2035, 2040 and 2045 respectively. The observed increase in demand quantities bore the implications of a situation when water would increasingly be scarce as the demand attributes for example, population and consumption rate increase (Table 2).

Table 2. Illustration of increasing water demand under HG_1 (Scenario I) across Yala Catchment

Year	Water Demand in Mm^3 for HG_1 (Scenario I)	Percentage increase from previous year
2016	88.8	0.34%
2020	96.4	1.37%
2025	110.1	2.90%
2030	122.8	4.24%
2035	137.8	5.92%
2040	155.2	7.55%
2045	175.8	9.46%

Scenario II: High Growth Scenario (3.5%) with Improved Industrial Development

Results of simulation against the second scenario - High Growth Scenario with increased Domestic, Institutional and Municipal Demand (Plus Improved Industrial Development) - demonstrate an increase in demand as simulated for the period running from 2016 to 2015, being 1.36% higher than reference scenario at 2016. The water demand under this scenario, compared to the reference scenario was simulated to progress to 3.15% for the year 2020, 2025 (5.61%), 2030 (8.23%), 2035 (11.22%), 2040 (14.48%) and 2045 (17.87%). These results indicate a situation whereby uncontrolled population and consumption rates, together would hamper development as water resources do not increase in quantities, but rather reduce because of activities leading to depletion.

Scenario III: Moderated Growth Scenario (2.2%) with Integrated Supply and Demand Measures

Simulation results of the third scenario - Controlled with Integrated Supply and Demand Measures - revealed a decline in demand for the period running from 2016 to 2045, being 1.13% lower that demand at reference scenario in 2016. A similar comparison simulated for years running to 2045 reveals further reduction for 2020 (1.16%), 2025 (1.40%), 2030 (1.44%), 2035 (1.46%), 2040 (1.66%) and 2045 (1.87%).

However, the trends for years 2016-2045 increased with a similar trend as reference scenario. As such, Nandi County would pick up water demand at 11.1 Mm^3, Vihiga (23.8 Mm^3), Kakamega (19.2 Mm^3) and Siaya (33.4 Mm^3).

The moderated growth scenario depicts a situation in which implementation of possible environmental conservation measures and sensitization for responsible utilization of water resources would enhance equitable sharing of water resources.

Scenario IV: Normal Growth Scenario with 1.5% Annual Irrigated Acreage Expansion

Simulation results of this scenario (Irrigated Agriculture Acreage Expansion) suggest an increased demand for the period running from 2016 to 2045 compared to the reference scenario as follows: 2016 (0.11%), 2020 (0.42%), 2025 (0.42%), 2030 (0.85%), 2035 (1.00%), 2040 (1.59%) and 2045 (2.68%).

Figure 7 illustrates simulated trends of Water Demand for all the four scenarios in comparison to Reference Scenario in Yala Catchment.

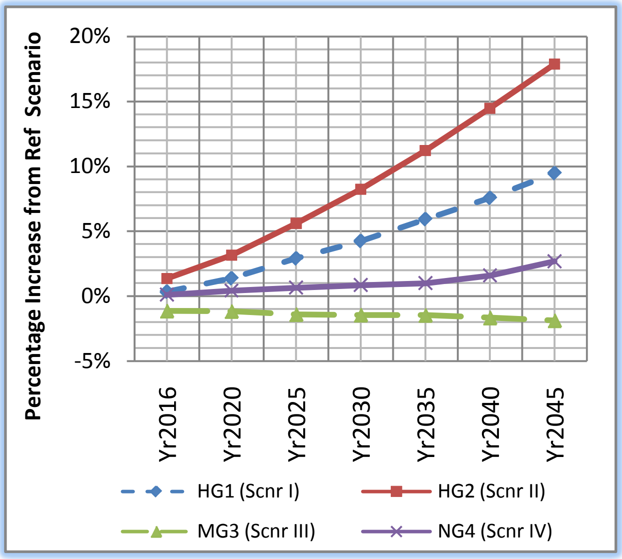

Figure 7. Simulated trends of Water Demand for all scenarios in comparison to Refernce Scenario in Yala Catchment.

For the period (2016-2045), in general, all scenarios simulated by WEAP demonstrated substantial increases in water that would be demanded between the years 2016 and 2045. However, water that would be demanded for Agriculture use category would remain constant throughout the years across all scenarios given the fact that population pressures may not enhance expansion on acreage expansions. However, in the case of scenario IV, which was tested for a 1.5%, irrigated agriculture acreage expansion, there would be a considerable increase across the counties, but this would depend on a number of demand parameters.

Though quite low, the Industrial Demand category occasioned substantial deviation pattern when WEAP was instructed to begin taking up water for this category of demand from Siaya and Kakamega in 2021, a much later year (after 5 years of non-activity). This was considered so because in the Current Accounts Scenario, there had been no manufacturing plant within Yala Catchment in the two counties.

High Growth Scenario-at-3.5% with increased industrial expansion was simulated by WEAP to expect the highest amount of water demand. This was followed by High Growth scenario at 3.2%. The Moderated Growth Scenario at 2.2% (with Integrated Supply and Demand measures) was observed to pick the lowest water that would be demanded across the forecast period. However this observation was slightly lower than the results for the Reference Scenario.

4. Conclusion and Recommendations

From the exploration of spatial and temporal distribution of available stream water in Yala Catchment, it can be concluded that high flows for the years 2016, 2019, 2023, 2026 would be due to flood regimes. The results of increasing demands as years progress imply a call for carefully considered supply and demand measures for the purpose of regulating activity levels, losses and consumptions. This would significantly aid satisfaction of water demand categories and demand sites in watersheds of similar nature as the studied Yala Catchment.

Acknowledgements

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