OPTIMAL WATER ALLOCATION MODEL FOR SUSTAINABLE PLANNING APPROACH IN YALA CATCHMENT, KENYA

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ABSTRACT: *Yala River in Kenya has experienced divergent water uses across its network, accompanied by the disproportionate state of lack of water-sharing agreements and non-consolidated planning and management frameworks. The catchment comprises four administrative boundaries namely: Nandi and Kakamega at the upstream, and Vihiga and Siaya at the downstream end. All these make up demand blocks that necessitated optimal water allocation for (i) Domestic-Institutional-Municipal Category, (ii) Agriculture Category and (iii) Industry Category. This study evaluated past trends of water use while simulating future water requirement (year 2016 to 2045) as allocation attribute using Water Evaluation and Planning (WEAP) model for purposes of planning and management. Calibration and validation were performed on two 10-year streamflow datasets, drawn from 4 gauging stations. Simulations were then conducted by WEAP for four scenarios namely: Reference (at 2.8% growth rate), High Growth (3.2%), High Growth (3.5%), and Moderated Growth (2.2%). Results indicated that at Reference Scenario, Domestic-Institutional-Municipal demand category would be allocated 66.9%. Agriculture and Industry categories, on the other hand, require 30.3% and 2.8% of the supply requirements respectively – proportionately spread along the simulated period. Water allocation, however, varied across demand sites (counties) depending on priorities of demand categories, and respective scenarios. WEAP allocated greater water quantities to Siaya County for Irrigation compared to other counties because of the large irrigation requirements, which utilize basin irrigation. Kakamega County was allocated relatively more water for Domestic-Institutional-Municipal use due to its higher population demand levels while Nandi and Vihiga counties were allocated relatively more water for industry use because of their active industrial activities compared to the rest of the counties. Due to the eminent water scarcity that was witnessed from the simulated Yala River water against increasing demand, it is recommended that water use from other sources (groundwater, rainwater and floodwater), should be exploited as supplement to the Yala Catchment flows.*

KEYWORDS: Optimal Water Allocation, Water Allocation Model, Sustainable Planning, Yala Catchment

INTRODUCTION

Yala River has experienced divergent water uses across its network, accompanied by the disproportionate state of lack of water-sharing agreements and non-consolidation of planning and management frameworks. With an estimated commutative streamflow volume of 533.3 Mm^3/y, the river travels a distance of 212 km and discharges 1,114 x 10^6 m^3 into Lake Victoria, (Basnyat 2007, NELSAP 2011). The catchment traverses four economic-political trans-boundaries namely Nandi, Kakamega, Vihiga, and Siaya counties. Each of the counties have had own development plans with little consideration of current or future water supply and demand. This threatens future livelihoods and points at eminent poverty levels if no scientific intervention would be attempted.

Within the political boundaries of Yala catchment, the highest population had been recorded in Vihiga County with more than 1 000 persons per square kilometer. Population growth in Vihiga and Kakamega counties was 3.0% while those for Siaya and Nandi counties was 2.8% *(LVBC 2013)*. The increasing population and associated water demand in Yala catchment calls for efficient water use and this had been advocated for with an approach of Integrated Water Resources Management (IWRM). Such an approach has seen various advocacy and policy entities implement projects on water resources with improved levels of efficiency (GWP 2010).

According to Droogers and Boer (2014), various water uses signify the means through which regulations are implemented by sharing water resources among competing users with regard to the environment, economy and social well-being of all. The main purpose of regulating water use is to ensure equitable allocation of the available water resources for various competing needs in a sustainable manner. Mayol (2015) reiterates that water allocation is central to the management of water resources It refers to the rules, and procedures through which access to water is decided for individual or collective use, and in relation to availability.

Weragala (2010) illustrate that several criteria are used to compare forms of water allocation such as: (i) Flexibility in the allocation of supplies; (ii) Security of tenure for established users; (iii) Real opportunity cost of providing the resource is paid by the users; (iv) Predictability of the outcome of the allocation process; (v) Equity of the allocation process; (vi) Political and public acceptability. Wang (2005) reiterates that the concepts of four basic mechanisms for water allocation include user-based allocation, marginal cost pricing, public allocation and water markets allocation.

Application of models to actual systems has enhanced clear understanding of such approaches, and this has always contributed to improved system design, operation, and management. Over the last 30 years, major advances have been witnessed in the ability to model engineering-related ecologic and hydrologic aspects of simple to complex or multipurpose water resource systems (Loucs and Beek 2005).
Various models have been developed to simulate and generate the understanding of aspects of water resources planning and allocation, operation and catchment management. 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 (Sethi, Pandey *et al*. 2015, Stockholm Environment Institute 2015). 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 (Stockholm Environment Institute 2015).

WEAP has been determined to have the capabilities of creating inclusive and integrated picture of various water supply sources and uses (Stockholm Environment Institute 2015). The model is also capable of forecasting future demand, comparing supply and demand, and identifying potential shortages under different scenarios (Mutiga, Mavengano et al. 2010). Using WEAP model, this study determined the quantities of water that should be allocated by policy making and implementing agencies in Yala Catchment.

MATERIAL AND METHODS

The preliminary determination of quantities of water to be allocated was done by establishing the per-capita water demand for a number of demand categories. This was based on county-by-county population data and demand priorities. A 45-year period streamflow data were obtained from Water Resources Management Authority (WARMA) – the Western Kenya Sub-Regional Office – running between 1970 and 2015.

A 10-year data was selected on the basis of consistency (1990-2000) and used for calibration and another set (2001-2010) for validation in WEAP. The data were obtained from previous records of gauging stations recognized as control stations. The gauging stations identified for the 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). The Yala Catchment boundary was created in the WEAP schematic platform (Figure 1) by adding it as vector layer, initially prepared using Q-GIS 2.6.1.

Figure 1: WEAP Schematic View of entire Lake Victoria North catchment

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. For each demand site, the Annual Activity Level, Annual Water Use Rate and Consumption were entered to assist in calculating the water demand. Monthly average head flow data at gauging stations were entered using WEAP data tree. The information entered included the minimum environmental flow requirement to meet the ecological needs; return flow; stream gauge; and transmission link for demand sites and supply source.

Taking the year 2015 as the base year for data simulation off-take, a 30-year forecast period was set from 2016, with the last year of the scenario analysis being the year 2045. 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. 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.

Other than the Reference Scenario, WEAP was run separately through 4 other scenarios. The first Scenario was the High Growth Scenario I, which was set to postulate *what-if* there would be High Population Growth from then normal 2.8 to 3.2% level. The second Scenario, the High Growth Scenario II, was set to postulate *What-if* there would be High Population Growth at the level of 2.8-3.5%. Thirdly, Moderated Growth Scenario III was set to postulate *What-if* there would be a Normal Population Growth (NG) but with Integrated (moderated) measures and controls of Supply & Demand hence reducing growth level to the level of 2.2% down from the rate of 2.8% given these assumptions. Finally the Normal Growth Scenario IV 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.

Water allocation for the simulated period 2016-2045 was conducted in three sets of categories namely: (i) Domestic, Institutional and Municipal Category; (ii) Agricultural Category; and (iii) Industrial Category. County-based approach entailed allocation for Nandi, Vihiga, Kakamega and Siaya counties. Finally, Scenario-based approach entailed allocation in accordance to Reference Scenario, Scenario I, II, III and IV.Results of water allocated to the categories above were retrieved from the WEAP software in the form of graphs and displayed with trends ranging from the year 2016-2045.

RESULTS AND DISCUSSIONS

Calibration results revealed the existence of a good Relationship between monthly observed and monthly simulated streamflow in control stations of Yala catchment, at significant correlations of between r=0.85 and 0.95. Results further demonstrate a divergent share of water within Yala River Catchment across Nandi, Kakamega, Vihiga and Siaya counties in the order of lowest to highest me an flows in terms of maximum, minimum and mean flows (Figure 2).

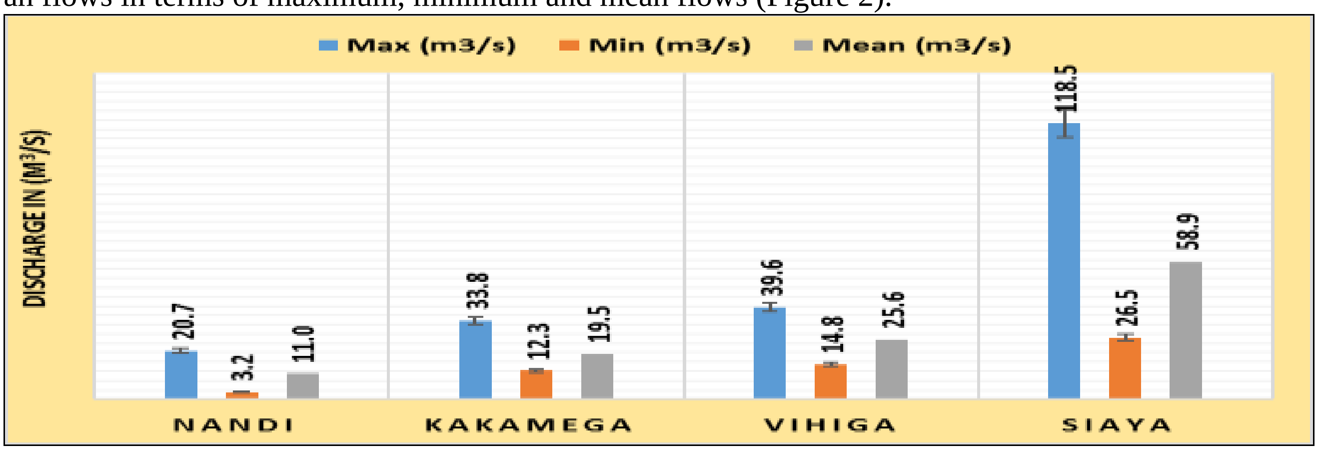

Figure 2: Comparison of Maximum, Minimum and Mean stream flows in Yala Basin across the four counties

Observed headflows indicated low levels at upstream counties (Nandi and Kakamega) and high levels at downstream counties (Vihiga and Siaya). As such, percentage cumulative availability of stream flow across Nandi county was observed to be 9.6%, Kakamega County (16.9%), Vihiga county (22.3%) and Siaya county (51.2%).

Water Allocation for Domestic-Institutional-Municipal Category

Results demonstrate that Domestic, Institutional and Municipal Category of water supply requirements across the entire Yala Catchment require 72.998 Million m^3 of water for Reference Scenario, which is 66.9% of the water supply requirements for Yala River Catchment demand sites as at 2016. During the same year, water supply requirements for other scenarios of this demand category would be 73.14 Million m^3 for HG(1), 73.49 Million m^3 for HG(2) and 72.96 Million m^3 for MG (3). However, NG(4) remained similar to the Reference Scenario at 2016, through to the year 2045. This is because the only change for Scenario IV was simulated for agriculture and not DIM demand category. Trends for DIM categories increase with years from 2016 -2045.

Out of the quantity of water that is required for Domestic, Institutional and Municipal Category of water demand across the entire Yala Catchment (72.998 Million m^3 at Reference Scenario), a total of 23.816 Million m^3 (32.6%) is allocable as supply requirements for to Kakamega County. Other counties that can be allocated water for DIM as follows: Siaya County at 21.503 Million m^3 (29.5%), Nandi County at 10.827 Million m^3 (14.8%) and Vihiga County at 16.85 Million m^3 (23.1%). This trend increases towards the year 2045 but changes with other scenarios as illustrated in *Figure 3*.

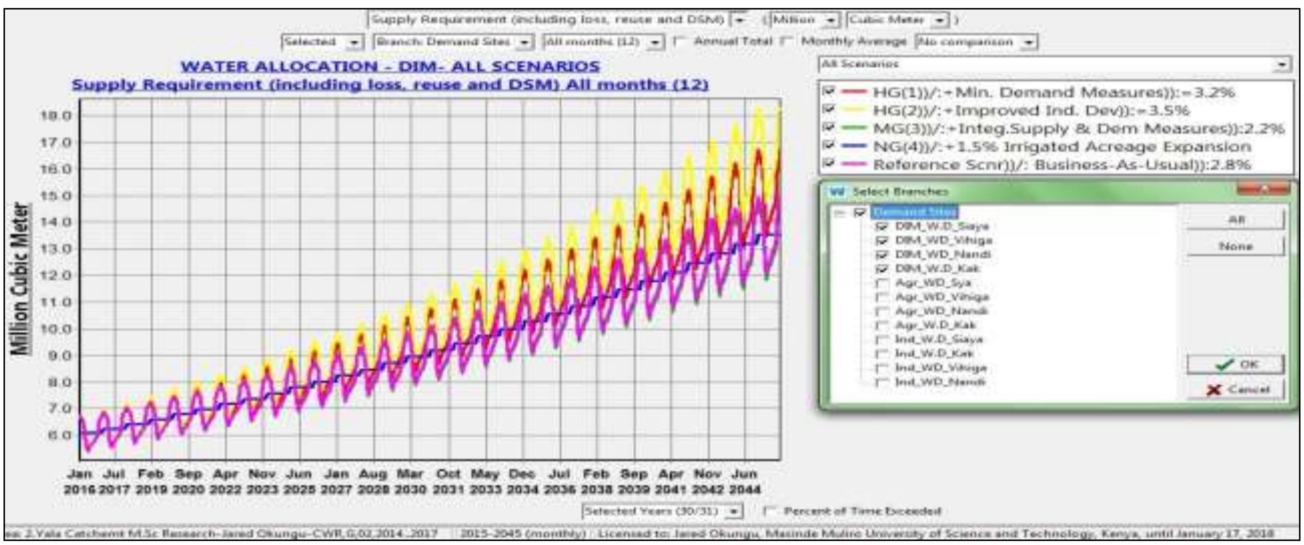

Figure 3: Water allocation for Domestic-Institutional-Municipal demand category from by all Scenarios across All Demand sites in Yala Catchment.

Further water allocation from supply requirements for Reference Scenario by counties have been analyzed and demonstrated relative to Water Allocation for Domestic, Institutional and Municipal Category for then simulated period 2016-2045 (Figure 4).

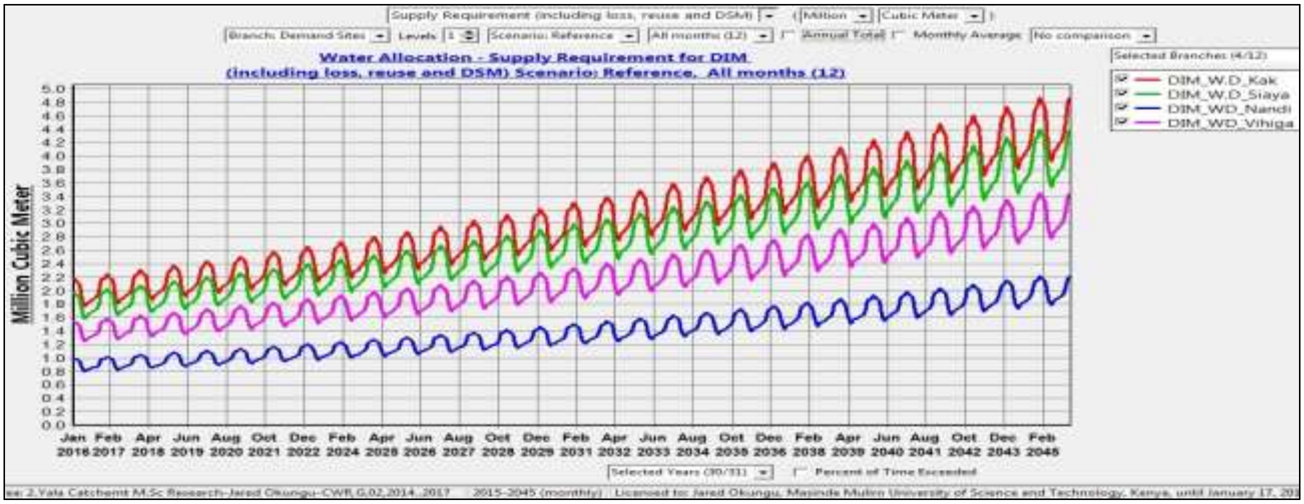

Figure 4: Water allocation for Domestic-Institutional-Municipal demand category from Reference Scenarios across All Demand sites in Yala Catchment.

Water Allocation for Agriculture Category

Simulation results suggest that the Agricultural Category of water supply requirements across Yala Catchment requires 33.025 Million m^3 of water at Reference Scenario. This amounts to 30.3% of the water supply requirements for the catchment's demand sites as at 2016. Results suggest that water supply requirements for agriculture would remain constant for all scenarios except Scenario IV (the case of Irrigated Acreage Expansion by 1.5% per annum). The water allocated for the Scenario IV range from 30.6 Million m^3 in the year 2016 to 31.16 Million m^3 for the year 2020. In a time-step of 3 years, the year 2025 would be allocated 31.86 Million m^3 under the same scenario IV, while the year 2030 would require 32.59 Million m^3 for year 2030, 33.33 Million m^3 for year 2035, 34.08 Million m^3 for year 2040 and 34.86 Million m^3 for the year 2045.

Out of the water supply requirements for Scenario IV in the year 2016, 11.26 Million m^3 (36.8%) is allocable for Siaya County, followed by Vihiga County at 7.71 Million m^3 (25.2%), Kakamega County at 7.5 Million m^3 and Nandi County at 4.13 Million m^3 (13.5%). This continues with an increasing proportionate trend towards the year 2045 as illustrated in *Figure 5.*

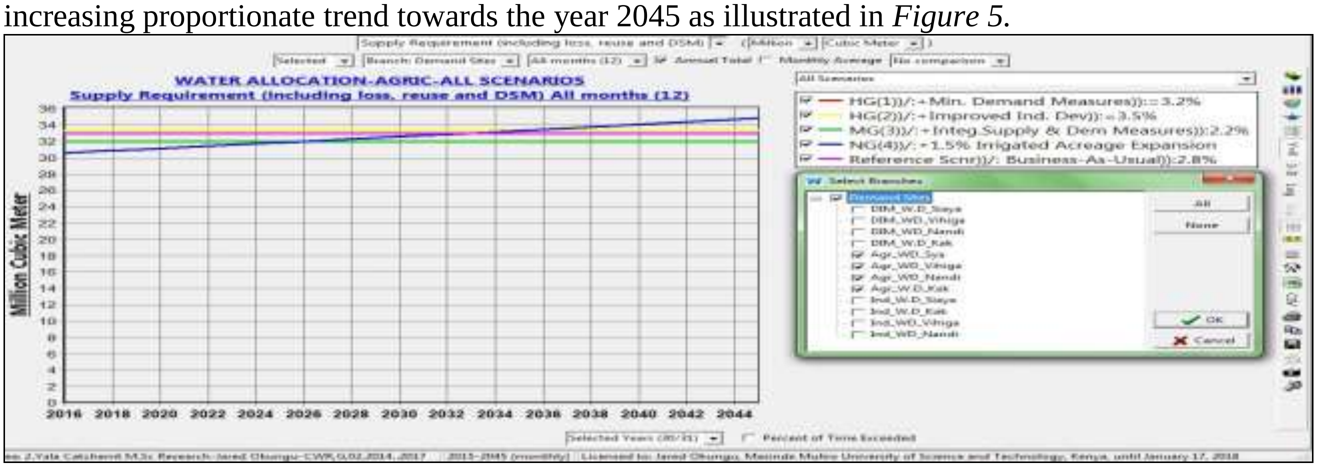

Figure 5: Water allocation for Agriculture Use from Reference Scenario across All Demand sites in Yala Catchment.

Water Allocation for Industry Category

Simulation results demonstrate lower industrial water requirements (allocation) in the Yala Catchment at only 3.103 (2.8%) of the sectoral allocation as at the year 2016 for Reference Scenario. This, however, jumps to 6.24 Million m^3 (5.1%) for the year 2021. The year 2021 was the star up year for expected operationalization and commencement of industrial demands in Siaya and Kakamega Counties - and continue with steady trend to the year 2045. Only two counties (Nandi and Vihiga) had an active production unit inputs from the year 2016 as current accounts situation. The stepped up allocation was simulated to exhibit a steady increase with about 1.0% increase towards the year 2045 as illustrated in *Figure 6.*

Figure 6: Water allocation for Industries from All Scenarios across All Demand sites in Yala Catchment.

At Scenario II, which agitates industrial development characterized by population increase, for instance, water supply requirements predicted an allocation of a total of 3.55 Million m^3 which would only be shared by Nandi and Vihiga Counties at 1.85 and 1.70 Million m^3 respectively, since Kakamega and Siaya counties were simulated to only begin operation in the year 2021. During this year (2021), however, Kakamega and Siaya Counties would pick up 22.7% and 22.8% of the supply requirements respectively, while Nandi and Vihiga Counties would be allocated 28.4% and 26.1% respectively, all running with an increasing trend up to the year 2045 as shown by the pattern in *Figure 7.*

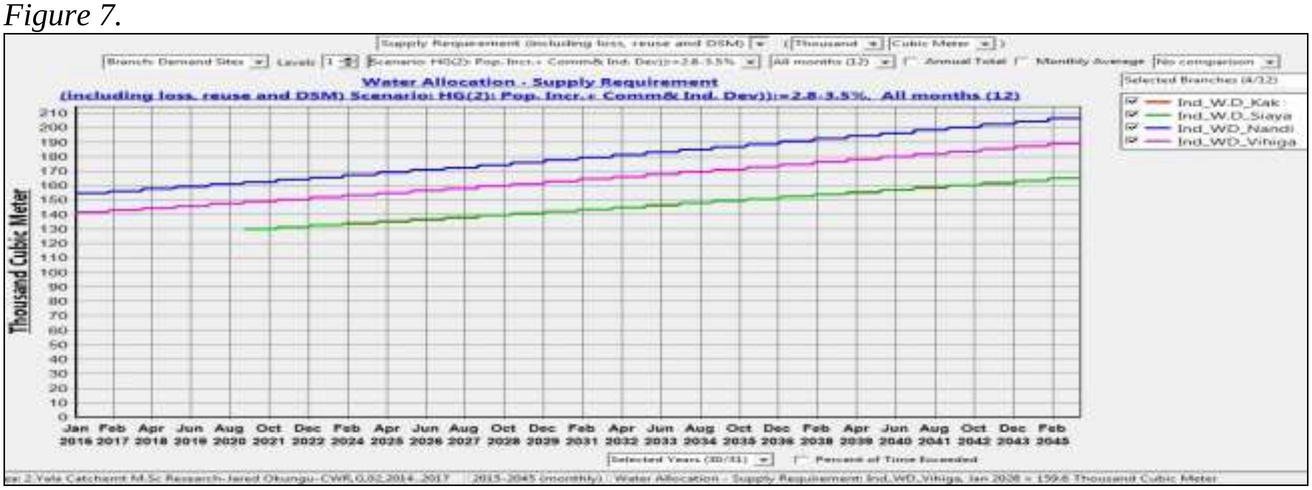

Figure 7: Water allocation for Industries from Scenario II across All Demand sites in Yala Catchment.

In general, all scenarios simulated depicted higher demands with Scenario III depicting lower increase in water demand, followed by Scenario IV and Scenario I. Scenario II was simulated to demand the most qualities of water across all the Yala Catchment. Results are shown in Figure *8*.

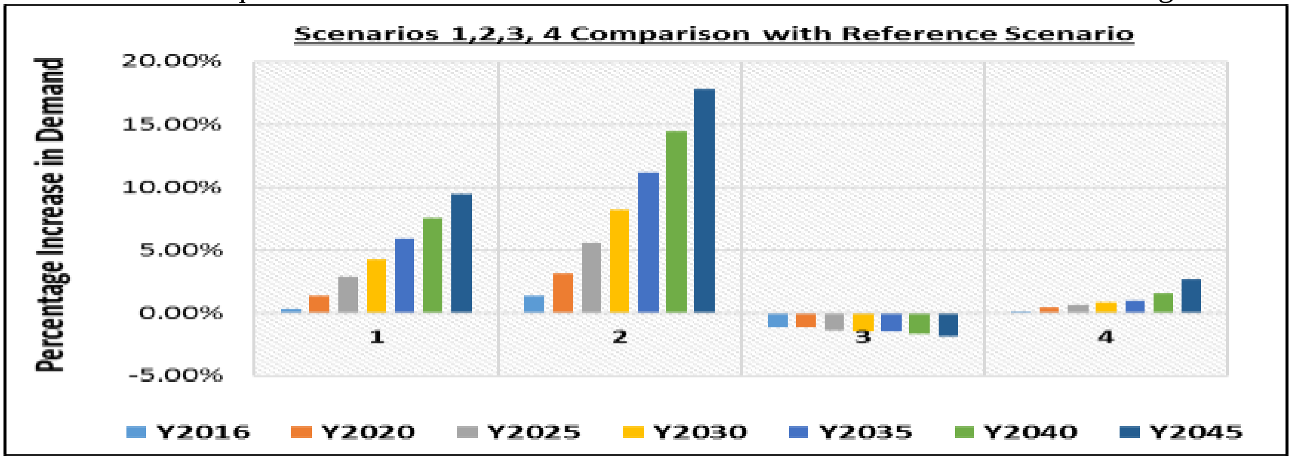

Figure 8: A 5-year progressive comparisn of Water Demand deviations from Reference Scenario, based on different scenarios

CONCLUSION AND RECOMMENDATIONS

WEAP simulated that Domestic, Institutional and Municipal water supply demand category would be allocated 66.9% of the supply requirements from among all demand categories. Agriculture and Industry categories, on the other hand, require 30.3% and 2.8% of the supply requirements respectively - generally spread along the years. These allocation requirements emulated the water demand patterns for various scenarios as previously discussed.

Water allocation, however, varied across demand sites (counties) depending on priorities of demand categories. In view of this, WEAP allocated greater water quantities to Siaya County for Irrigation, compared to other counties because of the large acreage of dominion farms, which use basin irrigation. On the other hand, Kakamega County was allocated relatively more water for Domestic, Institutional and Municipal use due to its high population compared to the rest. Lastly, Nandi and Vihiga were allocated relatively more water for industry use because of their active industrial activities compared to the rest of the counties.

Due to the eminent water scarcity that is witnessed from the simulated Yala River water against increasing demand, it is recommended that water use from other sources (groundwater, rainwater and floodwater), should be exploited as supplement to the Yala Catchment flows.

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REFERENCES

Basnyat, D. B. (2007). Water Resources of Somalia. Technical Report. Nairobi, Kenya, FAO-SWALIM.

Droogers, P. and F. Boer (2014). Water Allocation Models for the Umbeluzi River Basin, Mozambique. Netherlands, Wageningen. 132.

GWP (2010). Global Water Partnership. Available: http://www.gwpforum.org/en/The-Challenge/Whatis.

Loucs, P. D. and E. v. Beek (2005). Water Resources Systems Planning and Management. New York, USA, UNESCO.

LVBC (2013). Lake Victoria Basin Water Resources Management Plan - Phase 1. ATLAS. Nile Basin Commission.

Mayol, M. D. (2015). Assessment of Surface Water Resources and its Allocation: Case Study of Bahr el-Jebel River Sub-Basin, South Sudan. Institute of Water and Environment, Mekelle University. Master of Science Degree In Integrated River Basin Management (IRBM): 103.

Mutiga, J. K., et al. (2010). "Water Allocation as a Planning Tool to Minimise Water Use Conflicts in the Upper Ewaso Ng'iro North Basin, Kenya." Water Resour Management 24: 3939-3959.

NELSAP (2011). Identification of a Multipurpose Water Resources Development Project in the Yala River Basin in Kenya - Diagnostic / Situational Analysis Report. Nile Water Resources Development Project, Nile Basin Initiative.

Sethi, R., et al. (2015). "Performance evaluation and hydrological trend detection of a reservoir under climate change condition." Model. Earth Syst. Environ 1(33): 1-10.

Stockholm Environment Institute (2015). USER GUIDE for Water Evaluation And Planning System (WEAP) 2015 S. E. Institute. USA

Wang, L. (2005). Cooperative water resources allocation among competing users. Department of Systems Design Engineering. Waterloo, Ontario, Canada, University of Waterloo. Ph.D.

Weragala, D. K. N. (2010). Water Allocation Challenges in Rural River Basins. A Case Study from the Walawe River Basin, Sri Lanka., Utah State University, Sri Lanka. Ph.D: 589.