Modelling Water Demand and Efficient Use in Mbagathi Sub-Catchment Using Weap

J. Nyika*, G.N. Karuku, and R. N. Onwonga
Department of Land Resource Management and Agricultural Technology,
Faculty of Agriculture, University of Nairobi, P.O. Box 29053-00625, Nairobi, Kenya

Abstract

Water systems have complex component interactions necessitating development and evaluation of management amidst uncertainties of climate and constrained natural resources. Conceptual models such as WEAP when used are effective planning and management tools as they forecast future effects of resource use efficiency at sub-catchment level using existent hydrological and climate data thereby acting as corrective measure to poor resources management. This study aimed at using WEAP model to forecast demand and analyze scenarios on efficient water use in Mbagathi sub-catchment. WEAP model schematic was set to develop current and reference scenarios. Parameters used to run WEAP model were a GIS map of the sub-catchment, climate data from Kenya Meteorological Department at Dagorretti Corner Station, hydrological and water demand data from WRMA databases. High population growth and prolonged drought were predicted to increase water demand while reuse though not practised, was found by the model to be the most effective approach to manage unmet demands as compared to reduced conveyance losses and increased reservoir capacity. The study concluded that water reuse through exploitation of wastewater could be a viable solution to Mbagathi sub-catchment's water problems.

1. Introduction

Despite its fundamental importance, water is a scarce resource making it impossible to maximise on its net returns. Factors such as poor configuration of irrigation systems, climate variability, subsidy policies and production costs aggravate the situation making water expensive to manage and use [1]. Allocation of the resource, policies on water sustainability and environmental quality are issues of priority in water management [2-3]. Using water management models such as WEAP helps simulate available water resources effectively and reliably, as well as analysing the consequences of mutual-conflicting interests and divergent water allocation and management options as has been done in Lake Naivasha basin [4] and upper EwasoNg'iro North basin [5].

The threat of water scarcity due to overdraft of available resources and a growing population as reported by Katana et al. [6] necessitates drastic mitigation measures. In addition, the region experiences extended drought, over abstraction of water, poor water conservation strategies and corruption among water management enforcers as Koskei and Ngigi [7] reported. Reversing these problems through better planning on water resources management and assessment demands using WEAP necessitated the study whose objective was to use WEAP model to forecast water demand and water use efficiency in Mbagathi sub-catchment now and unto the future.

2. Materials and methods

Study area

The study was conducted in Mbagathi sub-catchment (1° 23' 0" S, latitude and 36° 46' 0" E longitude and an altitude of 1493 to 1883 meters above sea level) located in Nairobi metropolitan, Kenya. It falls in agro-climatic zone IV that is classified as semi-arid land [8]. Rainfall patterns exhibits distinct bimodal distribution. The first rains fall between mid-March and end of May locally known as long rains (LR), and short rains (SR) are received between mid-October and end of December. Average seasonal rainfall is between 800-1400mm. The sub-catchment has a minimum and maximum temperature of 100C and 240C, respectively [9]. The ratio of annual average rainfall to annual potential evaporation, r/Eo is 51%.

The sub-catchment's soils are a combination of Vertisols and Nitisols (WRB, 2006). In the upper sub-catchment areas, soils are friable clay, dark brown, well drained and deep [7] while the lower parts have cracking clays, which are dark grey or brown in colour and are poorly drained. The sub-catchment has diversified land use types with the upper part being subsistence while the lower part is commercial farming mainly floriculture and horticulture and also hosts the Nairobi national park [10]. The rest comprise of domestic and urban settlements, as part of Nairobi metropolitan.

Data requirements

Modelling in WEAP required a raster file, which are pixels of Mbagathi sub-catchment map and its main river made using GIS techniques. Data on water use for domestic, industrial, commercial and subsistence irrigation was derived from a survey involving 716 respondents selected through a snowballing approach. Secondary data on demand drivers such as population, irrigation withdrawals per person and per hectare, percentage consumption, return flows, losses and reuse as well as hydrological data on river gauge flows, flow requirements and groundwater storage were obtained from WRMA databases.

Calibration of WEAP model

Calibration was a three-step process involving training, testing and analyses of data. In training, effective precipitation, runoff/infiltration ratio and hydraulic conductivity were kept unfixed while groundwater characteristics were fixed. The period of calibration was 1999 to 2015, when naturalized flow and precipitation time series were available for the three stream-flow gauge stations that formed divisions A, B and C of Mbagathi sub-catchment. Calibration was manually done by trial and error optimization of unfixed parameters. Effective precipitation, runoff/infiltration ratio and hydraulic conductivity were assigned initial values of 100%, 50/50 and 1, respectively which were altered one at a time using steps of ± 0.5 %, ± 5/5 and ± 0.1 until the routine exhausted the assessment criterion. The model was run to test and compare changes in simulated and observed flow before and after parameter optimization.

Validation of WEAP model

To validate WEAP model performance, two objective functions estimated the goodness-of-fit of the simulation. In this study, two criteria were used: the Nash-Sutcliffe efficiency criterion and the least squares of logarithms: Equ 1 and 2:

Least squares objective function……………………………1

$$EFF = \frac{\sum_{i=1}^{N} (Qobs_i - Qsim_i)^2}{N}$$

Nash-Sutcliffe Coefficient 2

$$EFF = \frac{\sum_{i=1}^{N} (Qobs_i - Qsim_i)^2}{\sum_{i=1}^{N} (Qobs_i - Qbar_i)^2}$$

Where; Qobsi is the observed stream flow (m3/s); Qsimi; the simulated stream flow (m3/s), N the number of observations and Qbar is the observed monthly flow over the whole period.

LS prevented bias towards larger flows during optimization while EFF is an efficiency criterion where 1 means perfect agreement of observed and simulated flows while negative values show non-agreement. The correlation coefficient (R2) was also calculated to test the goodness-of-fit of the simulation.

Water demand scenarios build-up

Assessment of socio-economic and policy changes in the sub-catchment from 2015 to 2050 involved scenario building in three types i.e. current, reference and what if (future) scenarios. The baseline year, 2015 was used to develop the current scenario, while the reference scenario was an evaluation if no management measures are taken on the current scenario and the what if scenarios were assessments of future socio-economic developments. In this study, five what if scenarios were analyzed as follows:-

1. What if population growth increases, what are the effects on available water demand?
2. What if prolonged dry climate sequence occurs, what are the effects on unmet water demand?
3. What if the capacity of sub-catchment reservoir is increased what is the effect on water demand?
4. What if water conveyance losses are controlled, what is the effect on monthly-unmet demand?
5. What if water reuse is encouraged, what is the effect on monthly-unmet demand?

Scenarios generated were compared against their water requirements and impacts in the domestic, industrial, subsistence and commercial farming demand sites, as they had greatest impact on the resident's livelihoods. Predictions were made using the reference scenario after which, they were compared with proposed water use efficient practices. Water year method represented variations in groundwater recharge, stream flow and rainfall to evaluate the effects of prolonged drought sequence.

3. Results and Discussion

WEAP model calibration

A comparison of simulated and observed flows in the various sub-divisions of Mbagathi sub-catchment is shown in Table 1. Simulated and observed flow values were close and had minor errors ranging between -9 and 6%, which is a satisfactory range [11]. Simulated flows in gauging station 3AA04 had a 5.8% error while those of 3AA06 and 3BA29 had -8.9% and -5.6% errors, respectively. Errors were a result of the conceptual nature of WEAP model that assumes even distribution of rainfall, runoff and stream- flow throughout the sub-catchment, which under natural conditions is impossible. In upper Tana catchment, the conceptual nature of WEAP model assuming even distribution of rainfall and runoff resulted to simulation errors [12].

Table 1: Simulated and observed flows for the three stream-flow gauge stations in Mbagathi sub-catchment during the calibration period

Sub-catchment Division	Stream flow gauge station	Observed flows (mm^3)	Simulated flows (mm^3)	Error (%)
A	3AA04	195	184	+5.8
B	3AA06	201	183	-8.9
C	3BA29	103	109	-5.6
Mean		166	159	-4.2

Topographical differences from the location of stream-flow gauge stations that influence runoff and stream-flow amounts could be attributed to simulation errors. Stream-flow gauge station 3AA04 was located upstream of the sub-catchment, where there was high runoff compared to 3BA29 that was downstream. Flores-Lopez and Yates [13] made similar observations in south-eastern USA basins where stream-flow simulation errors were attributed to location differences of stream-flow gauge stations. The data fed to the model, which is subject to measurement and estimation errors of approximation could cause flow simulation inaccuracies as has been reported in WEAP calibration of stream-flows in Olifants, catchment of South African [14] and Hidukush-Karakoram basin of Himalayas [15].

A comparison of observed and simulated yearly flows for the calibration period is shown in Figure 1. The model showed closeness between observed and simulated flows. However, in 2001, 2002, 2006, 2008 and 2014 when the area had peak flows, WEAP underestimated simulated values compared to 2000, 2005, 2007, 2010 and 2012 when the model overestimated low flows. Over-estimation during drier years could be because the model simulated small but noticeable rainfall that causes stream flow increase, which is not the case in reality.

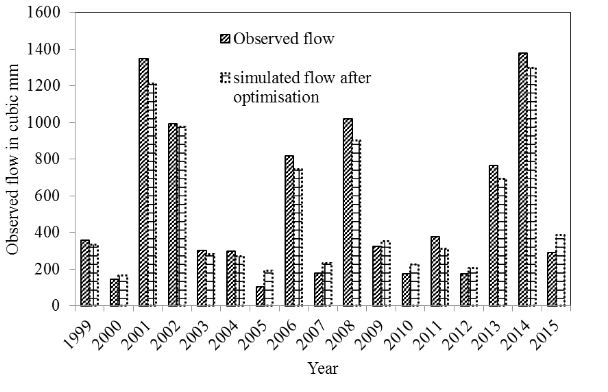

Figure 1: Comparison of simulated and observed yearly flow (1999-2015)

Similar observations were made in Limari basin of Chile [16] whereby WEAP model calibration overestimated low flows. The use of discharge alone to calibrate WEAP model could result to over- and under-estimation of non-calibrated water balance elements such as groundwater recharge and evapotranspiration that the model relies on during simulation hence the over- and under-estimation of predicted flows. Similar observations were made in Pangani basin of Tanzania where only stream-flow was used to calibrate WEAP model [17-18]. Over- and under-estimation of extreme flows could be a result of WEAP model priorities that capture base flow rather than high stream-flows during wet seasons and vice-versa. During wet seasons when water is plenty, the model does not prioritize on estimating peak and base flows hence their under-estimation unlike drier seasons when base flow estimation is a priority in WEAP owing to its importance to water users downstream hence over-estimation of low flows in Mbagathi sub-catchment. Similar observations are made in Quiroz-Chipillico watershed where WEAP model calibration of stream flows was erroneous owing to its priority differences [19].

Validation Results

The relationship between observed and simulated flows in Mbagathi sub-catchment during the validation period is represented in Figure 2. An acceptable performance of WEAP model was observed and R2was 0.964.

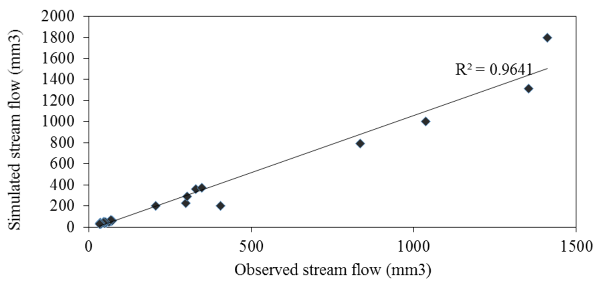

Figure 1: Observed and simulated stream flow of Mbagathi sub-catchment in the validation period

Statistical model efficiency fulfilled the requirement of R2> 0.60 recommended by Santhi et al. [20] and showed considerable capacity of WEAP model to represent sub-catchment processes accurately and predict their responses to various outputs. Similar results were reported in Nyando [21], Pekerra [22] and Ruiru basins [23] of Kenya where R2 was 0.88, 0.79 and 0.85, respectively. In Pungwe basin, Mozambique [24], Shanya watershed, Ethiopia [25] and in Rio Conchos basin, USA [26] acceptable R2 values of 0.85, 0.76 and 0.81, respectively ratifying the high reproducibility of observed flows by WEAP model.

Results on the goodness-of-fit in observed flows are represented in Table 2. The average sub-catchment EFF. was 0.77 indicating acceptable simulation capacity of the model. The LSL for the sub-catchment was 0.43. The two parameters however differed in the different sub-catchment divisions. EFF. compares observed and simulated flows using squared values hence the tendency to over-estimate higher flows while ignoring lower ones and explaining the differences between observed EFF. based on stream flow differences. During low flows, EFF. values have low sensitivity to WEAP model over- and under-predictions. Krause et al. [27] made similar observations when validating WEAP model in a study at Wilde Gera catchment, Germany. The short validation period of 17 years used in this study due to limited data availability could not capture the long-term variability of Mbagathi river discharge adequately and accurately hence the difference in EFF. values.

Table 2: Nash-Sutcliffe coefficient and least squares logarithms for three stream gauges in Mbagathi sub-catchment

Sub-catchment Divisions	Stream flow gauge station	EFF	LSL
A	3AA04	0.87	1.0
B	3AA06	0.85	0.07
C	3BA29	0.59	0.22
Mean		0.77	0.43

Evenly the stream-flow gauge stations were not representative of actual rainfall distribution across the sub-catchment hence discrepancies in EFF. results of its divisions. Mango et al. [28] made similar observation in a SWAT calibration where a shorter calibration period of 5 years and non-representative gauging of stream flow resulted to a 0.61 EFF. value. Differences in LSL could be because the function is dependent on volumes of flow that differ based stream flow gauge location as reported in Olifants catchment where LSL values of its eight sub-catchments showed extensive variability due to differences in flow volumes [29]. Instrument malfunctioning, reading and recording errors during extreme flows could result to discrepancies in EFF. and LSL. Abrishamchi et al. [30] made similar observation in WEAP model validation for Karkheh basin of Iran that recorded 0.43 EFF. and 0.28 LSL values, respectively.

Reference scenario analyses

Model prediction on changes in Mbagathi sub-catchment's water use in the reference scenario, which was model evaluation if no management measures were taken are represented in Figure 3. The model predicted an increment in water use whereby groundwater use rose from 11.98 to 24.54 million m3 compared to surface water use from 7.0 to 12.3 million m3 between 2015 and 2050.

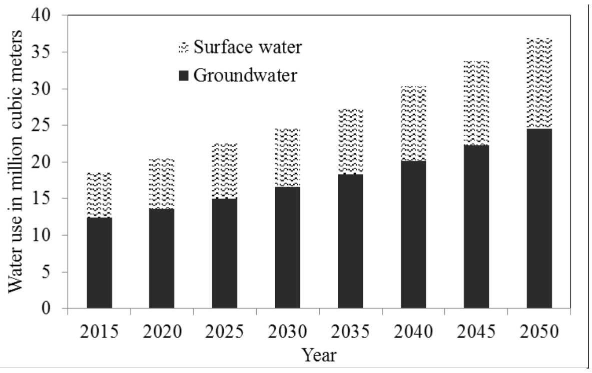

Figure 3: Ground- and surface-water use in the reference scenario

Increased ground- and surface-water use could be a result of a rising population leading to an increased demand for irrigation to produce food. Similar results were predicted using WEAP model in Godavari [31] and Krishna [32] river basins of India. Economic development pressures shifting the focus to commercial agriculture that is water consuming could explain the increased use trend. Nyikai [33] confirmed the shift from subsistence to commercial farming in Kenya due to its economic gains but noted the opportunity cost due to increased water use. Inefficient water use and poor water conservation practices could also lead to increased water use in future as predicted by WEAP model in Diadessa sub-basin, Ethiopia [34]. Similar evidence was reported by Arranz [35] in a study of Olifants catchment, South Africa using WEAP model. Groundwater use was predicted to be higher because of its perceived high quality, low cost and reliability compared to surface water in the sub-catchment whose quantity varies seasonally and is vulnerable to pollution [36].

Model predictions on reductions in groundwater storage of Mbagathi sub-catchment in the reference scenario is showed in Figure 4. Water storage was predicted to reduce by 278 million m3 between 2015 and 2050 from 385.59 to 107.46 million m3. Observed reductions could be possible because of extensive and intensive abstraction in the area without adequate recharge of Nairobi aquifer suite in drier seasons as established in Ngong sub-catchment [37] and Upper Ewaso Ngiro North basin [38].

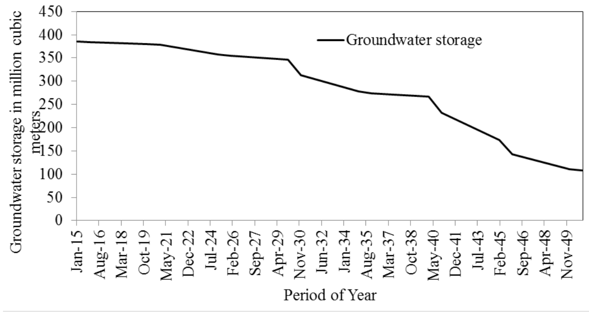

Figure 4: Projected Groundwater storage between 2015 and 2050 in Mbagathi sub-catchment

Pollution of surface water resources and under-exploitation of alternative water resources such as treated wastewater could lead to future groundwater overuse leading to depletion as predicted in Mbagathi sub-catchment. Similar projections were made in Bangladesh, Middle East, China and India [39-40]. Limited opportunities to fund operations and maintenance of this resource and incapacity of users to pay for it could lead to over-exploitation and ultimately, depletion due to poor management and monitoring in the sub-catchment as evident in Lamu, Kenya [41] and Southern Province, Zambia [42].

Effects of high population growth on water demand

Predictions on water demand changes in the high population growth scenario for the domestic, industrial, commercial and subsistence irrigation sectors of the study area compared to reference scenario are represented in Figure 7.5. Water demands were predicted to increase in the high population and reference scenarios though in the former, higher increments were predicted. Predictions showed 39%, 33.23%, 23.45% and 18.76% increments in water demand in the high population growth scenario compared to 29.73%, 25.87%, 16.59% and 9.45% in the reference scenario between 2015 and 2050 for commercial farming, domestic use, subsistence farming and industrial use divisions, respectively. Increased water demand in the subsistence and commercial farming sectors could be due to overstretched water resources, as it is expected that agricultural land will expand for food production to the rising population and economic sustenance of developing countries. In Tana river basin, population rise increased water use due to rising food demand and abstractions for commercial irrigation in the area [43]. Population rise and limited exploitation of alternative water sources could lead to increased domestic water demand in the study area. Rukuni, [44] reported similar evidence in Mzingwane catchment. Increased waste generation causing pollution on available water resources and limited wastewater treatment could explain the rise in industrial water demand.

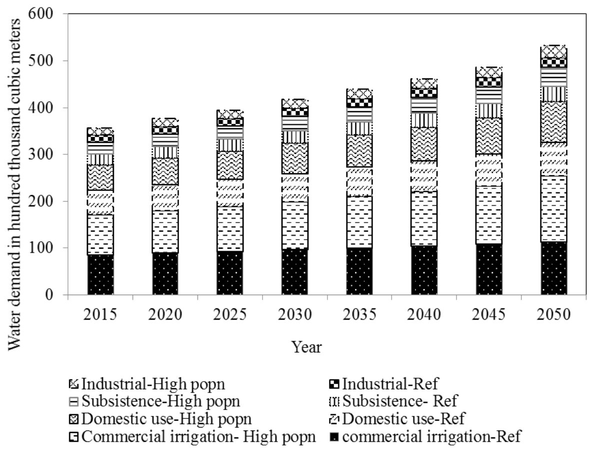

Figure 5: Water demand changes in the high population growth scenario

Similar projections were made in India as reported by Bhardwaj [45]. The projected demand in all sectors could be a result of over-exploitation of water resources without adequate replenishment allowance as predicted in Blue Nile [46] and Upper Ipswich river basins using WEAP model [47].

Effects of prolonged drought sequence on unmet demand

Predicted effects of prolonged drought sequence on unmet demand in the study area are shown in Figure 6. WEAP model projected a higher unmet water demand in the prolonged drought scenario for all land use sectors compared to the reference scenario. Unmet demand in commercial irrigation, domestic use, subsistence irrigation and industrial sectors was projected at 36%, 25%, 16.6% and 9% increment in the prolonged drought sequence scenario compared to 29.73%, 25.87%, 16.59% and 9.45% in the reference scenario between 2015 and 2050, respectively. A decline in available water due to low recharge of aquifers, reduced river flows and reduced environmental resilience possibly explain predicted increments in unmet demand for all sectors. In Sacramento river basin [48] and Limari basin, Chile prolonged drought scenario modelling in WEAP resulted to reduced depletion of water resources due to increased abstractions without replenishment.

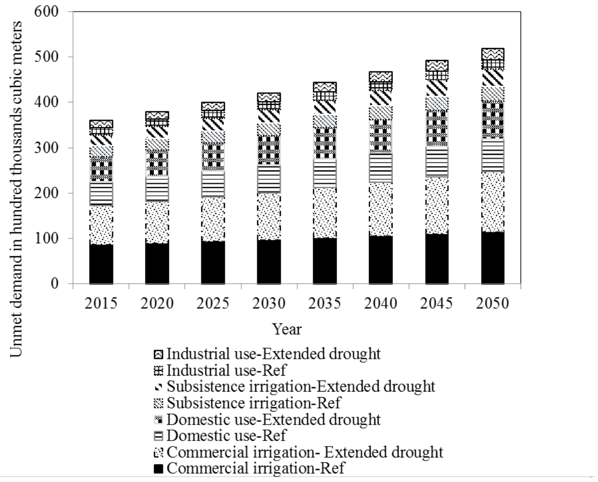

Figure 6: Changes in unmet demand in the prolonged drought sequence scenario

In Langat [49] and Upper Colorado [50] river basins of Malaysia and USA, respectively, WEAP model results predicted increased unmet demand in the prolonged drought scenario due to low aquifer recharge and productivity. Under exploitation of alternative water sources such as wastewater leading to overuse of surface- and groundwater resources could also explain the sub-catchment's predicted rise in unmet demand as has been reported in Ho Chi Minh City of Vietnam [51].

Effects of increased reservoir capacity on water demand

Predicted effects of increasing sub-catchment's reservoir capacity on water demand in various land-use sectors are shown in Figure 7. WEAP model forecasted different effects on water demand between 2015 and 2050 based on land-use. Predicted domestic water demand increased by 42% due to an expected population rise, rural-urban migration and increased availability of the resource encouraging inefficient use in the area.

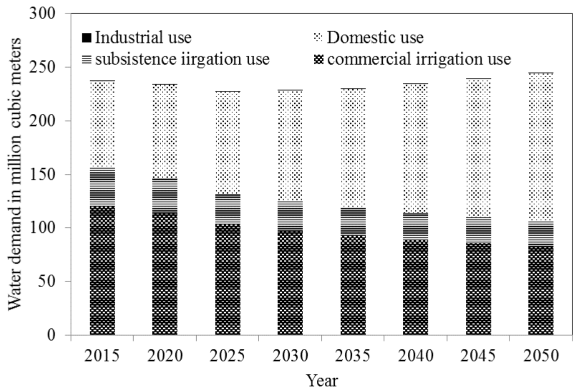

Figure 7: Effects of increasing reservoir capacity on water demand

Increased water availability in Nablus City [52] and western Algerian cities [53] encouraged inefficient use and rural-urban migration leading to demand increments following the construction of reservoirs. Commercial irrigation water demand was predicted to reduce by 27.6% because of a possible alteration in the flow regime of Mbagathi river leading to ground- and surface-water unavailability and reduced demand downstream the sub-catchment. Similar results were reported in India after construction of Narmada and Sardar-Sarovar dams [54]. Subsistence water demand in the study area was expected to reduce by 36.6% in 2050 possibly because of land use changes that will favour real estate development as reported in Nairobi basin by Mundia and Aniya [55]. Industrial sector experienced insignificant water demand reductions.

Effects of controlling water conveyance losses on unmet demand

Predicted monthly effects of controlling water conveyance losses in Mbagathi sub-catchment on unmet demand compared to the reference scenario are represented in Figure 8. The model predicted a higher reduction in unmet water demand for the reduced conveyance losses scenario compared to the reference scenario despite the observed monthly fluctuations in both cases resulting from rainfall variations. Controlling water conveyance losses would increase amount delivered to target users and enhanced efficiency explaining the observed unmet demand reductions.

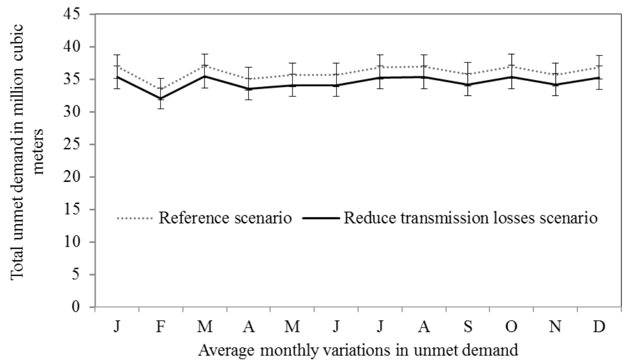

Figure 8: Effects of reducing transmission losses on unmet demand

In South African [56], Pakistan, Egypt and India [57] control of water conveyance losses resulted to effective accounting of used water hence increased efficiency. Replacing and repairing aged water pipes reduced municipal unmet demand in Muzzaffarabad, Azad Jammu and Kashmir districts in Pakistan, respectively [58] while adoption of drip irrigation that has reduced losses in Thessaloniki, Greece resulted to bettered water delivery to farms [59].

Effects of water reuse on unmet demand

Predicted effects of water reuse in Mbagathi sub-catchment on monthly-unmet demand are shown in Figure 9. The model predicted more than 50% reductions in unmet demand throughout the year and the method proved better in easing future unmet demand compared to controlled water conveyance losses scenario. Unmet water demand was predicted to reduce because reuse redirects wastewater for environmental flow allocation and aquifer recharge increasing availability. The national water supply of USA increased by 27% after wastewater reuse [60] due to increased resource availability. Reusing water substitutes demands that do not require high quality water, increases available supply, provides alternative water sources, reduces additional water control structures and protects ecosystems hence reducing unmet demand as predicted by WEAP model in this study [61].

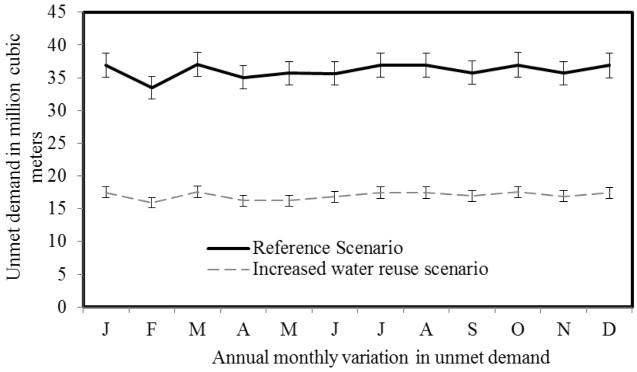

Figure 9: Effects of water reuse on unmet demand

In Israel [62] and Palestine [63], water reuse has been used as an alternative source of water to ease unmet demand. In India [64] and Bahrain [65] water reuse enhanced recharge of water resources and protected the ecosystem. In China, [66] wastewater reuse reduced the cost of water maintenance as no additional water supply infrastructure was required.

4. Conclusions

The information obtained from WEAP model enhanced understanding on water demand drivers and water efficient use, which will help in sustainable management of the resource in Mbagathi sub-catchment. Obtained results can be extrapolated to help in water management in Nairobi, Ngong, Machakos and Kajiado counties. The study established that WEAP is a useful tool in predicting future water demand and effects of adopting water use efficiency because it proofed that reusing wastewater, careful planning of reservoir placement and reducing water conveyance losses could result to better water management in future. Therefore, implementing these water management strategies should be a priority in the study area. After forecasting and building water-use efficient scenarios in WEAP, the study advocates for adoption of reuse, which is an under-exploited water source in the study area. To Nairobi, Kajiado and Machakos county residents in Mbagathi sub-catchment, the findings are a challenge towards efficient water use to ease current and future unmet water demand.

Acknowledgements

The authors acknowledge the financial support by Nuffic Group under Euro Mott McDonald Consultants to the first author to undertake the research as part of her postgraduate studies. Water users and WRMA who provided information for the study are equally appreciated.

References

[1] Mounir, Z., Ming Ma., C and Amadou, I. Application of Water Evaluation and Planning (WEAP): A model to assess future water demands in the Niger river (In Niger Republic). Modern Applied Science, 5 (1), 39-52.

[2] Uitto, J.I. (2004). Multi-country cooperation around shared waters: role of monitoring and evaluation, Global Environmental Change, 14, 5–14.

[3] Conway, D., Persechino, A., Ardoin-Bardin, S., Hamandawana, H., Dieulin, C., and Mahé, G. (2009). Rainfall and Water Resources Variability in Sub-Saharan Africa during the Twentieth Century, Journal of Hydrometeorology, 10, 41–59.

[4] Alfarra, A. (2004). Modelling water resource management in Lake Naivasha. Msc. Thesis, International Institute for Geo-Information Science and Earth Observation.

[5] Kinoti, J., Mavengano, S., Zhongbo, S. &Becht, R. (2010). Water allocation as a planning tool to minimize water use conflicts in the Upper Ewaso Ng'iro North basin, Kenya. Water Resources Management, 24 (14), 3939-3959.

[6] Katana, S., Munyao, T. and Ucakuwun, E. (2013). Hydrological impacts of land cover changes in upper Athi River Catchment, Kenya. International Journal of Current Research, 5 (5), 1187-93.

[7] Koskei, K. and Ngigi, T. (2013).Assessing changes on the floodplain of sandy rivers using geospatial techniques: case of Athi sub-catchment in Makueni. International Journal of Science and Research, 6 (14), 2024-27.

[8] Jaetzold, R., Schmidt, H., Hornetz, B., andShisanya, C. (2006).Ministry of Agriculture Farm Management. Handbook of Kenya (Vol. II, 2nd ed., Part C, Subpart C1). Nairobi, Kenya: Ministry of Agriculture.

[9] Krhoda, G. (2002). Nairobi river basin phase II: The monitoring and sampling strategy for Ngong/Motoine River, pp.55.

[10] Olago, P. and Aketch, F. (2000).Pollution assessment in Nairobi River basin. Pollution Assessment Report of the Nairobi River basin. Africa Water Network.

[11] Moriasi, D., Arnold, J., van Liew, M., Bingner, R., Harmel, R. & Veith, T. (2007). Model evaluation guidelines for systematic qualification of accuracy in watershed simulations.American Society of Agricultural and Biological Engineers, 50 (3), 885-899.

[12] Droogers, P. (2009). Climate change and hydropower, impact and adaptation costs: case study Kenya. Report Future Water, 85.

[13] Flores-Lopez, F. and Yates, D. (2013).A water system model for exploring electric energy alternatives in southeastern US basins. Environmental Research Letters, 8, 1-11.

[14] McCartney, M. P. and Arranz, R. 2007.Evaluation of historic, current and future water demand in the Olifants River Catchment, South Africa. Colombo, Sri Lanka: International Water Management Institute. 48p. (IWMI Research Report 118).

[15] Khan, A., Richards, K., McRobie, A., Fischer, G., Wiberg, D., Burek, P. & Satoh, Y. (2016). Accuracy

assessment of ISI-MIP modelled flows in the Hidukush- Karakoram-Himalayan basin. Geophysical Research Article, 18, 650-666.

[16] Vicuna, S., Garreaud, R. & McPhee, J. (2010) Climate change impacts on the hydrology of a snowmelt driven basin in semiarid Chile. Climate Change. Springer Publishers.

[17] Ndomba, P., Mtalo, F., and Killingtveit, A. (2008) SWAT model application in a data scarce tropical complex catchment in Tanzania. Physical Chemistry of the Earth, 33, 626–632.

[18] Notter, B., Huruni, H., Wiesmann, U. &Abbaspour, K. (2012).Modelling water provision as an ecosystem service in a large African river basin. Hydrology and Earth System Sciences, 16, 69-86.

[19] Flores-Lopez, F., Galaitsi, S., Escobar, M. &Purkey, D. (2016). Modelling of Andean Paramo ecosystems' hydrological response to environmental change. Water, 8 (94), 1-18.

[20] Santhi, C., Arnold, J. G., Williams, J. R., Dugas, W. A., Srinivasan, R., and Hauck, L. M. (2001) Validation of the SWAT model on a large river basin with point and nonpoint sources, Journal of American Water Resources Association, 37, 1169–1188.

[21] Dienya, R. (2007). Application of the WEAP model in integrated water resources management of the Nyando River Basin, Kenya. Msc. Thesis, Jomo Kenyatta University of Agriculture and Technology.

[22] Mugatsia, A. (2010). Simulation and scenario analysis of water resources management in Pekerra catchment using WEAP model. MSc. Thesis, Moi University.

[23] Thubu, J. (2012). Developing a sustainable water management plan for Ruiru, Thiririka and Ndarugu basins in Kenya using WEAP. MSc. Thesis, Jomo Kenyatta University of Agriculture and Technology.

[24] Droogers, P. and Terink, W. (2014).Water allocation planning in Pungwe Basin, Mozambique. Report Future Water, 129.

[25] Shawul, A., Alamirew, T. &Dinka, M. (2013). Calibration and validation of SWAT model and estimation of water balance components of Shaya mountainous watershed, Southeastern Ethiopia. Hydrology and Earth System Sciences, 10, 13955-13978.

[26] Ingol-Blanco, E. and McKinney, D. (2013). Development of a Hydrological Model for the Rio Conchos Basin. Journal of Hydrologic Engineering, 10.1061/(ASCE)HE.1943-5584.

[27] Krause, P., Boyle, D. & Base, F. (2005).Comparison of difference efficiency criteria for hydrological model assessment. Advances in Geosciences, 5, 89-97.

[28] Mango, L., Melesse, A., McClain, M., Gann, D. & Setegn, S. (2011). Hydro-meteorology and water budget of the Mara river basin under land use change scenarios. Springer Publishers, 39-62.

[29] Le Roy, E. (2006). A study of the development of water resources in the Olifants catchment, South Africa: Application of the WEAP model. Retrieved on 20 May 2015 from http://www.iwmi.cgiar.org/assessment/files_new/research_projects/River_Basin_Development_and_Management/Weap%20Modelling.pdf.

[30] Abrishamchi, A., Alizadeh, H. & Tajrishy, M. (2007).Water resources management scenario analysis in the Karkheh river basin, Iran using the WEAP model. Hydrological Science and Technology, 23 (1-4), 1-10.

[31] Amarasinghe, U.A., Sharma, B.R., Aloysius, N., Scott, C., Smakhtin, V. and de Fraiture, C. (2005).Spatial variation of water supply and demand across river basins of India. Research Report 83. Colombo, Sri Lanka: International Water Management Institute.

[32] Bharati, L., Smakhtin, V. and Anand, B. (2009). Modelling water supply and demand scenarios: the Godavari-Krishna inter-basin transfer, India. Water Policy, 11 (1), 140-153.

[33] Nyikai, R. (2003). Commercial and subsistence farming: What is the future for smallholder Kenyan agriculture? African Crop Science Conference Proceedings, 6, 591-596.

[34] Tena, B., Rao, S. &Abbulu, Y. (2016).WEAP modelling of surface water resources allocation in Diadessa sub-basin, West Ethiopia. Sustainable Water Resources Management, 2 (1), 55-70.

[35] Arranz, R. (2006). Future water demands and resources in the Olifants catchment, South Africa: A scenario analysis approach using the WEAP model. Thesis, Colorado State University.

[36] Mumma, A., Lane, M., Kairu, E., Tuinhof, A. and Hirji, R. (2011).Kenyan groundwater governance case study. The Water Unit, Transport, Water and ICT Department, Sustainable Development Vice Presidency. www.worldbank.org/water.

[37] Mulwa, J. (2001). Geological and structural set-up of Kiserian-Matathia area and its influence on groundwater flow and distribution. Msc. Thesis, University of Nairobi.

[38] Gichuki, N. and Kiteme, B. (2000). Water management constraints and opportunities: A case study of the Upper Ewaso Ngiro North Basin. Eastern and Southern Africa Journal, 8 (1), 15-28.

[39] Ali, M. Y., Waddington, S. R., Timsina, J., Hodson, D., and Dixon, J. (2009). Maize-rice cropping systems in Bangladesh: status and research needs. *Journal of Agricultural Science and Technology USA, 3*(6), 35–50.

[40] Wada, Y., van Beek, L. P., van Kempen, C. M., Reckman, J. W., Vasak, S.,and Bierkens, M. F. (2010). Global depletion of groundwater resources. Geophysical Research Letters, 37(20), L20402.

[41] Kuria, Z.N. 2008.Groundwater Resources Assessment of Lamu Island along Coastal Kenya. Prepared for National Museums of Kenya, November 2008, Nairobi.

[42] Bäumle, R., C. Neukum, J. Nkhoma, and O. Silembo. 2007. The Groundwater Resources of SouthernProvince, Zambia (Phase 1) Volume 1 – Technical Report. Prepared by Department of Water Affairs, Ministry of Energy and Water Development, Lusaka; and the German Federal Institute for Geosciences and Natural Resources, Hannover. Project No. BMZ PN 2003.2024.2/BGR 05-2315-01, Lusaka, Zambia, November 2007.

[43] Grieg-Gran, M., Noel, S. and Porras, I. (2006). Lessons learned from payments from environmental services. Green Water Credits report No. 2. ISRIC, Wageningen.

[44] Rukuni, S. (2006).Modelling the response of small multi-purpose reservoirs to hydrology for improved rural livelihoods in the Mzingwane catchment: Limpopo Basin. Retrieved on 25 June 2015 from http://www.waternetonline.ihe.nl/challengeprogram/D30%20Rukuni%20WEAP.pdf Retrieved on 14 February 2016.

[45] Bhardwaj RM. 2005. Status of Wastewater Generation and Treatment in India, IWG-Env Joint Work Session on Water Statistics, Vienna, 20-22 June 2005.

[46] Smith, M., de Groot, D., and Bergkamp, G. (2006).Establishing payments for watershed services. IUCN, Gland; 109pp.

[47] Zoltay, V. (2007). Integrated watershed management modelling: optimal decision making for natural and human components. MSc. Thesis, Tufts University.

[48] Purkey, D., Joyce, B., Vicuna, M., Hanemann, L., Yates, D. and Dracup, J. (2008). Robust analysis of future climate change impacts on water for agriculture and other sectors: a case study in the Sacramento Valley. Climate Change, 87 (1), 109-122.

[49] Azlinda, S. and Mohd, A. (2008).Assessment of water demand in Langat catchment using water evaluation and planning (WEAP).Hydrology, 4, 18-31.

[50] Yates, D., Miller, K., Wilby, R. and Kaatz, L. (2015).Decision centric adaptation appraisal for water management across Colorado's continental divide. Climate Risk Management, 10, 35-50.

[51] Dan, N., Khoa, L., Thanh, B., Nga, P. &Visvanathan, C. (2011). Potential of wastewater reclamation to reduce freshwater stress in Ho Chi Minh City Vietnam. Journal of Water Sustainability, 1 (3), 279-287.

[52] Rahma, U. (2009). Evaluation of urban water supply options using WEAP: the case of Nablus city. MSc. Thesis, An-Najah National University.

[53] Hamlat, A., Errih, M. and Guidoum, A. (2011).Simulation of water resources management scenarios in western Algeria watersheds using WEAP model. Arabian Journal of Geosciences, 1 (22), 2225-2236.

[54] Manatunge, J., Priyadarshana, T., and Nakayama, M. (2010) Environmental and social impacts of reservoirs: Issues and mitigation. Oceans and Aquatic Ecosystems, 1, 1-13.

[55] Mundia, C. & Aniya, M. (2006). Dynamics of land use/cover changes and degradation of Nairobi city, Kenya. Land Degradation and Development, 17 (1), 97-108.

[56] Wilson, K. (2016). Reducing water losses with intelligent pressure management. http://www.infrastructurene.ws/2012/05/25/reducing-water-losses-with-intelligent-pressure-management/.

[57] Sultan, T., Latif, A., Shakir, S., Kheder, K. and Rashid, U. (2014).Comparison of water conveyance losses in unlined and lined watercourses in developing countries. Technical Journal University of Engineering and Technology, 19 (2), 24-27.

[58] Azad, R. and Sarwar, T. (2014).Effect of watercourse aging on conveyance efficiency and water productivity in District Muzaffarabad, Azad Jammu and Kashmir. Sarhad Journal of Agriculture, 30 (4), 466-471.

[59] Arampatzis, G. and Evangelides, C. (2016).Water losses during distribution and application in collective pressurized irrigation networks. Journal of Irrigation and Drainage Engineering, 111 (3), 265-275.

[60] Kusanto, N. (2013). Sustainable water infrastructure: Water management and reuse. http://www.wise-intern.org/journal/2013/documents/Kusanto_WISE_WaterReuse_8_1_2013.pdf.

[61] Metcalf and Eddy. 2007. Water reuse. Issues, technologies, and applications. McGraw-Hill Publisher, New York.

[62] Friedler, E. and Penn, R. (2011).Study of the effects of on-site grey water reuse on municipal sewer systems. Grand Water Research Institute. http://greywateraction.org/wp-content/uploads/2014/12/Israeli-study-gw-affects-sewers.pdf Retrieved on 08 February 2016.

[63] Jamal, A. (2013). Using treated wastewater as a potential solution of water scarcity and mitigation measure of climate change in Gaza Strip, Journal of Water Resources and Ocean Science, 2 (5), 79-83.

[64] Kaur, R., Dhir, G., Kumar, P., Laishram, G., Ningthoujam, D. and Sachdeva, P. (2014). Wastewater production, treatment and use in India. ICAR News (Jan-Mar) 18(1), 7-8.

[65] Ansari, M. (2013). The water demand management in the Kingdom of Bahrain. International *Journal of Engineering and Advanced Technology, 2* (5), 544-554.

[66] Chu J, Chen J, Wang C and Fu P. (2004). Wastewater reuse potential analysis: implications for China's water resources management. *Water Resources 38*(11): 2746- 2756.