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Impact of development and management options on water resources of the upper Mara River Basin of Kenya

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Mara River basin; Nyangores catchment; policy scenarios; water conservation; water demand; water resources model.

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Abstract

This study employed the Water Evaluation and Planning model to evaluate selected policy-based water development and management options on water resources of the upper Mara Basin of Kenya. The major water resources of the region were identified and quantified to establish the current demand versus supply status. Data on domestic water consumption, agricultural demand and industrial consumption were collected through a rigorous fieldwork campaign and used to define the current state of water use and demand. The water resource model was calibrated and validated against observed discharges and subsequently used to simulate the selected policy-based options. Results indicate that an increase between 49% and 180%, depending on the assumed scenario, in annual water demand is expected by the year 2030. As a conclusion, the simulations demonstrate that there is both the need and significant potential to reduce the demand by implementing water conservation measures.

Introduction

Water insecurity consequent of environmental changes is today a major threat to land and water resources across the globe (Ercin and Hoekstra 2014; Jepson *et al.* 2017). In the developing regions, climate and land-use changes coupled with pressure from population increases have been noted to influence hydrological regimes and water resource availability (Hoffman *et al.* 2011; Olang *et al.* 2012; Schewe *et al.* 2014) leading to the loss of estuarine biodiversity (Kilonzo 2014; Verones *et al.* 2015). In the Mara River Basin of East Africa, water conflicts due to the competitive demands of the limited water resources are already threatening development, conservation and tourism within the globally significant watershed (Lotze-Campen and Welp 2007; Mwangi *et al.* 2014; Petersen-Perlman *et al.* 2017). The high water demand, which often exceeds the supply during dry seasons, presents a major concern to the local water resource managers of the basin. There is hence the urgent need to not only diagnose these changes, but also their likely effects on riparian and interconnected water and environmental systems with a view of providing statistics that can support the management (Dessu *et al.* 2014).

Like most developing nations, Kenya faces formidable freshwater planning and management challenges (Wang *et al.* 2007; Loucks and Beek 2017; Chepyegon and Kamiya 2018). The Nyangores catchment, one of the source tributaries of the Mara river, is considered to be the representative of the upper Mara River Basin of Kenya. There already exist human conflicts associated with water use and allocation in the area (Kilonzo 2014). The main reason here can attribute to high water demand and low supply. During low flows, demand often exceeds the requirements as is the case in dry season months and during drought conditions (Olang and Fürst 2010; Bartzke *et al.* 2018; Mehdi *et al.* 2019). Increasing drought conditions consequent of changes in climate are expected to escalate conflicts in future, largely driven by population increase and economic development (Okech 2010). To assist in the assessment of water resource planning and management options in the Nyangores, Olang *et al*. (2017) presented a geodatabase of maps for the Nyangores area to demonstrate how spatial mapping can support the management of the existing water resources. Their observations echo those of Dessu and Melesse (2012) and Mwangi *et al.* (2016) that call for regulation of upstream agricultural activities to minimize the degradation of water quality and quantity.

As is common in many basins in developing nations, water in the Nyangores catchment is typically allocated according to the institutional, historical, legal, political and social traditions and conditions (McKay 2011; Bangash *et al.* 2012). However, expected changes such as population growth or the implementation of new irrigation schemes, may in time, affect the water balance. It may also alter the existing water allocation pattern by changing land use and land cover, thereby, changing the patterns of run-off and infiltration (Bates *et al*. 2008). Moreover, according to the United Nations sustainable development goal number six (UNDP 2014), water-scarce catchments such as Nyangores, need to reform their water allocation institutions and methods so as to realize equitable access to water and sanitation for all (Wang *et al.* 2007). The allocation of limited water resources in river basins is one of the most critical issues. It is, therefore, fundamental to undertake an integrated analysis of the water resources at the watershed-scale, where individual water-related sectors, such as agriculture, domestic and industrial water supply are brought together in a framework (Bangash *et al.* 2012; Chepyegon and Kamiya 2018).

Apart from the challenges concerning the limitations in the available water quantity, water quality is also an issue in the Nyangores River and its tributaries (Minaya 2010; Kilonzo *et al.* 2014; Nyairo 2015; Jacobs *et al.* 2017). While investigating the threats posed to pristine water resources in the area, Mati *et al.* (2008) indicated that land-use change has led to a continued degradation and faster loss of vegetation. Consequently, there is a reduction in the quantity and quality of water in the catchment. Essentially, there is a vital need for a thorough evaluation of the current ecological and hydrological status of the river ecosystem in order to develop proper protocols for its management (Mango *et al.* 2011). It is also necessary to develop procedures that can be used to assess the water quantity and quality of the catchment (Olang and Kundu 2011).

The objective of this study was to evaluate the effects of development and management scenarios in the Nyangores catchment for purposes of future planning of the water resources of the basin. This was achieved with the help of the Water Evaluation and Planning Model, WEAP21. Current Water use data were mapped and scenarios were developed according to the four main drivers of water demand in the catchment, namely, irrigation, domestic, industrial and livestock water demand. The results of this study provide a significant insight into the water resource planning efforts in the greater Mara river basin of Kenya and Tanzania. Overall, water quality data were also collected but is not in the focus of this present contribution.

Materials and methods

Study area

The study was undertaken in the Nyangores catchment (Fig. 1) of the trans-boundary Mara River Basin (MRB) shared between Kenya (65%) and Tanzania (35%). The MRB is located in the south-western/north-western part of Kenya/Tanzania and covers an area of about 13 500 km^2. The Mara River flows for about 395 km, drains into Lake Victoria, and is thus a tributary to the Nile River. The studied Nyangores catchment covers a total area of approximately 933 km^2. The altitude within the catchment ranges between 2951 m around the sources in the Mau Escarpment and 1706 m downstream in Kaboson and the amount of precipitation varies according to these altitudes. The Mau Escarpment receives most rainfall with a mean annual rainfall between 1000 mm and 1750 mm (Mati *et al.* 2005). The mean annual rainfall then decreases with altitude to around 600 mm at Kaboson. The rainfall seasons are bimodal with the long rains starting in mid-March to June with a peak in April, while the short rains occur between September and December. The Nyangores catchment is largely hilly in topography with 50% of the total area above the altitude of 2200 m. The Nyangores River has two tributaries, namely Chepkositonik and Ainop'ngetunyek. Along the longest tributary, the river runs approximately 94 km before joining the Amala River at Kaboson. On an annual basis, a mean flow of 8.6 m^3/s or a runoff depth of about 390 mm/a at the gauging station in Bomet (1LA03) is observed. At this gauge, the catchment area is 693 km^2.

Data collection

Socio-economic data

The latest population census data for Bomet county and Nyangores catchment were obtained from the Kenya National Bureau of Standards Nairobi (KNBS 2011). Focused group discussions and review of county development policy documents were used to collect information on the socio-economic activities within the study area. This information included the industrial landscape (type of industries, number of industries and their water consumption), formal social groupings such as community-based organisations addressing both social and economic needs (women and youth groups) and their administrative locations within the sub-catchment (location of the industries and the community-based organisations).

Hydro-meteorological data and spatial datasets

Data were collected from the Nyangores Water Resource Users Association (WRUA), Water Resources Management Authority (WRMA) and the Bomet County Ministry of Water and Environmental Resources. The river discharge rates were derived from the gage height measurements provided by WRMA, using a rating curve developed by WRMA. The discharge measurements employed the area-velocity method, yet both random and systematic errors are anticipated due to the small number of reliable measurements

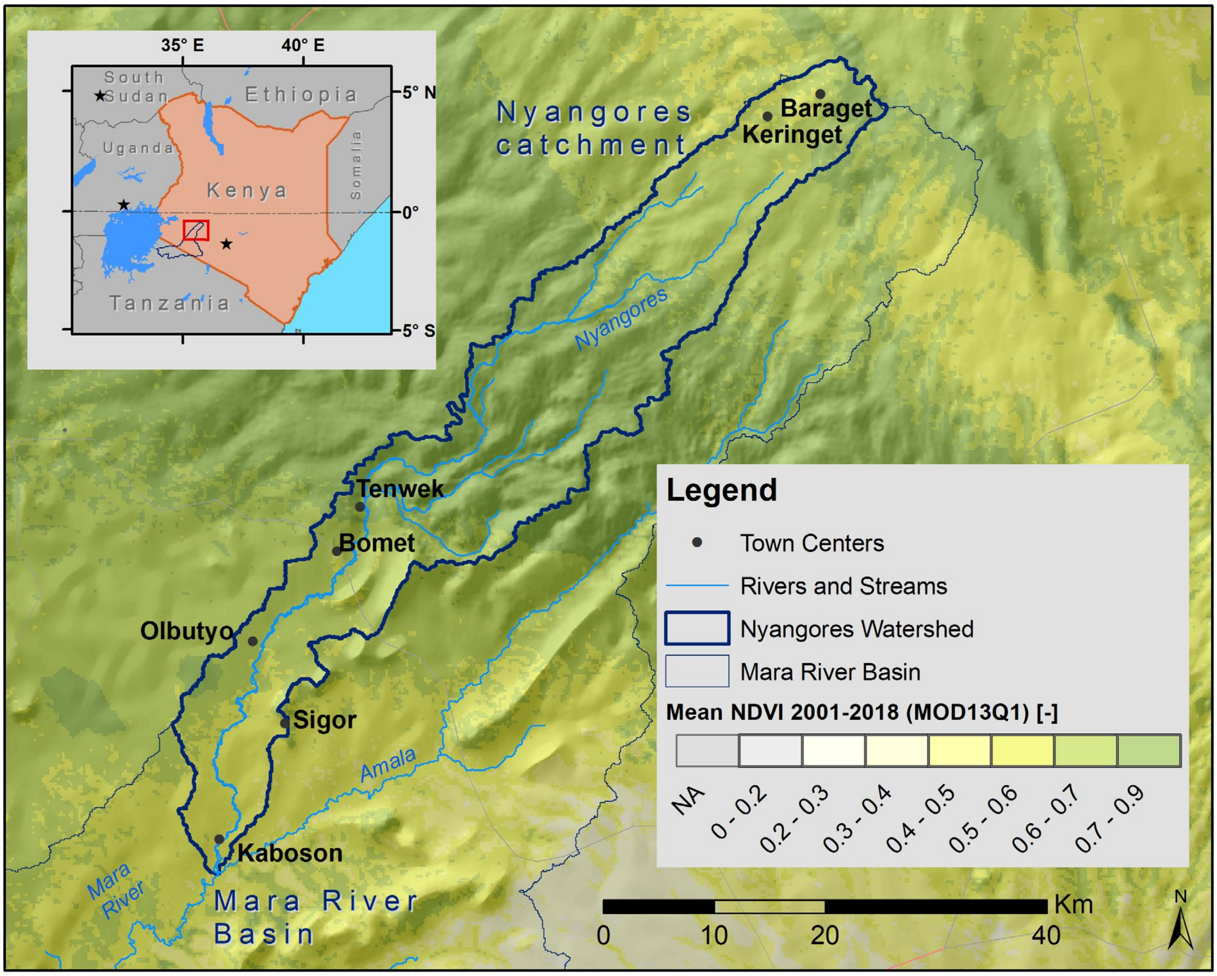

Fig. 1. The Nyangores catchment of the upper Mara River basin. [Colour figure can be viewed at wileyonlinelibrary.com]

(Juston and Gustafsson 2014). Using a GPS handset, data on the locations of major water sources and sinks were acquired. Discharge rates, population served by the water sources, abstraction permits, planned water works within the catchment and existing water policy documents were provided by the county government and the Water Authorities mentioned above. This was performed to assist in the assessment of water supply and demand across the subcatchment (Dessu *et al.* 2014). The acquired spatial locations were subsequently mapped using the ArcGIS application. Other GIS data such as catchment boundary, river network and administrative centres within the catchment were acquired from secondary sources (Fürst *et al.* 2015; Wimmer *et al.* 2015).

The WEAP model

The Water Evaluation and Planning System Version 21 (WEAP21) is an Integrated Water Resources Management model that integrates water supplies generated through watershed-scale hydrological processes with a water management model driven by water demands and environmental requirements (Sieber and Purkey 2013). WEAP21 considers demand priorities and supply preferences, which are used in a linear programming heuristic to solve the water allocation problem as an alternative to multicriteria weighting or rule-based logic approaches. It introduces a transparent set of model objects and procedures that can be used to analyse a full range of issues faced by water planners through a scenario-based approach. These issues include climate variability and change, watershed condition, anticipated demands, ecosystem needs, the regulatory environment, operational objectives and available infrastructure (Yates *et al.* 2005).

The catchment was divided into three subcatchments (upstream, mid-stream and downstream) in order to cover the different characteristics, for example, land use and topography, of the study area. To simulate the catchment run-off, the Simple Rainfall-Runoff Coefficient Simulation Method was employed. This method also determines evapotranspiration for irrigated and rain-fed crops using crop coefficients. The remainder of rainfall not consumed by evapotranspiration is simulated as runoff to a river or can be proportioned amongst runoff to a river and flow to groundwater.

The model was calibrated and validated manually through trial and error. A base year, 2014, was used for which water availability and demand were exhaustively determined (Sieber and Purkey 2005). The WEAP21 model parameters were calibrated for the period 2000–2005. The validity of these parameters was tested in the validation period of 2006–2010. The simulation period for calibration and validation is limited by available data.

The study adopted the water demand calculation methodology as outlined by Sieber and Purkey (2005) in the WEAP21 manual. Crop water requirement was calculated by assuming a demand site with simplified hydrological and agro-hydrological processes such as precipitation, evapotranspiration, and crop growth emphasising irrigated and rainfed agriculture. Non-agricultural land classes were also included. Irrigation water demand was calculated using the Soil Moisture Method (Sieber and Purkey 2005).

Water resource planning and management options; scenario definitions

In defining water management, Dziegielewski (2003) stated that water demand management (or conservation) involves any activity, practice, technological device, law or policy that has the ability to reduce water use. Therefore, options for water demand and allocation management amongst users to enhance water use efficiency would involve managerial, technological and policy aspects (Vincent 1992). Consequently, the development of policies that encourage proper water resource management can address the challenges of effective management and allocation of available but scarce water resources (Gersfelt 2007; Kadigi *et al.* 2012). These regulations must be designed and implemented in a manner that allows the proper water allocation, while achieving the required demand and social objectives (Caponera 2007). In Kenya, the Water Act (2002) implements the water management process at the grass-root level through the establishment of Water Resource Users Associations (WRUAs). WRUAs are important for reducing water allocation conflicts and have been recommended by various scholars (Mutiga *et al.* 2010; Wamuicho and Kihonge 2017). In Upper Ewaso Ng'iro North basin in Kenya, Mutiga *et al.* (2010) emphasised the formation of WRUAs as it incorporates ideas from different stakeholders who can easily solve water-related conflicts; the same idea has been replicated across major River basins in Kenya including the Nyangores catchment. WRUAs also enhance user's involvement and participation in defining and implementing the development of water use goals for the basin. In addition, they improve water management, water use efficiency, and coordinate water distribution and equitably collect water charges from members to improve water infrastructure and allocation mechanisms (Wang *et al.* 2010; Zhang 2013). Therefore, to link the policy instruments, management practice and technological considerations in a watershed system, hydrological models are applied to provide future scenario analysis. These comprehensive analyses allow planners and managers to make appropriate management decisions. The following scenarios were thereby developed:

Reference scenario

Also known as the business as usual scenario, this is the base scenario that utilizes current data to help in understanding the situation at the studied basin (Sieber and Purkey 2013). The model was run for the period 2000–2005 for calibration and 2006–2010 for validation. Scenario simulations were performed for the forecast period 2015–2030.

Higher population growth rate scenario

This scenario was developed to look at the possibility of a higher population growth (HPG) rate. According to the national census 2009, the population growth rate for the county is pegged at 2.8% per annum. However, envisioning a higher percentage growth rate of 5%, this scenario tried to cater for an unexpected rise in population which may well be, due to amongst other factors, intercounty migrations leading to higher populations. It was, thereby, assumed that an increased population leads to increased domestic water use.

Increased irrigation area scenario

This scenario was chosen for the study because the county government of Bomet, where the catchment falls, increased the irrigated land area by 100 ha each year for 6 years in the period 2013–2018 (GoK 2013). This meant by adding 600 ha to the 600 ha under irrigation in the base year for this study. In the increased irrigation area (IIA) scenario scenario, it was assumed that the irrigation area would further increase by 100 ha per year until 2030.

Improved water efficiency/conservation scenario

The county government has plans to invest heavily in the water harvesting infrastructure for institutions such as schools, colleges and health centres. There are plans to also rehabilitate existing water infrastructure to minimize the water loss. This is expected to impact water demand by reducing river and groundwater abstraction. This scenario assumed a 30% improvement in water use efficiency.

Results

Major water demand and supply sources

A total of 52 major water sources were identified, mapped and quantified in the Nyangores catchment. These are subdivided as 28 springs, 6 dams and boreholes, 1 well, 14 water intake points from the river Nyangores and 3 intakes from minor streams. The majority of the dams and boreholes, 90%, are located in the upstream, while the rest are found midstream (Fig. 2).

For the WEAP21 analysis, water demand data were calculated for the catchment area. This included (1) domestic water demand at 40 litres/person/day, (2) irrigation water requirement at 43.8 m^3/ha/day (average of 365 days/year, irrigation is not applied during the rainy seasons), (3) livestock water demand at 30 L/day per tropical livestock unit and (4) finally, average industrial water demand for each of the four tea factories at 83 m^3/day, since no other relevant industries exist. The values were quantified based on the analysis of the literature, statistical and field survey data. The irrigation water demand values were obtained from the county government agriculture office, industrial water demand from the tea industry, while water demand for the human and livestock population was calculated based on the current population against the water consumption rates per capita as indicated above. The results indicate that, currently, domestic water demand takes the largest share of water at 15 Mm^3/a, followed by irrigation demand at 9.6 Mm^3/a. Livestock consumes 2.4 Mm^3/a, while the tea industry consumes about 0.1 Mm^3 annually.

WEAP simulations for the study area

Based on the catchment information derived in GIS, a model for the Nyangores area was set up in WEAP21. The study area, thereby, covers 933 km^2 and was divided into three subareas, namely upstream (Kiptagich, Tinet, Keringet), mid-stream (Silibwet Township, Ndaraweta, Bomet) and downstream (Sigor, Chebunyo, Chepalungu, Kaboson).

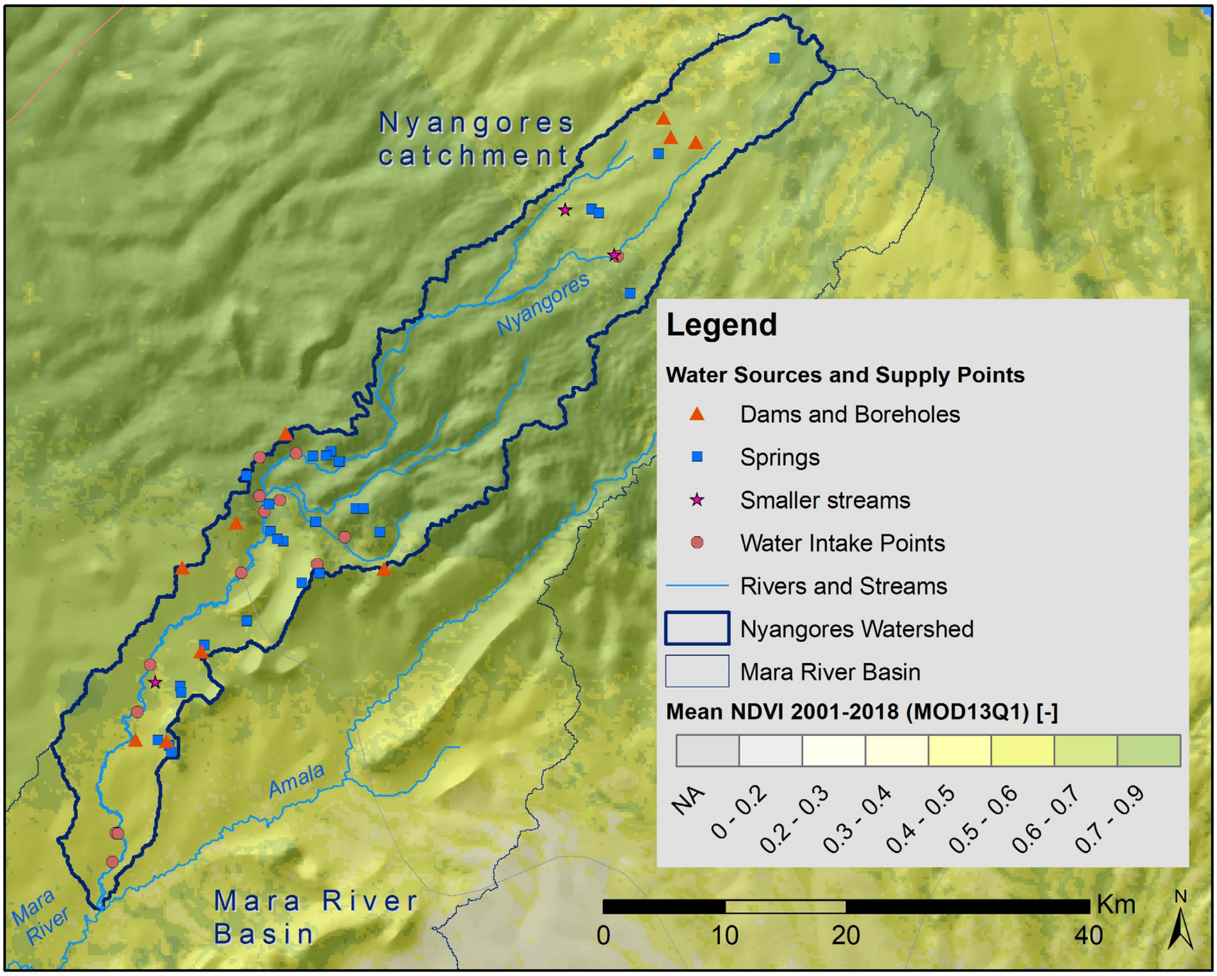

Fig. 2. Location of major water sources and supply points in the Nyangores catchment. [Colour figure can be viewed at wileyonlinelibrary.com]

Calibration and validation

Calibration is the process of adjusting the parameters of the model to correctly simulate historical observations. The hydrological calibration and validation were achieved by comparing the simulated and observed monthly stream-flow for the gauging station at Bomet (ILA03). Discharge data from 2000 to 2005 were used to calibrate the model parameters. The validity of these parameters was then tested in the validation period of 2006–2010. The results show that the general dynamics of runoff are mostly well captured by WEAP21. This is also true for the independent validation period (Figs 3 and 4).

This is also evident from (Table 1) showing metrics of the model performance. The regression coefficient R^2 of 0.92 during calibration highlights the hydrograph as captured by the model. The mean bias of 3.91 m^3/s or 23.2% in relation to the observed mean runoff, however, shows a larger quantitative bias in the calibration period. In the validation period, the model performance improves, at least when looking at the bias. The mean bias for the period 2006 to 2010 is now only –2.9% of the observed runoff. The regression coefficient R^2 between observed and simulated runoff decreases slightly to 0.88.

Reference scenario (Ref)

Figure 5 shows the annual water demand for the reference scenario. Under the business as usual scenario, the annual water demand was projected based on the prevailing demand and supply conditions. Based on the assumptions made concerning the different water demand sectors, the total water demand for the year 2030 is expected to be approximately 45 million cubic meters per annum (Mm^3/a).

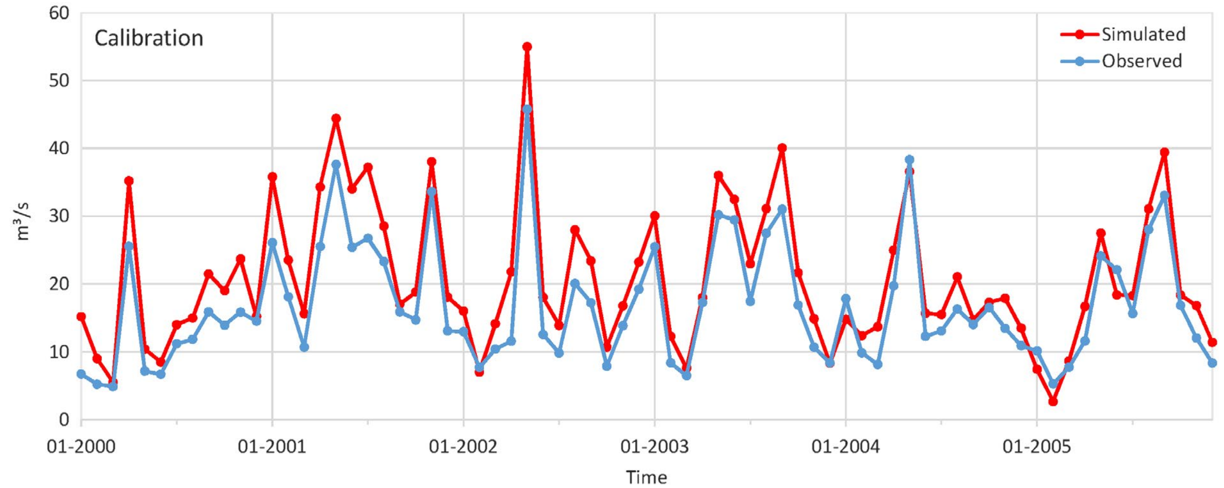

Fig. 3. Calibration hydrograph for the Nyangores River. [Colour figure can be viewed at wileyonlinelibrary.com]

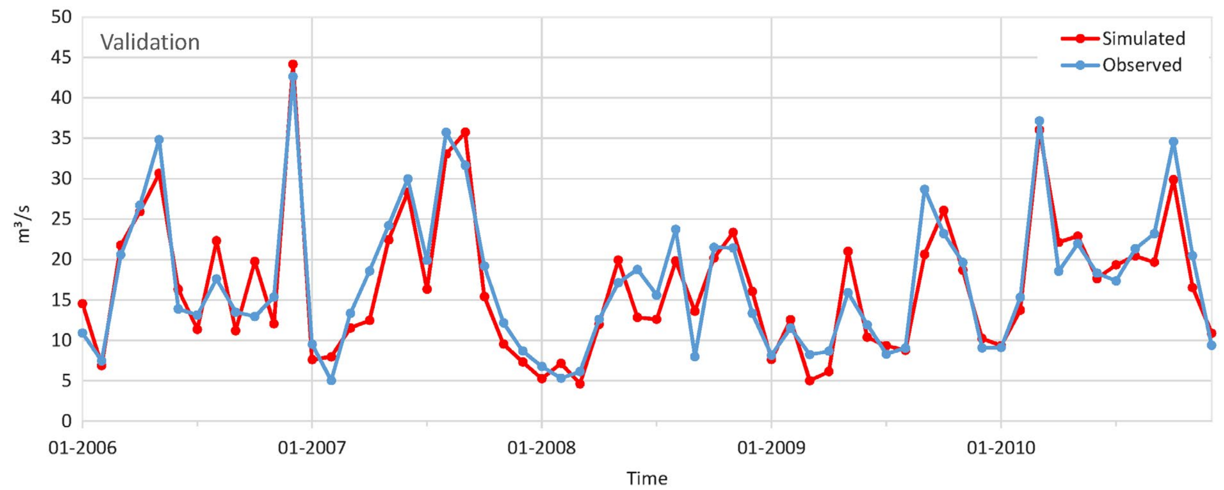

Fig. 4. Validation hydrograph for the Nyangores River. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 1 Model Performance for calibration and validation at the gauging station 1LA03 in Bomet

	Mean flow m³/s				
	Observed	Simulated	Mean bias (m³/s)	Mean bias (%)	Regression coefficient (R^2)
Calibration 2000–2005	16.87	20.78	3.91	23.2%	0.92
Validation 2006–2010	17.28	16.78	–0.50	–2.9%	0.88

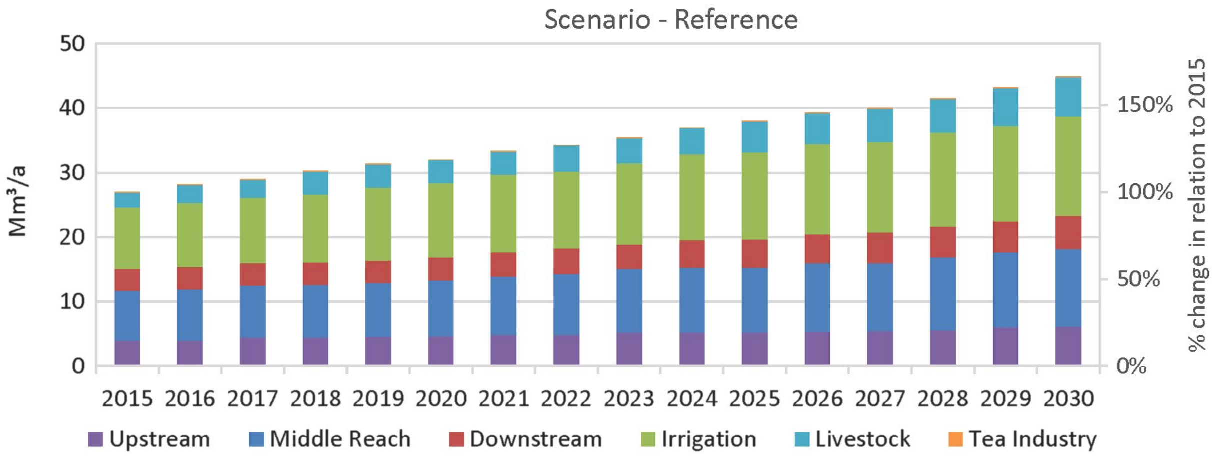

Fig. 5. Reference scenario: Annual water demand including percent change in relation to the year 2015. [Colour figure can be viewed at wileyonlinelibrary.com]

The largest share of this demand is expected to be consumed by domestic demand at 23 Mm³/a, moreover, tea industry water consumption is modelled at a neglectable demand of 0.1 Mm³/a. In total, the water demand in this scenario is projected to increase by about 66 % in comparison to the year 2015. The main driving factor for this increase is higher domestic water demand, but also a higher irrigation water demand is calculated.

Increased irrigation area

The county government has increased the irrigated areas by 100 Ha per year for the past 5 years, this new irrigation water demand is projected to reach 24.5 Mm³/a by the year 2030 (Fig. 6). This is a significant increase from the business as usual scenario. Based on the data for the year 2015, an increase of 99% is calculated for the total annual water demand for the year 2030. The main driver for the higher total water demand can be attributed to increased irrigation demand.

Improved water conservation

The introduction of improved water conservation (IWC) measures, IWC, would greatly reduce the overall water demand per year compared to the reference scenario. In total, water demand of 39.6 Mm³/a is calculated in the IWC scenario, compared to 45 Mm³/a in the reference scenario, leading to a reduction of nearly –12%. Compared to the year 2015, the IWC scenario projections for 2030, nevertheless, results in an overall increase in the annual water demand by 49%. Contrasted to the reference scenario, here the lower domestic and irrigation water demand might explain the differences (Fig. 7).

Higher population growth

Under the HPG Scenario of 5% p.a., the model projects a total domestic water demand in 2030 of 54 Mm³/a. The total water demand in this scenario by 2030 is projected to be 76 Mm³/a. This is a significant 69% increase compared to the reference scenario, in which a total water demand of 45 Mm³/a is estimated for 2030 (Fig. 8). Compared to the year 2015, the increase in annual water demand in this scenario would be even more significant, whereas an increase of nearly 180 % is calculated. Here, changes in the domestic water demand are the main driver for the increase.

Historic river flow and water demand estimates from the WEAP scenarios

Figure 9 shows a comparison of historic river flow at Bomet and water demand estimates from the WEAP21 scenarios for the year 2030 (‘HPG’, ‘IWC’ and ‘IIA’). For comparison,

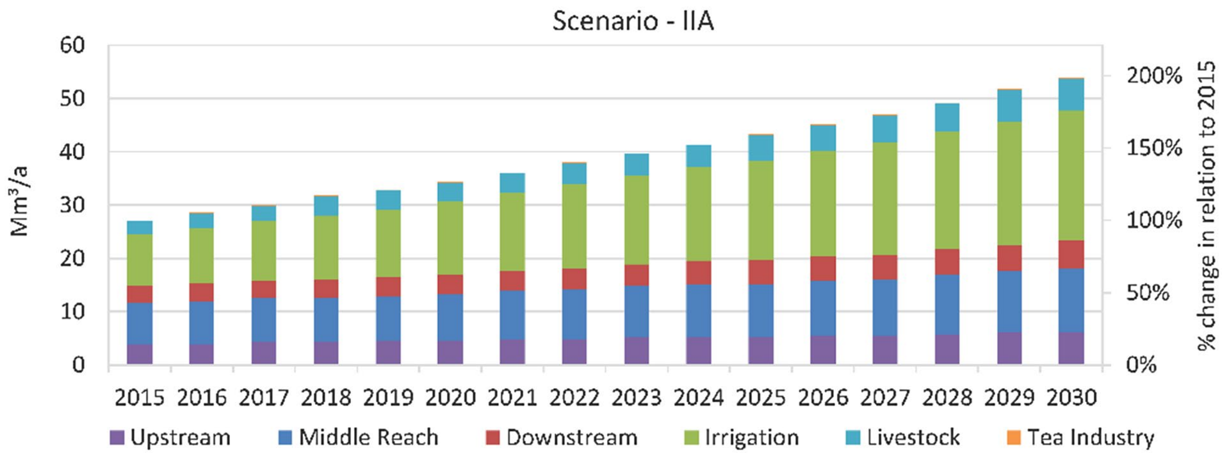

Fig. 6. Increased irrigation area scenario: Annual water demand including percent change in relation to the year 2015. [Colour figure can be viewed at wileyonlinelibrary.com]

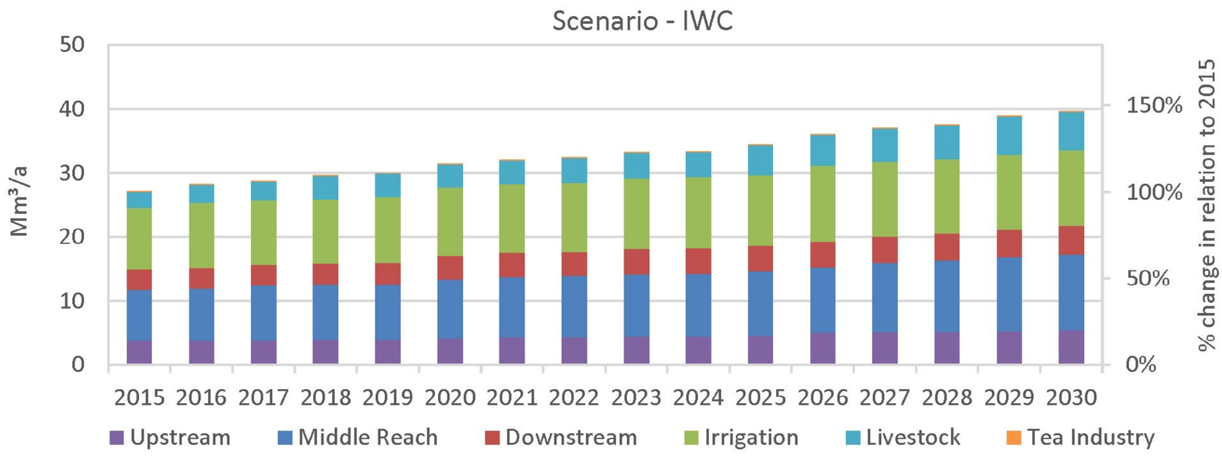

Fig. 7. Improved water conservation scenario: Annual water demand including percent change in relation to the year 2015. [Colour figure can be viewed at wileyonlinelibrary.com]

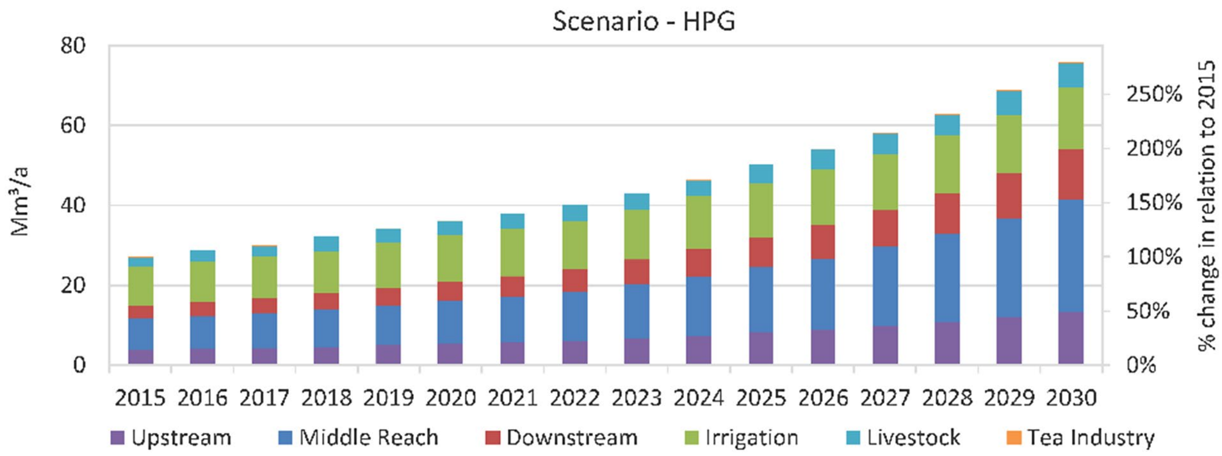

Fig. 8. Higher population growth scenario: Annual water demand including percent change in relation to the year 2015. [Colour figure can be viewed at wileyonlinelibrary.com]

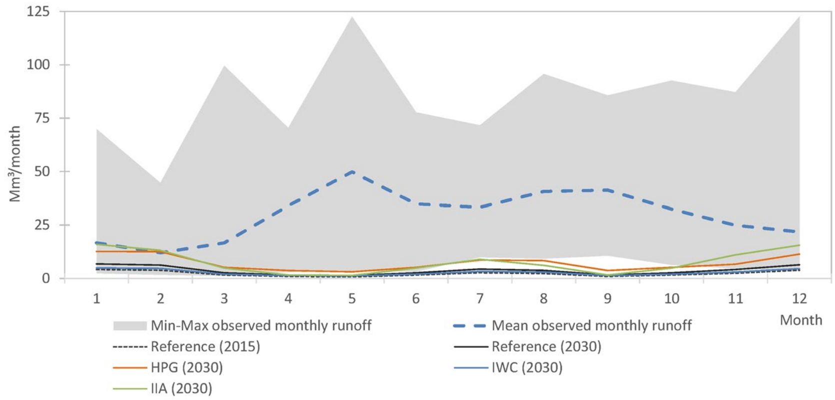

Fig. 9. Comparison of historic river flow at Bomet, water demand estimates for the year 2030 and the reference scenario for the year 2015. [Colour figure can be viewed at wileyonlinelibrary.com]

the reference scenario for the year 2015 is also included. The comparison shows, that in the dry season months of December to March, the water demand calculated in the single scenarios is higher, compared to the minimum runoff values observed in the past. This is an indication that water shortages can occur in these months, since the demand is higher compared to water availability. It is evident, that this is also the case for the reference scenario calculations of the year 2015, though the deficit is lower, compared to the future scenarios. The largest deficits are found for the future scenario 'HPG' and 'IIA', due to the higher water demand values calculated based on the assumptions made in these scenarios. These scenarios are critical, since the water demand is higher than single mean monthly runoff values, indicating that shortages may occur more frequently. It can be concluded that for all scenarios, at least on an annual basis, sufficient water is available to cover the demand, but that shortages may occur in (dry) single months or seasons. It necessitates the need for the construction of water storage structures in the catchment.

Discussion and conclusions

Using relevant and carefully selected development options in the Nyangores, this study draws attention to the unplanned water resources management efforts in the region. It depicts the possible impacts of this ad hoc approach to the water demand-supply system, the environment and subsequently, the long-term survival of the world-renowned Maasai Mara-Serengeti ecosystem. The simulation results obtained generally conform to other studies elsewhere within the region, such as Mati *et al.* (2008), Olang (2009), Mutiga *et al.* (2010) and Osoro *et al*. (2018). More particularly, however, the following conclusions could be drawn from the present study:

(1) The calibration and validation results show that WEAP21 captured the dynamics of runoff quite well. This consequently set the stage for the proper simulation of the water use in the area. Ultimately, for the year 2030, the four scenarios calculated (IWC, Reference, IIA and HPG) project an increase in water demand of 49%, 66%, 99% and 180%, respectively. The largest increase will be driven by the population which is expected to double from 566,153 (2015) to 1,176,999 (2030) at the assumed HPG scenario rate of 5% per annum. This potential increase requires strategic investment in water harvesting and water storage structures as well as the rehabilitation of existing water supply infrastructure.

(2) From the simulation of the water-demand-supply relationship, it can be concluded that an increase in annual water demand is very probable in the future, independent of the evaluated scenario. The simulations highlight, that the highest increases in water demand are to be expected, if (i) population increases significantly or (ii) larger agricultural areas are to be irrigated in the future. Moreover, they also show that there are potentials to significantly reduce water demand by implementing water conservation measures. Though it can be expected that these measures will not be very relevant for the rural domestic water demand, at least with the current, limited water distribution infrastructure, the water-saving potentials in irrigation are tremendous. These saving potentials will, however, only become effective if the state of the art irrigation methods is implemented. Minimising water losses in urban areas is and will in the future be an important task.

(3) Water shortage instances are expected to intensify in the dry season due to the increased demand and the uneven distribution of water availability. The expanded irrigation water requirements may especially escalate the water conflicts downstream. Principally, a technical measure such as dam construction can solve this problem; however, this requires substantial financial input as well as a trade-off on possible environmental impacts. Implementation of discharge dependent water use permits, or water allocation plans may mitigate these conflicts.

(4) To avert domestic water shortages in the future, the option of utilising currently unutilized water sources should be reviewed. Presently, boreholes supply only about 4% of the catchment population and the information concerning groundwater reserves in the subcatchment is limited. Investigations to assess the potential of groundwater to serve the broader public should be undertaken. Finally, the study recommends an integrated water resource management and development approach for the policymakers. Sustainable soil and water conservation efforts may be a key in minimising the degradation of the quantity and the quality of water, run-off reduction and groundwater recharge in the catchment.

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Conflict of Interest

The authors declare that they have no competing interests.

Data Availability Statement

The historical hydro-meteorological data that support the findings of this study are available from the county government and water resources authority. Restrictions apply to the availability of these data, which were used under the authorisation for the study. Otherwise, other data such as water use data is available upon request to the corresponding author.

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