Assessment of water demand dynamics in Arror watershed in Elgeyo Marakwet County, Kenya

Catherine Chebet, Emmanuel C. Kipkorir and Victor A. O. Odenyo

ABSTRACT

Water scarcity is a serious problem worldwide, which heightens the need to understand watershed dynamics and their impact on water quantity. The study examined water demand using the WEAP (Water Evaluation and Planning) model in the Arror watershed in Kenya. The primary sources of data included remotely sensed data and socio-economic data. The secondary data included climate, river discharge and soil data. Field surveys and questionnaires were used to collect socio-economic data. From the findings, the total annual water allocated (supply) for agriculture, domestic and livestock in the watershed was 10,333,441 m^3, with the highest annual consumer being agriculture in the lower part of the catchment at 7,154,457 m^3 for the reference scenario (1986–2012). The total mean annual demand for the same period was 10,461,123 m^3 and thus a mean annual unmet demand of 127,682 m^3. The highest mean monthly unmet water demand was that of agriculture in the lower part of the catchment in January (90,200 m^3). Management practices that would enhance the sustainable management of water resources include construction of a reservoir and enforcement of minimum environmental flows maintenance in the river and these are recommended for the Arror watershed.

Key words | allocation, coverage, unmet demand, water scarcity, WEAP

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INTRODUCTION

Large-scale removal of forest lands by humans in the 19th and 20th centuries has created significant changes to the hydrologic function of watersheds. Downstream flooding now occurs more frequently, with subsequent increases in loss of life and damage to infrastructure. Accelerated erosion, produced by changes in the biotic and hydrologic components of natural drainages (watersheds), has resulted in unprecedented large-scale siltation of developed lowlands. The general consensus across the globe is that deforestation is causing these undesirable impacts. However, the mechanisms for reversing the process through sound scientific management have not been developed (Mwiturubani & Wyk 2010).

Land and water resources should be managed on a watershed-wide basis because watersheds are formed by natural land masses and water flows into a common water body. In other words, watersheds are defined by natural hydrology. Each watershed has a unique characteristic that needs to be explored to develop a truly tailored management plan. Different watersheds suffer diverse environmental problems (flash flooding, reduced base flow, water quality problems, stream bank erosion and agricultural nonpoint source pollution) due to wide-ranging causes (urbanization and the increase in impervious area, mismanaged cattle grazing, among others) (Mwiturubani & Wyk 2010). Streams and rivers do not follow political boundaries, and the flow of water, pollution problems, etc. do not stop at political boundaries. Improper use of our natural resources causes flooding, erosion and sedimentation, stream bank erosion, water quality issues and reduction of groundwater and base flow augmentation (DeBarry 2004).

Water uses vary from municipal, industrial, recreational and commercial to residential functions. Therefore, one of

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the major goals of any watershed management plan should be to maintain the hydrologic budget. In order to properly manage a watershed, the comprehensive picture or holistic approach must be followed. Ensuring sustainable water resources requires comprehensive management of the many facets of water; water supply, storm water management, flood control, nonpoint pollution control and wastewater treatment and reuse. Water resources management begins with understanding the paths and uses of surface and groundwater, storm water, floodwaters, recreational waters, drinking water and irrigation water. An adequate supply of clean water is essential for maintaining the quality and health of natural ecosystems such as fisheries, forests, wetlands and aquatic habitats (DeBarry 2004).

Arror River, the subject of this paper, has its source in Cherangani Hills Forest, one of the five water towers in Kenya that serve as a steady source of water to the North Rift and Western regions of Kenya. A study by Muchemi (2004) indicates that the natural resources in the Arror watershed and the entire Kerio River basin are being depleted at an alarming rate. The depletion is caused by rampant illegal settlements, logging, overgrazing, illegal extension of farms and charcoal burning, leading to severe damage to the region's economy with an impact on energy, tourism, agriculture and water supply to towns and institutions. Moreover, the majority of people in the area practice shifting cultivation and free-range cattle holding, resulting in the degradation of water sources, soil erosion, declining soil fertility and landslides. These activities have destabilized the River Arror catchment, thereby impacting negatively on economic development at both the local and national levels and threatening food security and livelihoods as well.

Due to the degradation of the watersheds and poor farming systems upstream, the river flows downstream have reduced and the river even dries up during the dry seasons. This has affected the communities living downstream as they depend on the rivers for irrigation water, livestock and domestic use. Many sectors are competing for the limited amount of water available in the River Arror and this often leads to conflicts between the downstream and upstream water users. There is, therefore, a need to quantify the impact of degradation on the water quantity, the water demand, allocations, and hence the shortages in the watershed. Based on the study, this paper explores the dynamics of water demand in the Arror River watershed using the water evaluation and planning (WEAP) model.

According to Sieber (2006), WEAP has emerged as an integrated approach to water development that places water supply projects in the context of demand-side issues, water quality and ecosystem preservation. The WEAP system was used in this study because of its ability to integrate water resources evaluations. It also aids in the hydrological understanding of the watershed and hence predicts the hydrological response of various conservation techniques. This assists the decision-makers and local stakeholders (i.e., municipalities, water users' associations, interest groups), to understand the water balances at different levels in a basin (Stockholm Environment Institute (SEI) 2005). Water managers can then include this additional information to make catchment management plans more sustainable, taking into account the impact of upstream users on downstream users. WEAP has been applied in various studies and has been proved to be a good tool for planning for water resources in watersheds. Mounir *et al.* (2011) applied the WEAP model to assess the future water demands in the Niger River and found that WEAP provides a seamless integration of both the physical hydrology of the region and water management infrastructure that governs the allocation of available water resources to meet the different water needs. The findings revealed that there was a need for optimization of Niger River resources for the future needs of its population.

Haddad *et al.* (2007) tested the applicability of WEAP as a decision support system (DSS) tool for water resources management in a watershed or localized district. The feasibility of developing a DSS and its useful implementation for localized watershed water resource systems was clearly demonstrated by the results of this study. The results of the study also revealed that WEAP can be applied to support water management in the district.

MATERIALS AND METHODS

Study area

The study area is a region in the Cherangani Hills that drains into the approximately 112 km long Arror River, a main tributary of Kerio River, which feeds into Lake Turkana, the world's permanent desert lake. The river is approximately 112 km and is located in Elgeyo Marakwet County, Kenya. The bulk of the catchment is in the Embobut and Kipkunur forests at altitudes between 3,200 m and 2,300 m above sea level (asl). The river flows through three administrative divisions of Marakwet East and West, the sub-counties of Kapyeko, Kapsowar and Tunyo. It extends from latitudes 0°51′ to 1°19′ north and from longitudes 35°15′ to 35°45′ east (Figure 1). The Arror River watershed area covers approximately 286 km^2 and is the largest among all of those which drain to the Kerio valley. The catchment is characterized by three physiographic regions: the highlands, formed by the Cherangani Hills (forested); the midlands which is characterized by the Elgeyo escarpment; and the lowlands which is the base of Kerio valley within the Great Rift Valley. The Arror watershed can be divided into three main topographical zones which run parallel to one another in a north–south direction: the highland plateau, which rises from an altitude of 2,800 m to 3,350 m asl; the Marakwet escarpment, which ranges from 1,200 m to 1,500 m asl, and the Kerio valley, which lies between 900 m and 1,500 m asl. The major water users in the watershed are environmental flow requirements, domestic, agriculture and livestock.

Data sets and sampling

The primary data sources included Landsat satellite images, digital elevation model (DEM) and the socio-economic data. Landsat 5 thematic mapper (TM) (for the year 1986, January) and Landsat 7 enhanced thematic mapper (ETM) (for 2000 and 2012, both for the month of January) with a resolution of 30 m were used in the analysis of the land use/cover of the catchment. Anderson *et al.*'s (1976) classification system was modified and seven classes were considered for the purpose of the study: coniferous forest cover, deciduous forest cover, grassland, bare ground, riverine vegetation, crop land and wetlands. A DEM with a 90 m resolution obtained by the Shuttle Radar Topography Mission (SRTM) was downloaded from the Global Land Cover Facility (GLCF).

The DEM was used to delineate the watershed and determine the slopes of the study area. Field surveys and questionnaires were administered to collect information on the causes of land use changes, the possible solutions and other socio-economic data. The target population comprised all the residents of Arror watershed. The total population of the watershed areas was approximately 10,000 in the year 2012 as projected in the 2009 national census (Republic of Kenya (ROK) 2010). Multi-staged cluster sampling was used to randomly select the respondents.

The desired sample size was determined using the formula of Fisher *et al.* (1991), as indicated in Equation (1):

$$n = Deff * \frac{Z_{\alpha/2}{}^{*} P(1-q)}{d^2} \tag{1}$$

where *Deff* is the design effect in case of multi-stage cluster sampling (for cluster samples set at *default* value of 2). In this case, $p = 0.7$ and $q = (1 - p) = 0.3$. Using standard parameters of 95% of significance (α) and $Z_{\alpha/2} = 1.96$ were chosen. Inserting these values in the above formula resulted in a value of 646 households.

Questionnaires were used to collect the socio-economic data. The respondent had to be aged 18 years and above and must have stayed in the region for at least 2 years. Further discussions with key professional informants, the County Forest Officer, Agricultural extension officers, the Water Resource Management Authority (WRMA) officers and County environmental officers were carried out. The statistical data were first coded and entered into SPSS for analysis. Other data included the climate, soil, Arror River discharge and population data which were obtained from various organizations.

Setting up the WEAP model

WEAP is a generic computer package originally developed by the Stockholm Environment Institute in Boston, USA and is suitable mainly for surface water planning (SEI 2005). It develops a model schematization consisting of a network of nodes connected by links or branches. Water allocation priority rules are set within WEAP based on either first come first served, or specific use or user, and/or making allocation proportional to demand (Haddad *et al.* 2007).

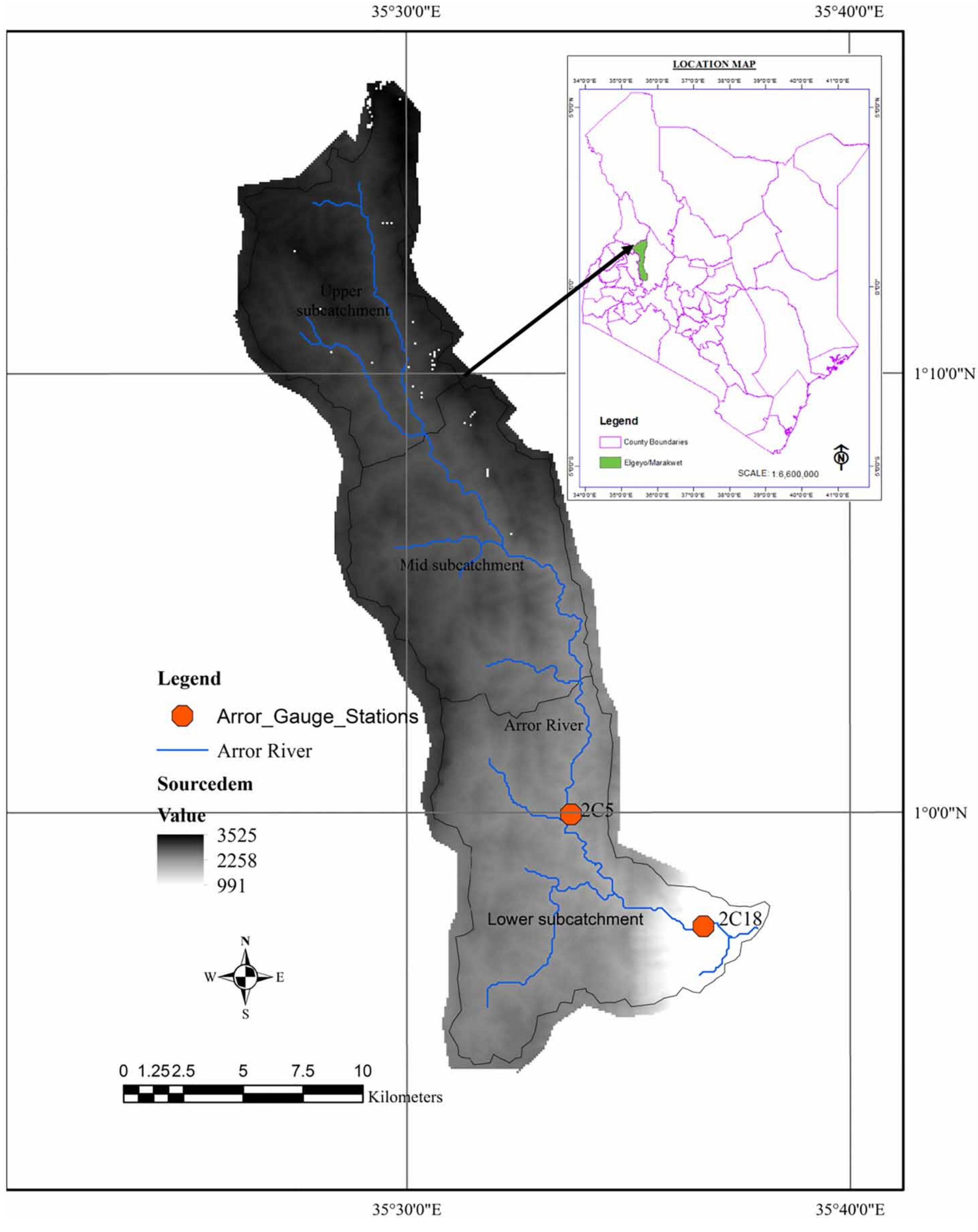

Figure 1 | Location of Arror watershed.

The WEAP tool is one of the components of integrated water management support methodologies (IWMSM) that can be implemented relatively easily to evaluate scenarios on different water allocation strategies in a user-friendly environment (SEI 2005). The WEAP model consists of the demand, which in the case of this watershed are mainly domestic, livestock and crop farming. Domestic water use is the most important, and has the highest priority. The second most important use is livestock and the third is agriculture, with other uses having least priority. In the study, the Arror River was considered as the main source of water supply. The other variables that are required for the model include the state of the Arror watershed (land use, climatic conditions and soil). All three major variables (the demand, supply and Arror watershed) combined with literature from other studies help in decision-making for watershed management. The WEAP model makes it possible to integrate all these variables, and thus make informed decisions on the planning and management of the water resource in a watershed.

In WEAP, the typical scenario modelling effort consists of three steps. First, a current accounts year is chosen to serve as the base year of the model; second, a reference scenario is established from the current accounts to simulate likely evolution of the system without intervention; and third, what-if scenarios are created to alter the reference scenario and evaluate the effects of changes in policies and/or technologies. The data used in modelling for current accounts were for the period 1986–2012. For allocation of available resources, a number of options tested by developing several scenarios and future water demands were projected. The WEAP software was used to evaluate the future water demands in the Arror watershed region (SEI 2015).

The characterization of the water system involves collecting and entering the following data: water uses (demand sites), flow gauging stations and flow requirement (ecological reserve). The data input in WEAP is structured according to the schematic set-up of the catchment.

Geographical characteristics of the catchment

Three topographical map sheets (scale 1:50,000), namely, Kapsowar-sheet 90/1, Cherangany-Sheet 75/4 and Tot-sheet 76/3, all of series Y731 (D.O.S.423) were combined to form the river system. The total area covered by the Arror River catchment is approximately 286 km^2. The catchment was sub-divided into three sub-catchments based on the main tributaries. The three sub-catchments were then named as the upper, middle and lower catchments covering 76.15 km^2, 92.9 km^2 and 117.27 km^2, respectively.

The catchments

For catchments in the WEAP model, the study utilized the rainfall–runoff method which is a simple method that computes runoff as the difference between rainfall and a plant's evapotranspiration. The evapotranspiration is estimated by first entering the reference evapotranspiration (ETo), then defining crop coefficients (Kc) for each type of land use. Then, crop water requirement (ETc) for a specified period is computed as the product of Kc and ETo to reflect differences occurring from plant to plant (Allen *et al.* 2005). The data necessary for this study under the catchments in the WEAP model were the land uses and they were defined using Kc and climate.

Land use

Land use in the WEAP model includes the total area of the catchment, the crop coefficient (Kc) and effective precipitation. The land uses in the watershed in GIS were incorporated into the WEAP system. The percentage area covered by each land use was considered, and for agriculture the principal crop in the watershed was chosen as the representative crop for the area for the purpose of analysis. The Kcs for each of the three catchments were calculated with the help of the guidelines in the FAO-56 paper (Allen *et al.* 1998) where the dominant land uses were considered. The Kc of the dominant crops, which were potatoes, maize and millet for the upper, middle and lower sub-catchments, respectively, were obtained from Puttemans *et al.* (2004). The effective precipitation, which is the percentage of precipitation available for evaporation, was calculated based on the total monthly precipitation.

Climate data

The monthly rainfall data for 1986–2012 (27 years) were utilized. Since the evaporation data for the study area were not available, an ETo calculator was used to obtain the reference evapotranspiration (ETo) of the catchment (Allen *et al.* 1998). The ETo calculator computes ETo from meteorological data by means of the FAO Penman–Monteith equations. In this study, the monthly maximum and minimum temperature data were used to compute ETo. The climate data were sourced from the Kenya Meteorological Department (KMD), which is the official custodian of climatic data in Kenya. The KMD data were complemented with data collected by the Kerio Valley Development Authority (KVDA). Climatological data for the Arror watershed are limited due to the absence of well-maintained meteorological stations. The stations, Kapsowar and Arror, that are within the study area had only rainfall data which also had numerous gaps.

Temperature data for 1985–2012 were extrapolated from the neighboring Eldoret, Kitale and Chebiemit stations to create dummy stations. Time series for daily maximum and minimum temperatures (Tmax and Tmin, respectively) were generated using the temperature lapse rate method of Minder *et al.* (2010). In the IDW method used to develop time-series rainfall data, sample weights were inversely proportional to the distance from the point estimated. All stations with long-term data sets were used in the algorithm to determine the weighted rainfall for the new station. The dummy stations include Kipkunur and Koitilial (Appendix, Tables A1–A4, available with the online version of this paper).

Demand sites

There are three main uses of water in the study area and hence three main demand sites, namely, domestic, agriculture and livestock. Other demand areas are commercial, institutional and industrial, but they were not included in this analysis. Water use activities and rates for all the demand areas identified were then developed.

For domestic use, the annual activity is the total number of people in the study area while the annual water use rate is the demand per person per year. The population census reports of 1979, 1989, 1999 and 2009 were used for the purpose of estimating the annual activity of the three catchments (Republic of Kenya (ROK) 2010). The annual use rate was assumed to be 25 litres per head per day, as specified by the Ministry of Water Development Design manual, as the demand for rural areas when served by communal water points (Republic of Kenya (ROK) 1984).

For livestock, the annual activity is the total number of livestock in the area and the annual water use rate is the average demand per animal per year. The main source of water for livestock in the study area was the river. The animals kept in the study area were mainly cattle, goats, sheep and donkeys. The total number of livestock was approximated from the information obtained through interviews combined with the census data on the number of households (Figure 2). The livestock demand was assumed to be 75 litres per day per livestock unit (LSU). LSU can be one grade cattle or three native cattle or fifteen sheep (Republic of Kenya (ROK) 1984).

Regarding agriculture use, the data on the exact amount of water used for irrigation were not available and farmers also do not know how much water they use for irrigation; therefore, irrigation water demand for the watershed was estimated using the computed ETc and effective precipitation (P) concept as outlined in FAO-56 (Allen *et al.* 1998). The total size of land in square metres under cultivation obtained through interviews with the residents and from the census reports was considered as the agricultural annual activity (Figure 3). The volume required per square metre was considered as the water use rate. For agriculture, the monthly variations were imposed because of the crop coefficients (Kc) that vary throughout the year depending on the crop water requirement at various stages of growth. This value varies from crop to crop and also changes as a crop goes through the different stages of growth.

Reserve requirements

The key principles of the Kenya Water Act (2002) are sustainability and equity (Republic of Kenya (ROK) 2012). The Act emphasizes that, as we use water resources to promote social and economic development, it is crucial to protect the environment while ensuring that the water needs of present and future generations can be met. This is partly achieved by leaving enough water in a river, referred to as the reserve, to maintain its ecological functioning; it was

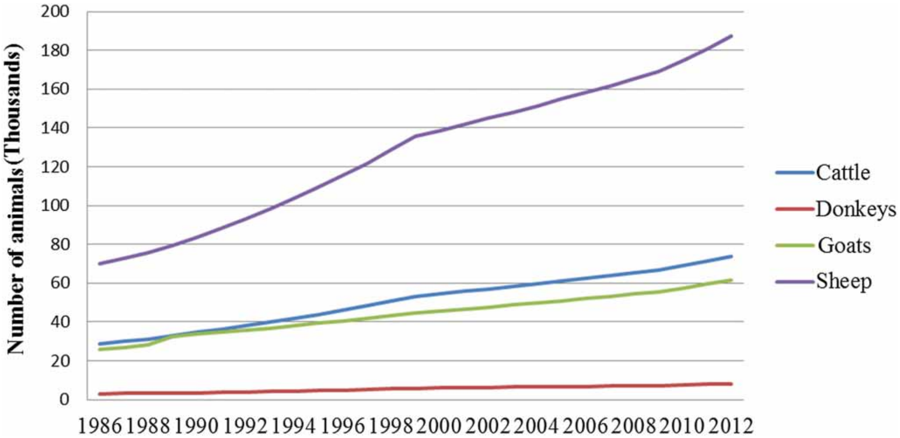

Figure 2 | Arror watershed livestock population.

therefore assigned the highest priority over all other water uses and must be met before water resources can be allocated to any other uses.

Calibration and validation of the WEAP model

After setting up the WEAP model, calibration had to be undertaken before exploring the various scenarios. Calibration was done by using the data for the current scenario and comparing WEAP output to the observed situation. Before calibration, sensitivity analysis was performed. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters). Effective precipitation and Kc were identified as the parameters to be modified during calibration. Model calibration was then followed by model validation in order to assess the performance of the model. According to Refsgaard (1997), model validation is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations. The model performance was evaluated using standard statistics: mean error (ME), mean square error (MSE) and model coefficient of efficiency (EF), also known as NSE and R^2 (Moriasi *et al.* 2012).

Scenarios

Several scenarios were considered in the study, one being the reference scenario, in which the current situation is

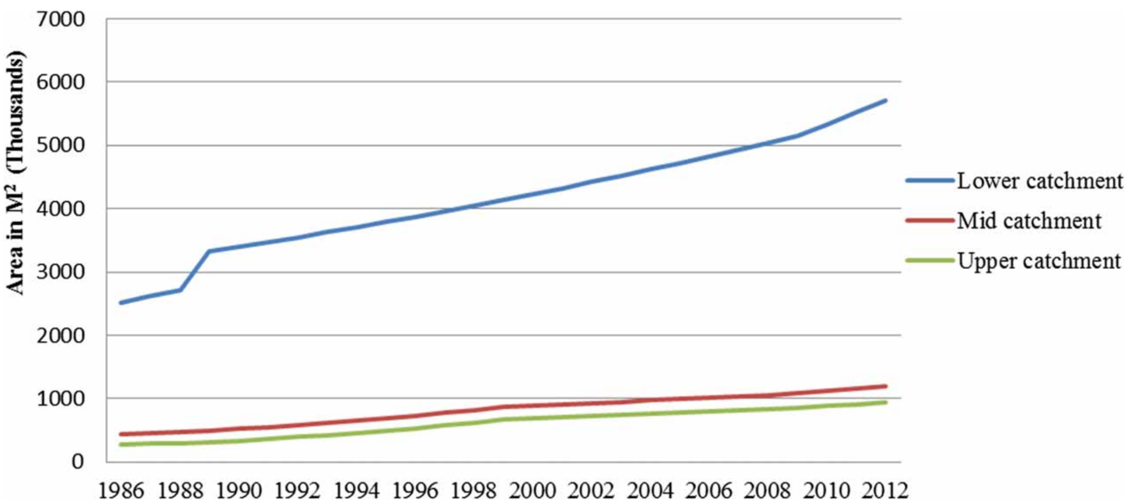

Figure 3 | Areas under irrigation in the three sub-catchments of Arror watershed.

extended to the 'future' (1987–2012). The other scenarios considered were to address a broad range of 'what if' questions, such as: What if population growth patterns change? What if ecosystem requirements are tightened? What if the cultivated area is increased? What if reservoirs are constructed? The water allocations, demand, unmet demands and demand coverage for the various water uses were then compared for the different scenarios. Figure 4 shows the location of the reservoir that was used to simulate the impact of reservoir construction on water demand in the watershed.

Water year method in WEAP

According to the WEAP model, the water year method allows use of historical data in a simplified form and exploration of the effects of future changes in hydrological patterns. The water year method can also be used to test the system under historic or hypothetical drought conditions, so that climate changes will be more understood and can be presented in one scenario but not used in a reference scenario (SEI 2005). A scenario based on the water year method was also considered in this study. Hydrologic fluctuations are entered as variations from a normal water year (the current account year is not necessarily the normal water year). The water year method requires data for defining standard types of water years (water year definitions), as well as defining the sequence of these years for a given set of scenarios (water year sequence). A water year type characterizes the hydrological conditions over the period of one year. The five types that WEAP uses are: normal, very wet, wet, dry and very dry. The rainbow model was used to obtain the historical pattern, which was then used to derive historical rainfall series.

RESULTS AND DISCUSSION

The water demand was analysed in a DSS based on the WEAP model. The WEAP model had to be calibrated and validated before its application.

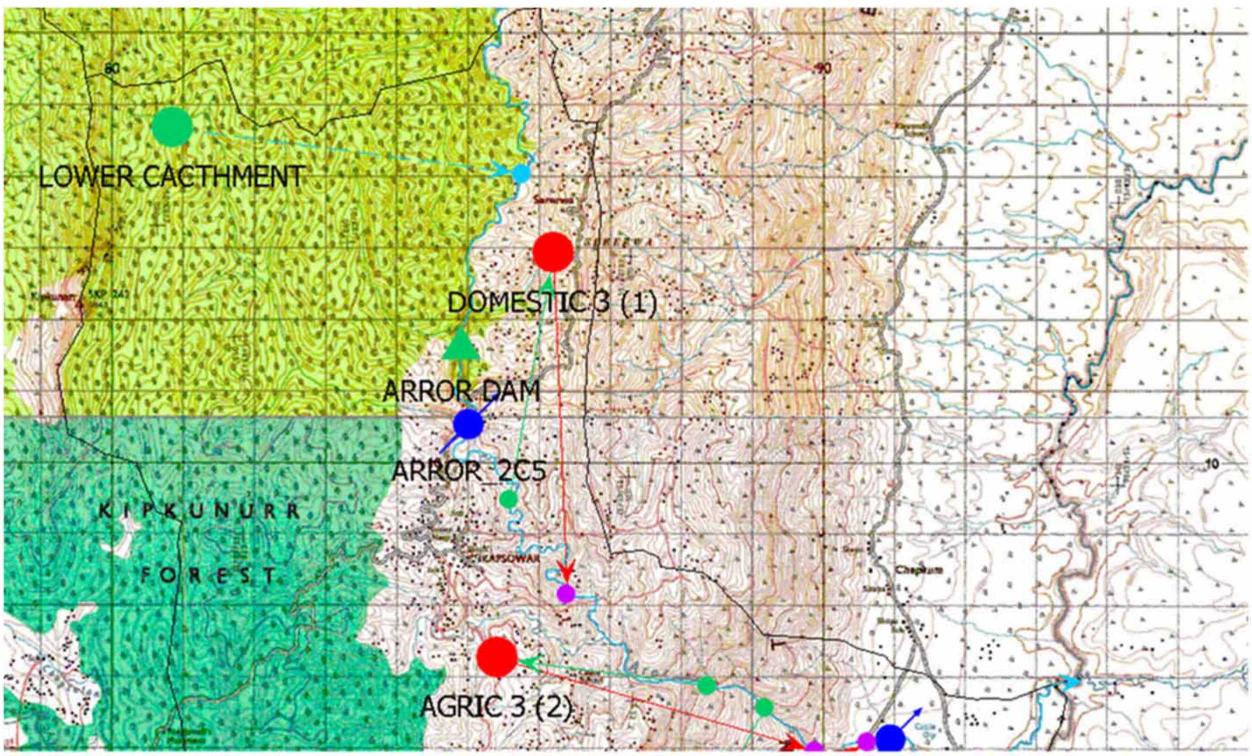

Figure 4 | Location of the dam set for future scenarios.

Calibration and validation

The observed mean annual stream flows for the period 1986 to 1999 at station 2C18 (a station located near the catchment outlet) were used to calibrate the model, and 2000 to 2012 for validation. The results indicated that the model was able to predict the general trend of the catchment processes reasonably well (Table 1).

In Figure 5, the time series shows the observed stream flows and the simulated stream flows of the reference scenario. The graph shows that the simulated flows follow the trend of the observed flows.

Scenario analysis

Reference scenario

The reference scenario is the scenario in which the current situation is extended to the 'future' (1987–2012). No major changes are imposed in this scenario. A linear population increase was assumed based on the Central Bureau of Statistics reports (Republic of Kenya (ROK) 2010). The model mimics reality over the period 1987 to 2040, given the constraints of simplification of the model and data limitations. This scenario was used to analyse the water allocations, the unmet demands as well as the demand coverage in the Arror watershed.

Table 1 | Statistical analysis of the performance of river flows in Arror River

	ME (Fraction)	MSE (Fraction)	R^2 (Fraction)	NSE (Fraction)
Calibration (1986–1999)	−0.003	0.026	0.88	0.85
Validation (2000–2012)	0.057	0.018	0.96	0.95

ME: mean error; MSE: mean squared error; NSE: Nash–Sutcliffe model efficiency coefficient; R^2 goodness of fit.

Water allocation in the watershed: The upper and mid catchments depend mainly on rain-fed agriculture, while the lower catchment farmers depend on irrigation since rainfall there is quite erratic and scarce. In the whole catchment, a large percentage of water is utilized for agriculture followed by livestock and the least is domestic.

The mean annual water allocation over the period 1986–2012 showed that agriculture demand site in the lower catchment was allocated the highest amount of water (Table 2).

Demand coverage and unmet demand: The annual water demand for the reference scenario extended to 2040 shows that the demand for water by the various uses in the three sub-catchments has been increasing steadily over time (Figure 6). For the upper and the lower sub-catchments, the highest demand was for agriculture with a mean annual demand of 468,055 m^3 and 7,254,685 m^3, respectively, while for the middle catchment, livestock displayed the highest demand compared to the rest of the demand sites with an annual mean of 1,064,483 m^3. Domestic demand was the lowest in all three sub-catchments with an annual mean of 177,445 m^3, 182,048 m^3 and 42,225 m^3 for the upper, middle and lower sub-catchments, respectively.

The average monthly demand for agriculture in the lower sub-catchment was the highest in most months of the year as compared to other demand sites. The lowest demand for the lower sub-catchment agriculture was posted in the months of August (209,975 m^3) and September

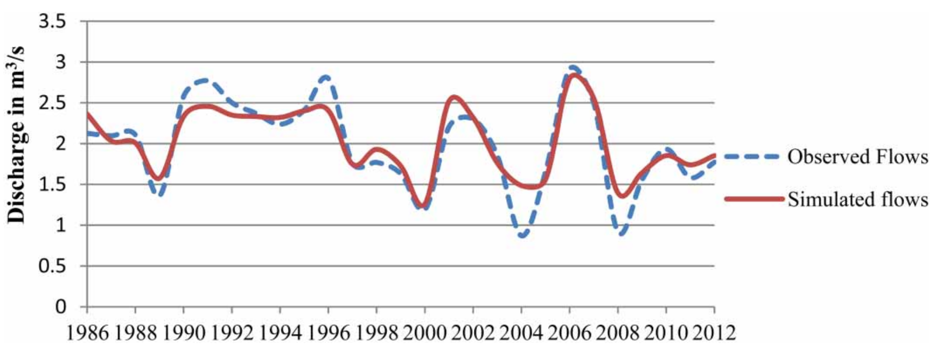

Figure 5 | Mean annual discharge (1986–2012).

Table 2 | Average annual water allocation 1986–2012

Demand sites	Supply delivered in m^3
Agric lower	7,154,457
Agric upper	455,810
Agric mid	583,781
Domestic lower	42,225
Domestic upper	177,445
Domestic mid	182,048
Livestock mid	1,064,483
Livestock lower	254,811
Livestock upper	418,381

(104,345 m^3). The rest of the demand sites did not show substantial variation throughout the year (Figure 7).

The results on the total average monthly water demand for the whole catchment show that agriculture is the main consumer of water throughout the year in the Arror watershed with mean monthly demand of 604,557 m^3, 49,915 m^3 and 39,005 m^3 for the lower, middle and upper sub-catchments, respectively (Figure 8). It also shows that the highest demands for agriculture are in the months of January, February, March and December, which are the driest months of the year and hence evapotranspiration is at its peak. During this period most farmers also use water from the river for irrigation since rainfall is very low or missing completely. This conforms to earlier studies by UNDP (1990) which concluded that in Africa, 88% of stored water is consumed by agriculture, mainly in irrigation. Domestic water consumption is very small (30 to 40 litres/day/capita). It is anticipated that as Africa increasingly develops, the demand for water for food production and for domestic use, as well as for industrial development, will also increase (UNDP 1990).

In order to understand the magnitude of water shortage in the catchment, the unmet demands for the various sites had to be determined. The results for the total monthly unmet demands for 1986–2012 showed that agriculture in the three sub-catchments had some unmet demands in January 1994 (78,406 m^3), January 2000 (458,946 m^3), January 2001 (571,289 m^3), December 2001 (296,562 m^3), January 2003 (47,806 m^3), January 2005 (359,011 m^3), January 2009 (784,765 m^3), December 2009 (46,539 m^3), January 2011 (250,855 m^3) and January 2012 (553,218 m^3). This is because January is the driest month of the year in the catchment. This is due to low rainfall and high evapotranspiration in the lower sub-catchment, coupled with the fact that a lot of abstractions take place in the middle sub-catchment which reduces the amount of water that reaches downstream. The average annual amount of water supplied to the various demands in the middle and upper sub-catchments, as shown by the results from the WEAP output, was 2,881,948 m^3. This clearly illustrates the impact of the activities of the upstream users on the downstream dwellers. The rest of the years had their demands met in all the sub-catchments throughout the year. The total unmet demand

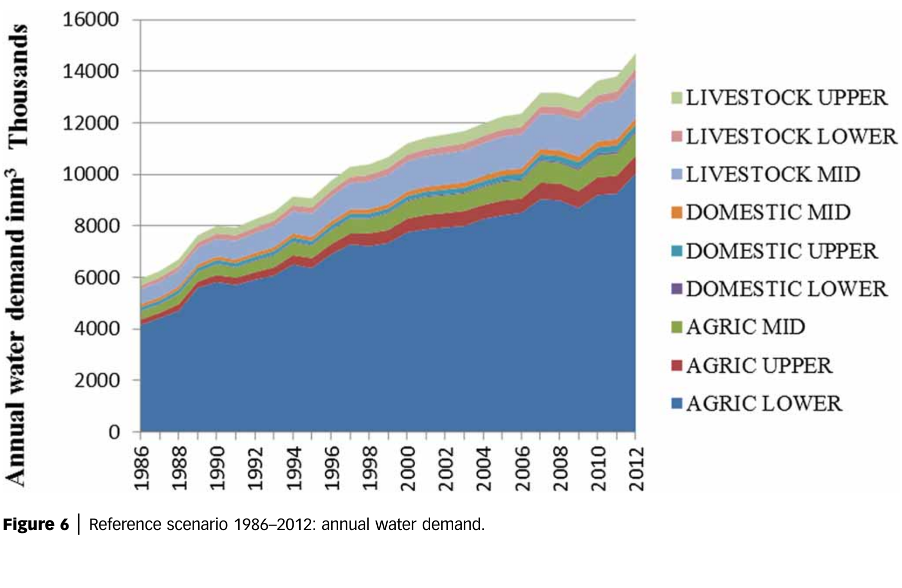

Figure 6 | Reference scenario 1986–2012: annual water demand.

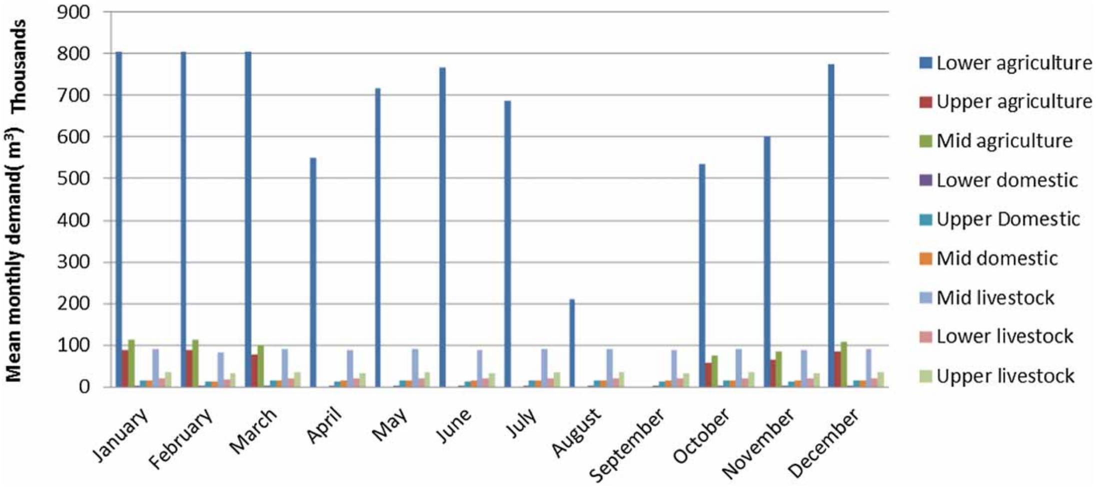

Figure 7 | Reference scenario 1986–2012: mean monthly water demand per sub-catchments.

in the catchment in the period 1986–2012 (reference scenario) was 3,450,000 m^3.

In the reference scenario 1986–2012, the highest mean monthly unmet demand was that of agriculture demand site in the downstream catchment in the month of January which stood at 90,200 m^3. In the month of January, still there was unmet demand for the agriculture midstream and upstream catchments at 13,700 m^3 and 11,000 m^3, respectively. In December, there was an average unmet demand of 9,900 m^3, 1,500 m^3 and 1,200 m^3 for the downstream, midstream and upstream, respectively. The rest of the months from February to November had their supply requirements fully met.

When the reference scenario was extended to 2040, apart from January and December, February also had some unmet demands in the three agriculture demand sites only. In the same period, the mean unmet demands for January increased to 401,000 m^3, 60,000 m^3 and 50,000 m^3 for the lower, middle and upper sub-catchments, respectively. In December it was increased to 152,000 m^3, 23,000 m^3 and 19,000 m^3 for the lower, middle and upper sub-catchments, respectively. For February it was 97,000 m^3, 15,000 m^3 and 12,000 m^3 for the three sub-catchments in the same order (Figure 9). These results show that the unmet demands increased with time and this can be attributed to an increase in population, which in turn leads to increased demand for food, calling for

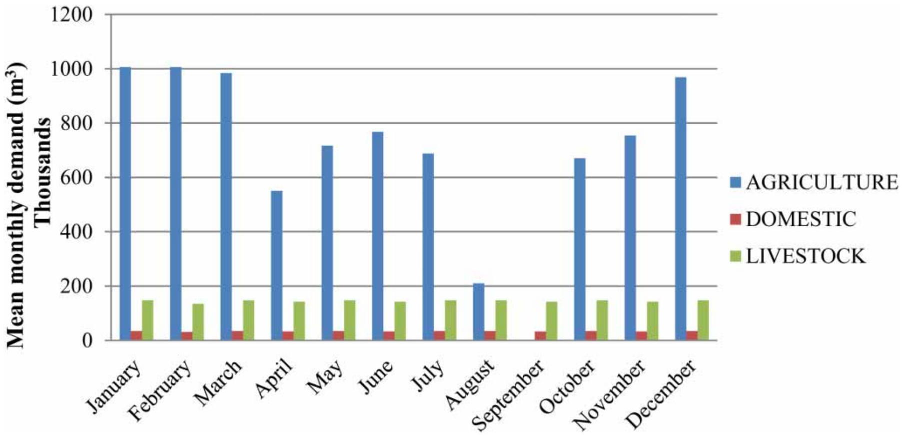

Figure 8 | Reference scenario 1986–2012: mean monthly water demand for the whole catchment.

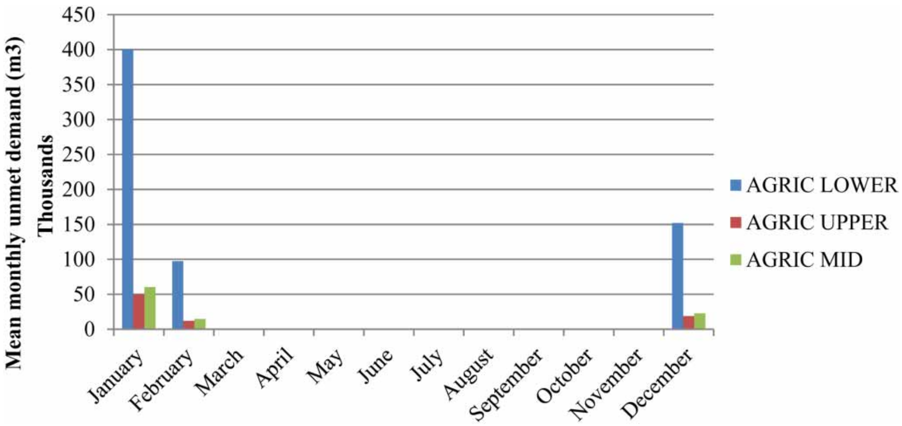

Figure 9 | Reference scenario 1986–2040: mean monthly unmet demand.

expansion of agriculture and increased number of livestock kept. This will definitely lead to more demand for water in terms of domestic, livestock and agriculture, which is the highest consumer of water in the catchment. On the other hand, there are issues of climate change and poor management of the catchment which may affect the supply side of the equation negatively. There are other issues like industrial development, which actually affects the demand for water but was not considered in this study. With all these combined, it is expected that there will be an increase in demand and supply may reduce with time, and thus, there will be critical water shortage in the catchment by the year 2040.

The total annual unmet water demand for the reference scenario extended to 2040 indicates that the demands for all sites in the whole catchment were satisfied in all the years before 1994. It shows that 1994 was the first year to experience some shortage, then 2000 and 2001 among others, with 2037 expected to have the highest unmet demand of 5,813,000 m^3.

On average, the demand site coverage (percentage requirement met) for the 1986–2012 period was 100%, except for January and December where the coverage was 90% and 95%, respectively, for all the three agriculture demand sites. For the 1986–2040 period, the demand coverage was 100% for all demand sites for 9 months; that is, from March to November. In January, February and December the agriculture demand coverage for the three sub-catchments was 77%, 95% and 92%, respectively, whereas the rest of the demand sites were 100% each. The low demand coverage in these 3 months of the year could be attributed to the fact that most people in the catchment depend on river water and the river flows are quite low during these months given that they are the driest of the year. During the rainy seasons the agriculture demand sites are fully covered since the rain water supplements the river water.

Other scenarios

Apart from the reference scenario, other scenarios were also considered so as to evaluate their impact on the water supply and demand in the catchment. All the scenarios were inherited from the current accounts scenario. These included the following:

- *Increased population growth from 2.7% in the reference scenario to 3.5% per annum from 2013 to 2040*: This scenario was used to model the impact of higher population growth rate on the water demand. This was meant to answer the question; What if population growth rate increased?
- *Increased irrigated agriculture from a growth rate of 2.9% to 5% per annum*: This scenario was used to answer the question: What if irrigated agriculture was increased at a higher rate than that of the reference scenario?
- *The water year method so as to factor in the historical climate change*: This scenario was used to simulate climate variation based on the historical trend. The water year method projects future inflows by varying the inflow data from the current accounts according to the water year sequence and definitions specified in the Hydrology

section of the WEAP model. It was used to test a hypothetical event or set of events, or wish to approximate historic patterns.

- *Increased population combined with water year method*: This scenario simulates the impact of increased population and hence higher demand combined with climate variation on the water resources in the catchment.
- *Reservoir added*: This scenario was used to determine the possible impacts of construction of a reservoir on the water demands and stream flows in the catchment. It was also used to estimate the increase in irrigated agricultural area for a given reservoir capacity. The priority was set to 99 (the lowest possible priority), so that it will fill only after all other demands have been satisfied. There were three scenarios where one reservoir was introduced in the catchment but its capacity was varied (25, 50 and 100 million cubic metres). The purpose of the reservoir was limited to flow storage and flow regulation only. This is a scenario for water resource development.
- *Minimum flow requirement added*: A minimum flow requirement is minimum monthly flow required along a river to meet water quality, fish and wildlife, navigation, recreation, downstream or other requirements. It is the minimum average monthly in-stream flow required for social or environmental purposes (SEI 2005). The study used the flow duration curve (FDCShift) in WEAP to estimate the minimum flow requirement of the river. This scenario addressed the question: What if minimum flow requirement is introduced in the river?
- *Minimum flow required added under reservoir*: In this scenario the two scenarios were combined so as to simulate the impact on water quantity when both of them are introduced in the catchment.
- *Reservoir added under increased agriculture*: Various capacities of reservoirs were simulated under increased agriculture.

The impact of the various scenarios on water demand

The result for the annual water demand shows that the demands in all scenarios increased steadily over time although the increased irrigated agriculture scenario increased at a higher rate than the rest of the scenarios. The 'higher population growth rate' and the 'higher population growth rate with the water year method' scenarios posted slightly higher increases in demand than the other five scenarios. This shows that if irrigated agriculture is expanded in the study area there will be a great impact on the water resources, in that the demand for water will go up and if the supply is maintained at the same level there will be a shortage (Figure 10).

On average, the increased irrigated agriculture scenario shows the highest unmet demands, being severe in January, February and December. January has the highest unmet demand under seven out of the eight scenarios followed by February and December. The 'reservoir added' scenario is the only scenario without any unmet demands throughout the year. The 'flow requirement added' scenario had unmet water demands in more than half of the year.

Regarding the varied reservoir capacity scenarios, the least storage capacity that will reduce the unmet demand is 15 million m^3. When a reservoir is introduced in the catchment, water becomes adequate for all the demands. When agriculture is increased by 5%, the upper sub-catchment agriculture demand site is expected to have an average monthly unmet demand of 5,085 m^3 in January, but for the rest of the months all demand sites are fully satisfied. For the reference scenario, there was a deficit of 510,000 m^3, 124,298 m^3 and 193,654 m^3 for January, February and December, respectively. The monthly unmet demand for the increased agriculture without a reservoir showed that there will be a mean monthly water shortage of 950,915 m^3, 438,318 m^3, 14,405 m^3, 2,351 m^3 and 521,895 m^3 for the months of January, February, March, November and December, respectively. On increasing the irrigated agricultural area in the lower catchment and leaving agricultural land in the other two sub-catchment to continue with the same trend as the reference scenario, unmet demands were realized in February (8,090 m^3) and March (45,739 m^3).

After running several simulations it was found that the minimum reservoir capacity that would ensure no water scarcities in the catchment would be 25 million m^3, but this would not allow for the expansion of the irrigated agricultural area. However, the most appropriate storage capacity for the reservoir would be 100 million m^3. With this reservoir constructed in the catchment, the farmers in the lower sub-catchment will be able to irrigate up to 150% of the current agricultural land comfortably without

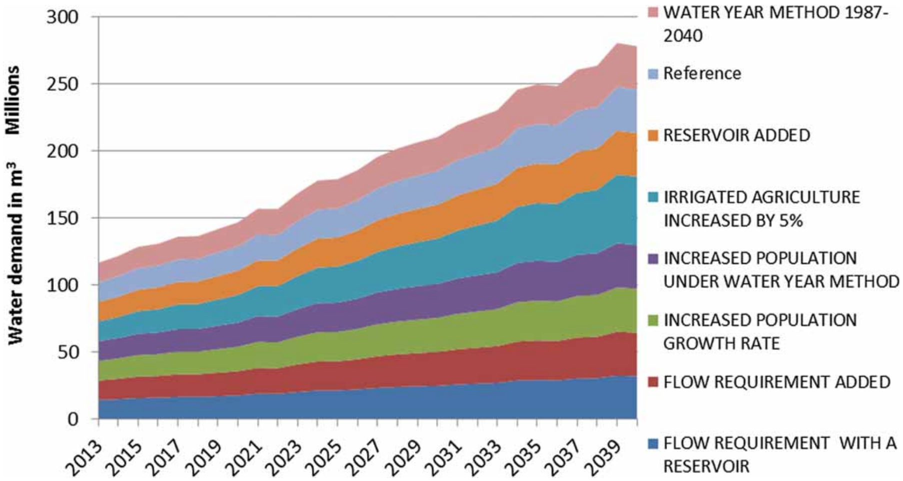

Figure 10 | Annual water demand for all the scenarios 2013–2040.

any water shortages. With such increase in agricultural area it is expected that by 2040, the irrigated agriculture in the lower catchment will be 27% of the total potential irrigable area as compared to the current cover of less than 10%.

Demand site coverage for the various scenarios: 2013–2040

Regarding demand site coverage, the best scenario that displays 100% coverage throughout the year, on average, is the 'reservoir added' scenario. This is then followed by the 'reference' and the 'increased population growth rate' scenarios, which have some slight drop in coverage for all the three agriculture demand sites in January, February and December. The 'irrigated agriculture increased' scenario had some deficit in the months of January, February, March, November and December for all three agriculture demand sites. The 'water year method' scenario also had the same coverage as the 'reference' scenario except for January, where the domestic and livestock demand sites for the upper and the middle sub-catchments had their demand coverage as slightly less than 100%. The 'increased population with water year method' scenario displayed the same results as the 'water year method'. The results for 'flow requirement added' as well as the 'flow requirement with a reservoir' scenarios show that, apart from the shortages displayed by the reference scenario, domestic and livestock demand sites in the upper sub-catchment experienced some substantial shortages in most of the months of the year.

Reliability is the percentage of the time steps in which a demand site's demand was fully satisfied. For demand reliability, the results show that all the domestic and livestock demand sites in the middle and lower sub-catchments were fully satisfied in all the scenarios over the 28 years (2013–2040). All the agriculture demand sites posted less than 100% in all the scenarios except for the 'reservoir added' and the 'flow requirement with a reservoir' scenarios, which were 100% for all the demand sites for the entire period. This means that all the demand sites were fully satisfied under these scenarios for the whole period. This is because a reservoir stores excess water during the rainy seasons and this is utilized during the dry seasons, thus ensuring water availability throughout the year. The 'flow requirement added' scenario also posted the lowest demand reliability for domestic and livestock demand sites in the upper sub-catchment (73.8%) in addition to the agriculture demand sites. This is attributed to the fact that the flow requirement scenario ensures that a minimum flow is maintained in the river and thus reduces the amount of water available for consumption.

CONCLUSION

The study's results on development of the DSS based on the WEAP indicated that the model is able to predict the general trend of the catchment processes. The time series showed the observed stream flows and the simulated stream flows of the reference scenario followed the same trend. The simulation of the various scenarios showed varied impact on water demand in the watershed. This DSS was able to predict the future water demands and shortages under various scenarios, e.g., the increase in population, expansion in agriculture, some watershed management interventions put in place and the changes in climatic conditions based on historical trend. This is very useful information for watershed and water resource planners. With this, the water resource planners and other stakeholders will be able to make informed decisions as they plan for water resources in the catchment.

Agriculture and livestock keeping are the main economic activities in the study area. The upper and mid catchments depend mainly on rain-fed agriculture, while the lower catchment farmers depend on irrigation since rainfall there is quite erratic and scarce. In the whole catchment, a large percentage of water is utilized for agriculture followed by livestock and the least is domestic. The mean annual water allocation over the period 1986–2012 showed that agriculture demand site in the lower catchment was allocated the highest amount of water. The study concluded that agriculture was the main consumer of water throughout the year in the Arror watershed. It is quite apparent that water demand is increasing with time and by the year 2040 there will be higher water shortages in the catchment if appropriate measures are not put in place.

For total monthly unmet demands, agriculture demand in the lower sub-catchment was the most affected. On the demand reliability, the domestic and livestock demand sites in the middle and lower sub-catchments were fully satisfied in all the scenarios over the period 2013–2040. The demand reliability in the 'reservoir added scenario' was 100% for all the demand sites for the entire period. The 'flow requirement added scenario', on the other hand, posted the lowest demand reliability for domestic and livestock demand site in the upper sub-catchment. In general, the unmet demands are expected to go up while demand coverage is expected to decrease in future if the same trend continues.

A reservoir whose main purpose will be irrigation and generation for hydroelectric power should be constructed in the watershed. This will ensure water availability throughout the year and in all parts of the watershed (upstream, midstream and downstream) and check soil erosion as well. It is therefore recommended that experts should carry out an assessment of the catchment with a view to identifying the best location of the reservoir, its capacity and other parameters required as well as its prospects for hydroelectric power production.

The maintenance of minimum environmental flows in the Arror River should be observed so as to minimize water shortages in the watershed. This will lead to ecological sustenance of the river ecosystem. It is therefore recommended that a study be carried out so as to establish the minimum environmental flows for the Arror River as every catchment has unique characteristics that need to be considered when determining this.

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