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Full Length Research Paper

Impact of introducing reserve flows on abstractive uses in water stressed Catchment in Kenya: Application of WEAP21 model

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Kenya is implementing Integrated Water Resources Management (IWRM) policies. The water policy provides for mandatory reserve (environmental flow) which should be sustained in a water resource. Four out of the six main catchments in Kenya face water scarcity. Further water resource quality objectives for many rivers are yet to be determined. This study applied Water Evaluation and Planning System (WEAP21) to study the implications of implementing the water reserve in Perkerra River which is among the few rivers that drain into Lake Baringo. The Tennant method was used to determine minimum environmental flows that should be sustained into the lake. WEAP21 was used to perform hydrological and water management analysis of the catchment. Mean monthly discharge time series of the catchment monitoring stations indicate that Perkerra River is becoming seasonal. The results further show that implementing the reserve with the present level of water management and development will increase the demand by more than 50%. With good regulation policies Chemususu dam project will reduce the impact of the reserve on abstractive uses by 20 to 40% and ensure that Perkerra River does not dry up.

Key words: WEAP21, environmental flows, sustainable management, demand, allocation.

INTRODUCTION

Water resources management is becoming more and more crucial in the face of increasing water demand and climate change. The system of water resources management where abstractive uses were the only major factors considered is no longer viewed as sustainable. This is demonstrated by the pace at which more governments are changing and reviewing their respective water policies to reflect Integrated Water Resources Management (IWRM) principles (GWP, 2010; WFD, 2003). Sustainable water management is based on conservation and good stewardship of water resources management which include setting water quality objectives and the reserve. This ensures that river and groundwater systems have water to maintain themselves and their functions, uses and benefits to people (Dyason et al., 2003). In the Kenyan water policy, the "reserve" (environmental flows) for a given river is defined as the level of instream flows necessary to provide for basic domestic uses as well as to sustain the river ecosystem (Gok, 2007). The water policy (Gok, 2002) introduced water resources management systems and structures that enable catchment based IWRM. The policy gives environmental flows first priority over all other uses. Such radical changes in policy present both opportunities and challenges. Among the challenges is allocating water to environmental flows in a water stressed catchment, where several restrictions will have to be introduced to maintain reserve flows in the river.

Perkerra catchment in Kenya is among such sub catchments that often face water scarcity. The catchment is drained by the Perkerra River which drains into Lake Baringo. Moreover, Perkerra and Molo Rivers are the only perennial rivers that flow into Lake Baringo. The lake is in a semi arid area with high annual evaporation rates of 1650 to 2300 mm compared to annual rainfall of 450 to

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900 mm. The lakes' survival thus depends on the inflows of the rivers. The two rivers originate from humid hill slopes of the catchment where annual rainfall varies between 1,100 to 2,700 mm. Studies indicate that Lake Baringo has receded from 160 km^2 in 1960 to 108 km^2 in 2001 and the depth has reduced from an average of 6 to 1.7 m in the same period (Ngaira, 2003; Odada et al., 2005).

The Lake is the lifeline of four communities living next to it. Studies also show that the fresh water lake is slowly turning saline, while the four fish species (Oreonchromis niloticus, Barrbus Intermedius, Clarias gariepinus and Labeo cylindricus) are reducing in stocks with *Labeo cylindricus* almost becoming extinct in the Lake. The drying up of inflowing rivers has interfered with their breeding habits (Aloo, 2002; Odada, 2005). Perkerra River is also the lifeline of Perkerra irrigation scheme which is a major abstractive use in the lower end of the catchment. The government of Kenya (Gok, 2007) through vision 2030 is planning to increase water storage within catchments by construction of dams. Among these projects is the construction of Chemususu dam in the upper end of Perkerra catchment on one of the major tributaries of Perkerra River. This project is expected to be commissioned in 2011.

The allocation of the current abstractive uses upstream of Perkerra catchment was issued without considering environmental flows downstream. The process of transforming policy into actionable goals and targets is therefore a challenge to the Water Resources Management Authority (WRMA) and stakeholders. Downstream users and environmental flow demands are most affected in the current water management scenario. Environmental flow assessment has not been done for majority of catchments in Kenya with the exception of the Mara River. Traditionally, environmental flows are estimated during the design of a major dam/water resource project. However, this study highlights the drying up of Lake Baringo and the reduction of flows in Perkerra River in the absence of such a major project.

There are many methodologies used to quantify environmental flows. The methods can be put into three broad categories as historic flow, hydraulic and habitat based methods (Jowett, 1997; Mann, 2006; Sun and Yang, 2004). The building block methodology refined in South Africa is the most comprehensive and has become the common approach used (King et al., 2008). However, the Tennant method (1976) is mostly used to estimate environmental flows when using discharge time series (King et al., 2008; Acreman and Danbur, 2004; King et al., 2000; Jowett, 1997). The method uses a percentage of average annual flow (AAF) to determine fish habitat quality. From 58 cross sections from 11 streams in Montana, Nebraska and Wyoming, Tennant concluded that 10% of AAF is the minimum for short term fish survival, 30% of AAF is considered to be able to sustain fair survival conditions and 60% of AAF is excellent to outstanding habitat (Tennant, 1976). These quantities are employed internationally, regardless of physical and hydrologic setting, due to the simplicity of using only the average annual hydrograph (Mann, 2006). This method has the advantage of maintaining the hydraulic characteristics of a river in proportion to the river size. It tends to reflect the river under natural flow (Beecher, 1990; Jowett, 1997). There is a close relationship between natural flow and existing ecology, thus this method is suitable for providing the desired level of ecological function of a river. Mann (2006) recommends this method for instream flow protection scenarios. Studies by Jowett (1997) indicate that this method assumes that lower than natural flows will harm a river's ecosystem and thus the receiving waters ecology in the case of Lake Baringo. This is therefore a plausible technique for estimating environmental flows by use of historical flow measurements.

IWRM allows all water sector stakeholders to participate in the complete cycle of catchment water resources management. Sustainability principles allow water to be managed for present and future generations. Environmental flows should also be maintained to enable sustenance of the river ecological system through its entire regime that will allow the enjoyment of present and future generations. This study was carried out to investigate the level of compromise expected on abstractive uses that will be necessary to restore environmental flows to Lake Baringo.

The Water Evaluation and Planning (WEAP21) system was developed by the Stockholm Environmental Institute, USA. WEAP21 is a surface and ground water tool based on water balance accounting principles, which can test alternative sets of supply and demand conditions (Assata et al., 2008). It integrates a range of physical hydrologic processes with the management of demands and installed infrastructure in a seamless and coherent manner (Yates et al., 2005). Both the engineered and biophysical components of a water system are represented to facilitate multi-stakeholder water management dialogue on a broad range of topics, including sectoral demand analysis, water conservation, water rights and allocation priorities, reservoir operations, hydropower generation, pollution tracking, ecosystem requirements, and project benefit-cost analysis. It is designed for comparative analysis where a base case (scenario) is developed and then alternative scenarios are created and compared to the base scenario. It is useful for what-if analysis of various policy scenarios and long range planning studies (Assata et al., 2008). It provides a platform for detailed modelling of water demand management strategies of the various water sectors (e.g. municipal, agriculture). WEAP21 has been adapted to many catchments (Alfara, 2004; Hagan, 2007; Levite et al., 2003; Vogel et al., 2007). The model was applied to Perkerra catchment to simulate IWRM because it addresses the gap between water management and

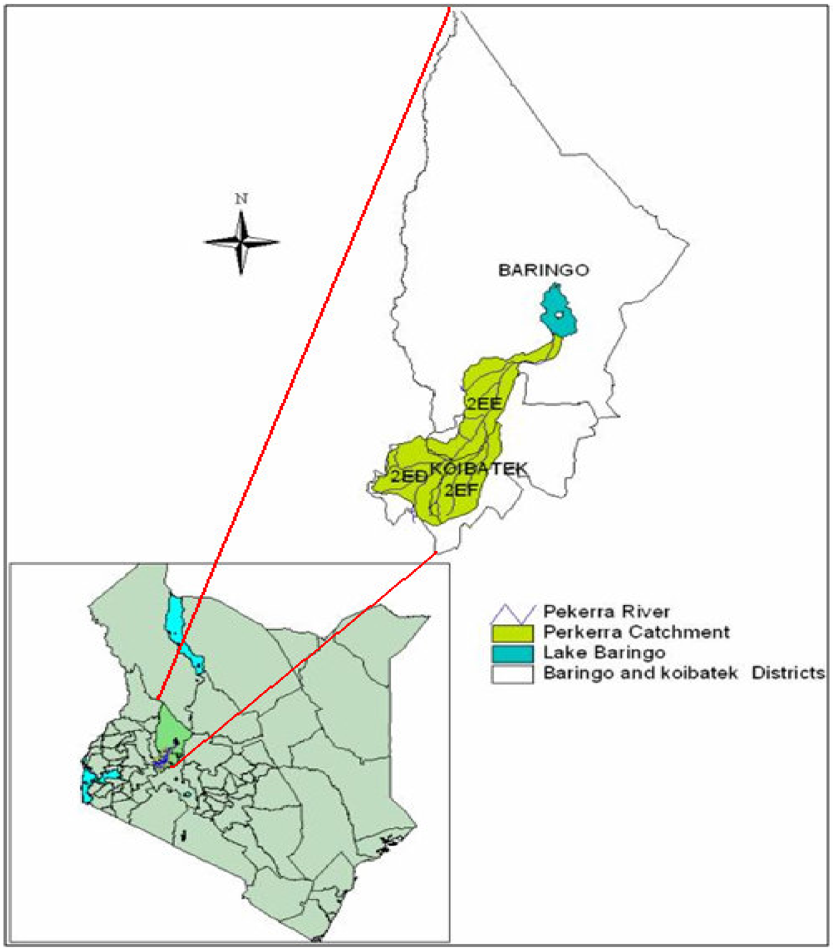

Figure 1. The Perkerra catchment in Kenya.

catchment hydrology. Rainfall runoff is simulated using either the Food and Agriculture Organization (FAO rainfall-runoff) or the soil moisture sub-routines in WEAP21. The model simulation is structured as a set of scenarios with monthly time steps. WEAP21 solves the water allocation problem by a linear programme with the objective of maximizing demand node satisfaction constrained by water availability, demand priority, supply priority and proximity to supply.

The aim of this study was to analyse the implications of implementing environmental flows to Lake Baringo on present water demand in the catchment. This is the first study undertaken to estimate environmental flows in Perkerra River into the lake in the context of IWRM. The study attempts to provide knowledge on the water resources situation to facilitate stakeholder discussions. Simple techniques were used to estimate various data components for example the Tennant method, linear population growth, and the Food and Agriculture Organisation (FAO)-rainfall runoff simulation in WEAP21. These simplistic approaches were selected to overcome the shortcomings of unavailability of comprehensive data in the study area and to suggest an initial solution to restoring environmental flows to Lake Baringo.

METHODOLOGY

The FAO-Rainfall-runoff method in WEAP21 was used to simulate runoff. This method defines land use by crop coefficients, Kc, catchment area and effective precipitation while the climate is defined by precipitation and reference evapotranspiration, ETo. Perkerra catchment covers 1207 km^2, and it has three main sub-catchments, which are coded as 2EE, 2EF and 2ED as shown in Figure 1. The sub-catchments, 2ED and 2EF, have an average altitude of 2600m Average Mean Sea Level (AMSL) and they experience sub-humid to humid climatic conditions, whereas 2EE is in the lowlands with average altitude of 1100m AMSL where semi-arid to arid climatic conditions are prevalent.

Rainfall data was obtained from the Kenya Meteorological Department (KMD). The Reference Evapotranspiration (ETo) was obtained using averaged climatic data of the New_FAO_Locklim datasets while Kc coefficients were obtained from the FAO drainage paper (FAO, 1998). Eight rainfall stations within the catchment had comprehensive data for 2000 to 2009. Thiessen polygons were used to generate aerial rainfall over the catchment. The river system was schematised from an ArcView GIS layer. The runoff from the catchment nodes in WEAP21 represented the headflow of the streams. The catchment discharge monitoring station is located at Marigat River Bridge (station 2EE7B). The

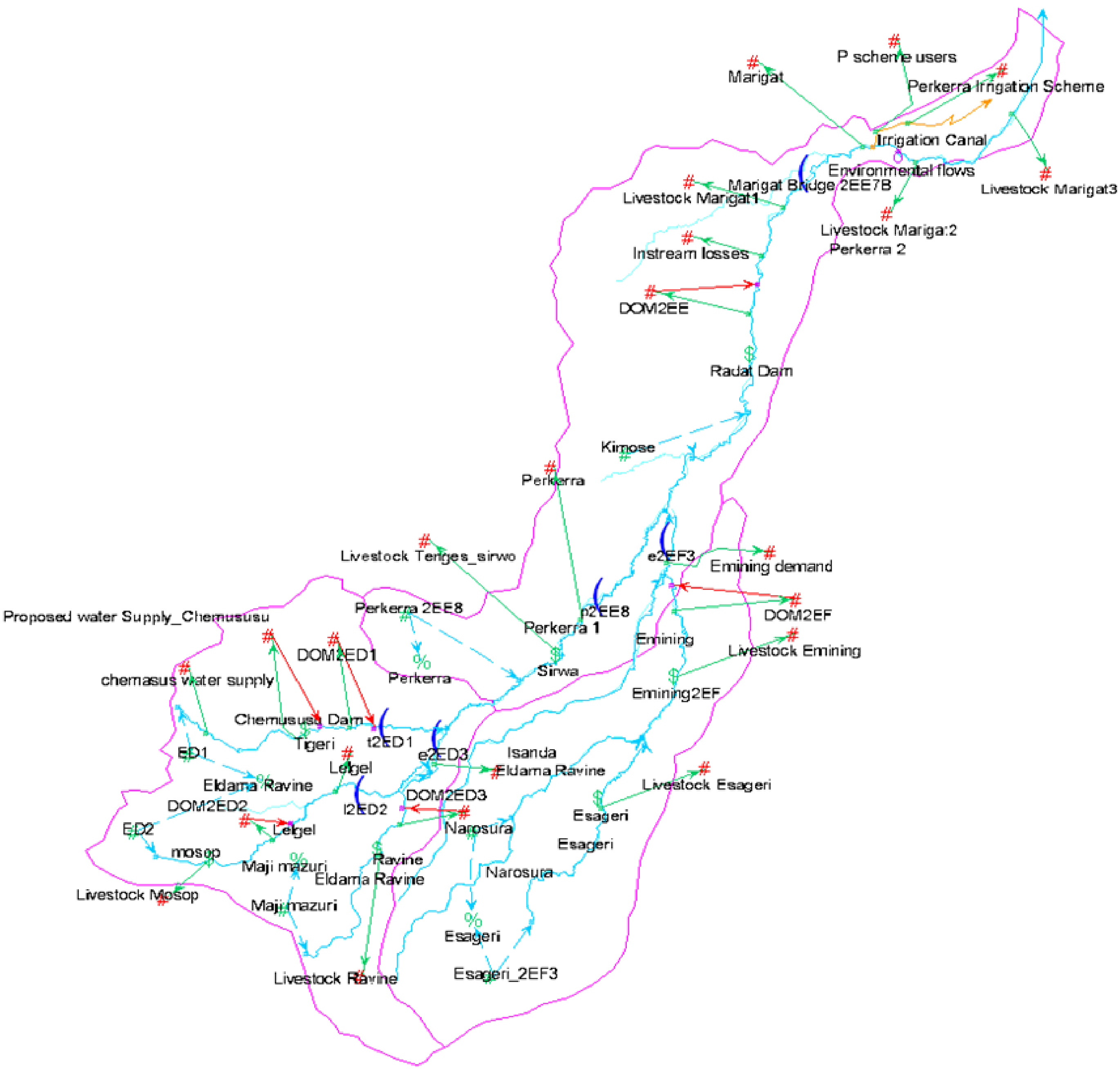

Figure 2. Schematic presentation of the Perkerra catchment system and demands in WEAP21.

simulation was done for 2000 to 2009.

Demand abstraction nodes were spatially located along the river system. The demand was classified as domestic, livestock, irrigation and industrial with reducing order of allocation priority respectively. Domestic demands were approximated in two categories; using water use permits given to water supply schemes for domestic purposes and village populations which do not have access to piped water and it was assumed they fetch water directly from the river. It was also assumed that livestock are driven to the river to draw water. Irrigation water demands were modelled according to the water use permit given to all the users. It was assumed that permit holders do not exceed permit allocations and that there was minimum variation in usage.

In WEAP21, reservoirs are modelled as demand nodes on the stream, and as supply sources to meet downstream demands. There are a total of 35 water pans in the catchment with storage capacity of between 10, 000 to 25, 000m^3. No operation rules were imposed in the management of the water pans because they do not have control structures to implement such regulations. A linear depth to storage curve was used to estimate surface area in WEAP21. Chemususu Dam, which was considered in scenario analysis was modelled using information of its design report (GoK, 1989), with a buffer coefficient of 0.6. The buffer coefficient is the fraction of the water in the buffer zone available each month for release. The schematisation of the catchment is shown in Figure 2. The Tennant method (1976) was used to estimate environmental

Table 1. Estimation of environmental flows downstream of Perkerra irrigation scheme abstraction point based on Tennant method.

Naturalised Q at STN 2EE7B in m^3/s (%)	1.9	2.1	2.3	3.7	4.2	2.8	3.4	5.2	4.0	2.3	4.3	4.7
60	1.14	1.26	1.38	2.22	2.52	1.68	2.04	3.12	2.4	1.38	2.58	2.82
30	0.57	0.63	0.69	1.11	1.26	0.84	1.02	1.56	1.2	0.69	1.29	1.41
10	0.19	0.21	0.23	0.37	0.42	0.28	0.34	0.52	0.4	0.23	0.43	0.47

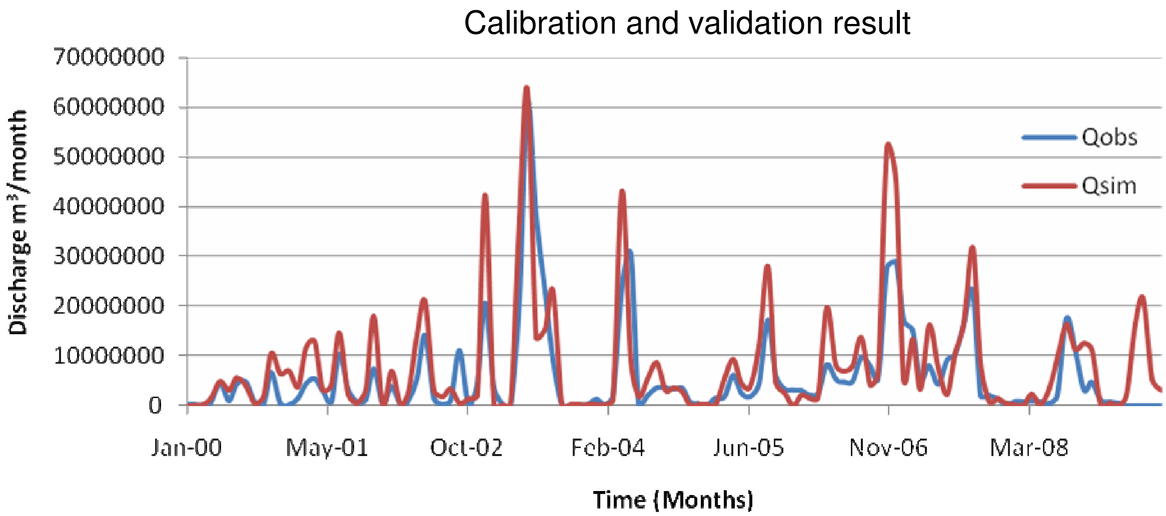

Figure 3. Calibrated results of the reference scenario.

flows as a percentage of naturalised stream flow. The mean monthly naturalised stream flow data were obtained from the National Water Master Plan report of 1992. Observed stream flow data was obtained from WRMA database, 30% of the mean monthly naturalised flow (Table 1) used as instream flow requirement below the Perkerra irrigation scheme abstraction canal node.

Two scenarios were built for what-if analysis of the base (reference) scenario. They investigated the impact of implementing the reserve in the reference scenario and when the dam project is implemented in the catchment as it is recommended by the government of Kenya.

RESULTS AND DISCUSSION

The result of the reference scenario was calibrated using observed flows at station 2EE7B. The observed flow (Qobs) and simulated flow (Qsim) in Figure 3 show that the model captures the peak and low flows. Statistical analysis of the result gave a model efficiency coefficient of 0.999, which indicates that the model is good (Nash and Sutcliffe, 1970). The model was therefore used to analyse other scenarios in the same period. The reference scenario forms the base scenario; it mimics the system in its current status.

Environmental flows to Lake Baringo are shown by the monthly discharge time series below Perkerra irrigation scheme abstraction node shown in Figure 4. The results show sharp peak hydrographs and near nil or nil discharge values. This indicates that beyond this point, the river often runs dry during the dry period which occurs mostly between December and March of each year. This has a possible negative impact on Lake Baringo downstream and especially on the fish species that depend on the flows of the perennial rivers for breeding. The sharp peaks of hydrographs show that the catchment has a small recession constant or water storage in the catchment is very low, thus all the runoff quickly drains downstream.

In WEAP21 demand coverage is equitably distributed throughout the whole catchment as shown in Figure 5, which illustrates demand coverage of February, 2008; one of the driest seasons over the simulation period.

Figure 5 shows that in February 2008, the high priority demands are all met at 55%. The graph indicates that the model ensured equitable allocation to the various uses. This is because WEAP21 uses a linear program to allocate water to various uses. This may not be the actual situation because, the catchment has minimal structures that regulate abstraction; therefore the model does not simulate the demand coverage accurately in such a system where the upstream users have 'priority' of use. Conversely, the water policy advocates for equitable water resource allocation. The abstraction limits are issued and monitored by WRMA. But because of

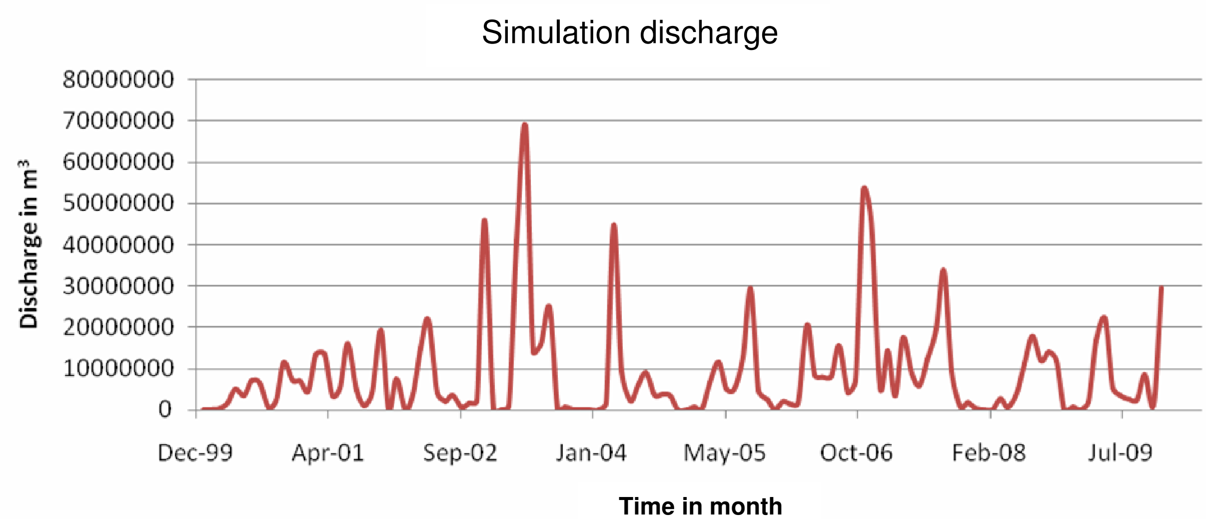

Figure 4. Stream flow discharge below Perkerra irrigation abstraction point.

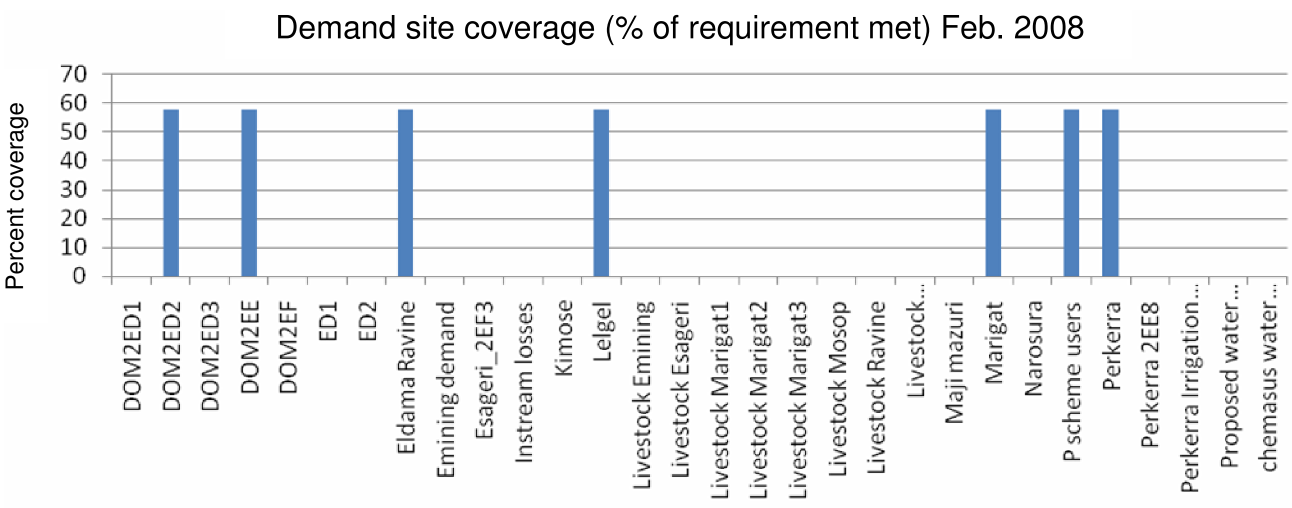

Figure 5. Demand coverage of abstractive uses upstream to downstream of Perkerra catchment in February, 2008, reference scenario.

poor infrastructure to ensure permit allocations are not exceeded, it is not guaranteed that users will not exceed their allocations. This is evident from the calibration results where the simulated hydrograph is slightly higher than the observed hydrograph (Figure 3). The actual situation could be worse than what the model results are indicating.

Water managers will have therefore to strengthen the Water Resources Users Associations (WRUAs) and put in place other structural measures that will help in achieving equitable allocation of the water resources in the catchment. This simulation in WEAP21 is a useful tool in fostering such a discussion.

Scenario analysis allows studying what if questions that arise due to policy changes, water development and other management restrictions that can be implemented in a catchment. Two scenarios were simulated; the first scenario is the addition of an instream requirement node to the reference scenario, the second scenario investigates the impact of Chemususu dam project on the first scenario. In WEAP21 environmental flow is modeled as instream flow requirement node, which is given high priority as that given to domestic water use. With the commissioning of Chemususu dam project, a reservoir stock of 13,000,000 m^3 is expected and a yield of 13,000 m^3/d to supply water to towns within the catchment and beyond to Nakuru town.

Figure 6 is the comparative results for the average

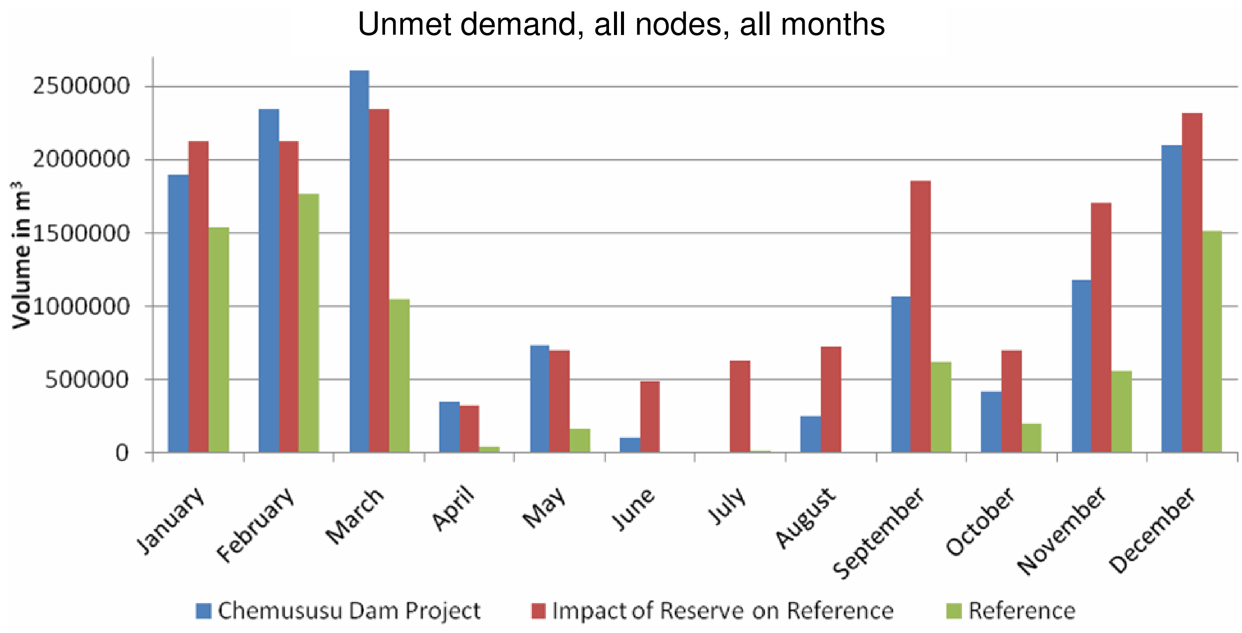

Figure 6. Comparisons of average monthly unmet demand of the reference scenario, impact of the reserve in the reference scenario and Chemususu Dam project scenario.

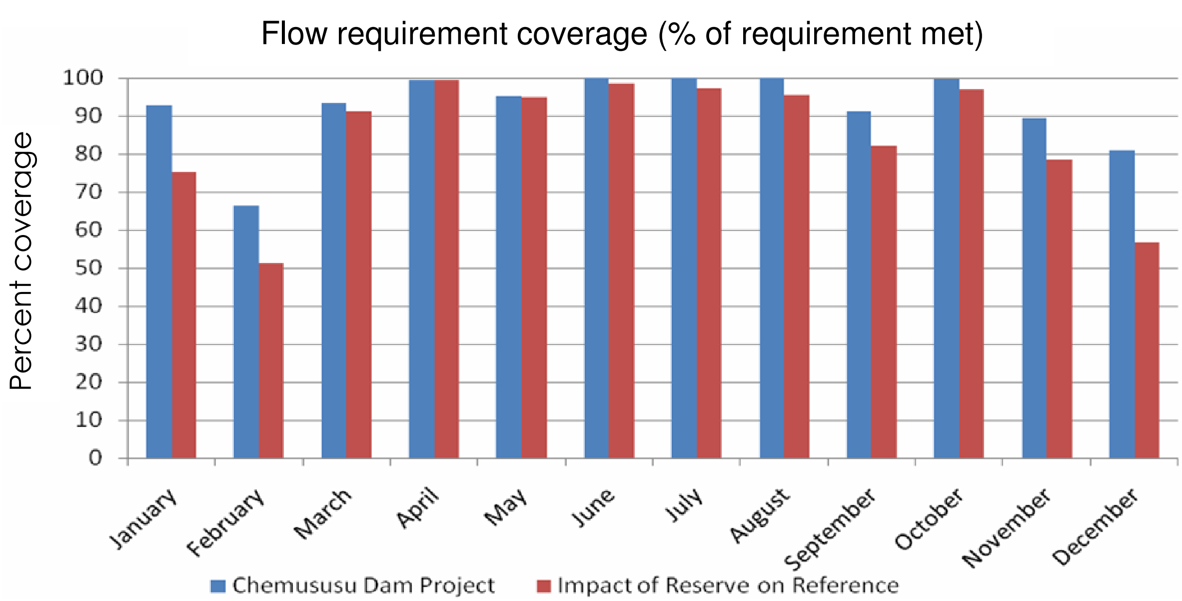

Figure 7. Average monthly demand coverage of instream flow requirements when implemented on the reference scenario and when Chemususu Dam project is completed.

monthly unmet demands from 2002 to 2009. The results indicate that implementation of the reserve (environmental flow) on the current system based on a percentage of naturalized flow will cause more than 100% increase in unmet demands. This implies that abstractive water demands should be reduced by 50%. This cannot happen especially to domestic uses, therefore demand management strategies need to be implemented for environmental flows to the lake to be guaranteed.

Figure 7 shows the percent coverage of environmental flows for the two scenarios. The reserve will not be met 100% but it will have seasonal variations. In the current situation of the catchment, if the reserve is enforced with

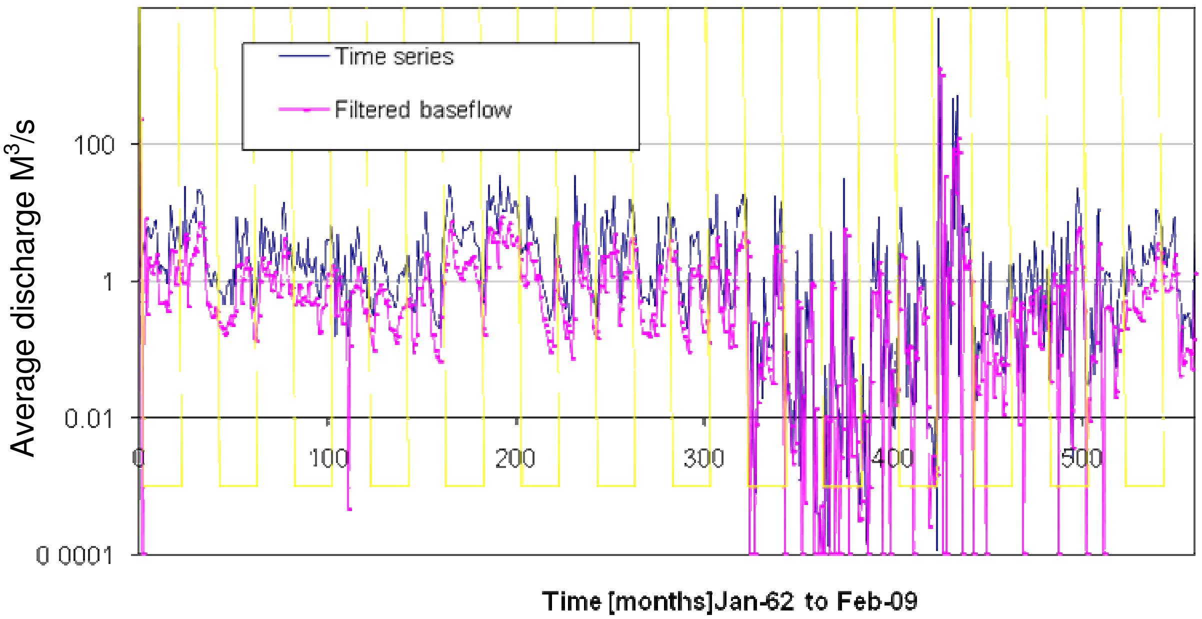

Figure 8. Time series of monthly average discharge at station 2EE7B, (Perkerra catchment monitoring station) from Jan 1962 to Feb. 2009.

measures to ensure equitable allocation of water, then on average, the reserve will be covered by less than 50% in December, January and February and 100% between June and November.

Comparing results of the two scenarios; impact of reserve on reference scenario and chemususu dam project scenario, Figures 6 and 7, the unmet demand averagely reduce by between 15 and 40% with construction of Chemususu dam project. On average, the reserve is least covered in February (20%), and it is covered by 100% between June and December. The other four months, the reserve is met by more than 55%. This implies that storage in the catchment will reduce water shortages in the catchment by 20 to 40%. The river may continue to flow the whole year round if a percentage of monthly average naturalized flows are used to implement the reserve. The seasonal floods will continue each year depending on the rainfall intensity and distribution over the catchment.

Figure 8 shows the results of the analysis of the observed mean monthly discharge time series at station 2EE7B for 47 years (1962 to 2009). The results indicate that in the last decade, the recession time for the hydrographs has reduced. The peak for high and low flow events has also increased. This is an indication that the river is slowly becoming seasonal. This shows that there have been significant changes in the catchment hydrology. This further confirms the reported threat to fish survival in Lake Baringo by previous studies (Aloo, 2002; Odada, 2005). This trend is worsened by the high evaporation rates experienced in the lake, thus leading to even higher rates of recession in the lakes' surface area.

Conclusions

Environmental flows should be guaranteed to Lake Baringo for sustainable management of Perkerra catchment. It is evident that demand coverage of water abstractive uses will reduce with the implementation of environmental flows to Lake Baringo, especially in the current scenario. However, water storage will increase the level of water demand coverage, though the dry periods of December to March will still face scarcity. Other measures would include inter-catchment water transfers, rehabilitation of the catchment to increase the recession time and ground water recharge.

The findings of this study provide initial recommendations to the management of Perkerra catchment in terms of implementing the reserve pending further investigations. This is because of the assumptions made to initiate the study, for example the assumption that the naturalized flows which were generated in the 80's to provide an estimate of the reserve depict the true flow fluctuations, ground water was not considered in meeting abstractive uses and it is also assumed that water resources are equitably allocated. The river has experienced changes in its flow regime. Thus it is hoped that with the implementation of the catchment management strategy, more data will be collected to provide information on ground water recharge and its influence on river flows. Information of groundwater abstraction is lacking which would enhance demand analysis in the catchment. It is also noted that there are no storage dams in the catchment; therefore users use their own strategies of water abstraction which makes demand analysis difficult. Strengthened WRUAs may help to bring about self regulation of water users.

The study has shown that Tennant method can be used to conduct a rapid estimation of environmental flows. It has also shown that WEAP21 model is potentially a useful tool for a rapid assessment of water allocation decisions in a river basin, in particular to locate geographically where key demand points occur. Its user-friendly interface gives it the added capability of facilitating dialogue among the various stakeholders with an interest in water allocation and management in the basin.

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