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Hydrological Impacts of Flood Storage and Management on Irrigation Water Abstraction in Upper *Ewaso Ng'iro* River Basin, Kenya

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Abstract The upper *Ewaso Ng'iro* basin, which starts from the central highlands of Kenya and stretches northwards transcending different climatic zones, has experienced decreasing river flows for the last two decades. The *Naro Moru* sub-basin is used to demonstrate the looming water crisis in this water scarce river basin. The objective of the study was to show the extent of dry seasons' irrigation water abstractions on river flows, and to assess the hydrological impact of flood storage on temporal water distribution and irrigation water management. Decreasing river flows are attributed to over-abstraction mainly for irrigating horticultural crops. The number of abstractors has increased four times over a period of 10 years. The amount of water abstracted has also increased by 64% over the last 5 years. Moreover, the proportion of unauthorized abstractions has been increasing over the years, currently at about 80% and 95% during high and low flows respectively. This has resulted in alarming conflicts among various water users. The situation is aggravated by low irrigation efficiency (25–40%) and inadequate flood storage facilities. The paper analyzes over 40 years' observed river flow data and 5-year interval water abstraction monitoring

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records for 15 years. It assesses whether flood storage and management, can reduce dry seasons' irrigation water abstractions without significantly reducing river flows to affect the sustenance of natural ecosystems downstream. The results demonstrate that flood storage and management can reduce water abstraction and increase river flows during the dry seasons, without significantly reducing high flows to affect the downstream water users. However, socio-economic, hydrological and environmental implications should be considered if a sustainable river basin water resources management strategy is to be developed and implemented. The case study of *Naro Moru* sub-basin is representative of the situation in the other sub-basins, and hence can be taken as a pilot basin for developing an integrated water resources management strategy that will foster socio-economic development with minimal negative hydrological impacts in the water scarce upper *Ewaso Ng'iro* river basin.

Keywords River water withdrawals · Low river flows · Water conflicts · Flood storage · River basin water resources management

1 Introduction

The study was carried out in *Laikipia* district of the upper *Ewaso Ng'iro* river basin in Kenya. The 15,251 km^2 river basin, which stretches to the plains of northern Kenya, is part of the *Juba* basin as shown in Fig. 1. The 173 km^2 *Naro Moru* river sub-basin, which spreads westwards from the peak of Mt. Kenya to the semi-arid *Laikipia* plateau between latitudes 0°03′ and 0°11′ south and longitudes 36°55′ and 37°15′ east, was used as the case study. The altitude of *Naro Moru* drainage basin ranges from about 5,200 m at the peak of Mt. Kenya to 1,800 m at its confluence with *Ewaso Ng'iro* River. The river sub-basin lies

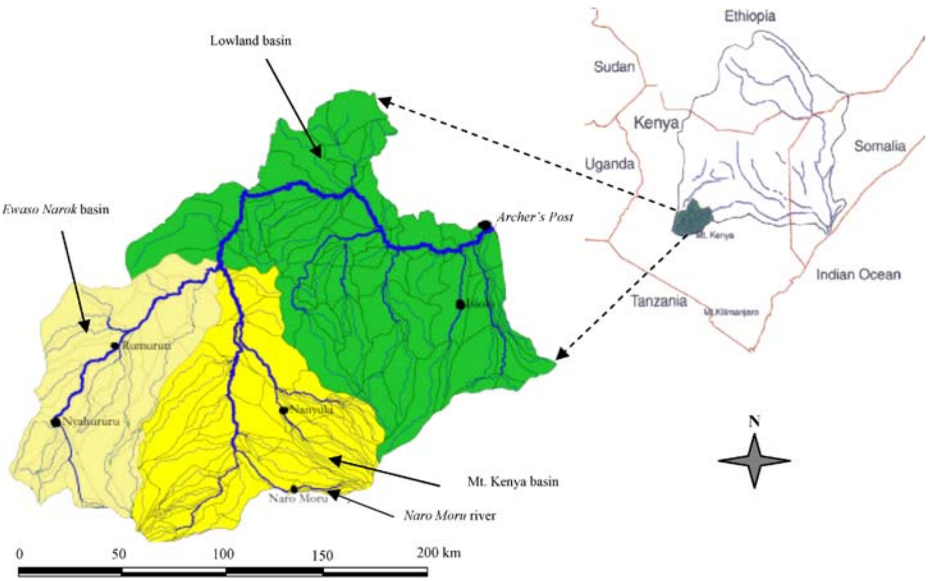

Fig. 1 Location of *Naro Moru* sub-basin and main basin of *Ewaso Ng'iro* river

within humid to semi-arid agro-climatic zones, and is characterized by low amount of rainfall due to its location on the leeward side of Mt. Kenya. The catchment rapidly changes from highland to lowland climatic conditions with the smaller part having a humid climate exhibiting surplus rainfall and the larger part being a semi-arid environment.

Recent land use changes, especially sub-division of ranches and intensification of agriculture, have put pressure on the fragile environment. This has resulted in a dilemma on how to sustain production while at the same time conserving natural resources and managing upstream–downstream water conflicts (Liniger et al. 2005). Land use changes have been accompanied by reduction in river flows, environmental degradation and declining agricultural production. Water scarcity, particularly in the lower reaches of the major streams, has increased over the years resulting to conflicts among various uses and users (FAO 2003; Gichuki 2002). Water scarcity and conflicts are aggravated by low and poorly distributed rainfall, and high potential evaporation.

Rainfall distribution is bimodal and highly skewed with the highest, rainfall amounts and intensity, being received in the upper forest zone (Gichuki et al. 1998). Mean annual rainfall within the catchment increases from 650 mm at the outlet to 1,500 mm at 3,300 m altitude and then drops to 500 mm in the moorland (NRM 2003). More than 70% of the catchment receives on average <900 mm year^{-1}. The annual evaporation is high, on average above 2,500 mm year^{-1} and exceeds annual rainfall for most part of the year. The deficit increases towards the savannah zone. Poor distribution of water is the most limiting factor to socio-economic development in the river basin (Kithinji and Liniger 1991). Excess water during in the rainy seasons is followed by severe water scarcity during subsequent dry seasons. To enhance crop production, over-abstraction of irrigation water during the dry seasons has been rampant. Water abstraction increases from 20% in the wet season to over 70% in the dry season (Aeschbacher et al. 2005). As a result, river flows has progressively decreased by about 30% since 1960. This decrease is attributed to increased water abstraction and periodic drought cycles since there is no corresponding decline in long term rainfall trend.

According to NDMC (2006), drought is a protracted period of deficient precipitation resulting in extensive damage to crops, resulting in loss of yield. It originates from a deficiency of precipitation over an extended period of time, usually a season or more. This deficiency results in a water shortage especially for crop production, and hence leads to complete crop failure. This refers to agricultural drought, which links various characteristics of meteorological (or hydrological) drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits, reduced ground water or reservoir levels. To reduce the impacts of persistent intra-seasonal drought (i.e. agricultural drought), rainwater storage is a prerequisite in *Naro Moru* sub-basin and the entire *Ewaso Ng'iro* river basin. Therefore, flood storage is imperative in upgrading rainfed agriculture under drought prone semi-arid environments.

Although *Naro Moru* catchment accounts for only 1.1% of the upper *Ewaso Ng'iro* basin, it can be taken as a representative sub-basin, which reflects typical constraints and challenges affecting socio-economic development in the entire basin. These include unreliable rainfall patterns and quantities, a wide variety of stakeholders with diverse interests, highland–lowland interdependence, unevenly distributed natural resources, and decreasing river flows, which lead to conflicts between upstream and downstream users (Aeschbacher et al. 2005). *Naro Moru* River has six gauging stations distributed from the top of Mt. Kenya to the point where it joins the *Ewaso Ng'iro* River as shown in Fig. 2.

The gauging stations divide the river into four sections (reaches) according to the ecological belt, i.e. moorland, forest, foot zone and savannah. Much of river flow is concentrated within the two rainy seasons, i.e. November–December and April–June as

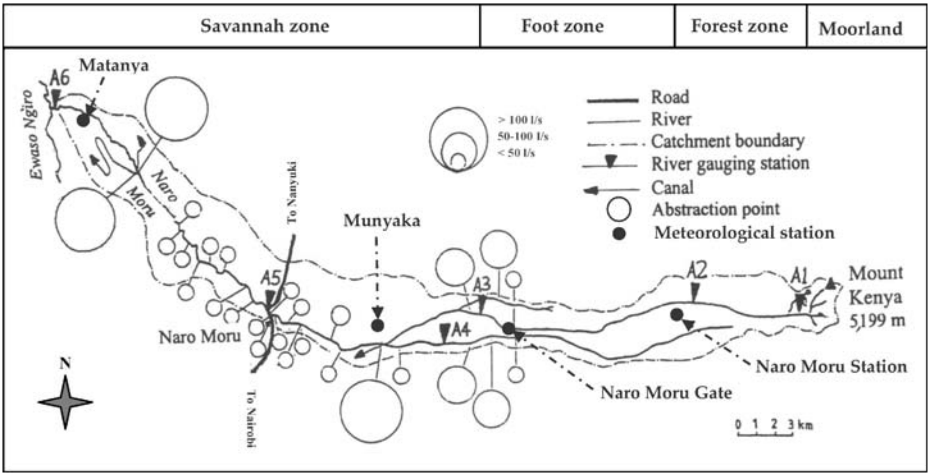

Fig. 2 River gauging stations, rainfall stations and some water abstraction points in *Naro Moru* basin

shown in Fig. 3. River discharges during the dry months consist mainly of base flow. The semi-arid savannah only yields runoff during the rainy season. The locations of ecological belts (i.e. forest and foot zones and savannah zone) and meteorological stations referred to in Fig. 3 are shown in Fig. 2.

The water demand has been increasing continuously due to population growth, especially due to immigrant farmers from adjacent high agricultural potential districts due to pressure on land resources. Subsequently, immigration has resulted to land use change in the lower zones from natural vegetation to small-scale agriculture, which have led to increased water abstraction and drastically reduced river flows. There was substantial increase in small-scale farming from 1984 to 1992, which led to decrease in grassland and grassland mixed with trees (Roth 1997). The water crisis presented here is common in many other river basins in the world. Hedelin (2007) and Xia et al. (2007) attests to this by noting that pressure on the world's water resources is increasing, restraining social and economic development in many countries, and threatening ecological values in others.

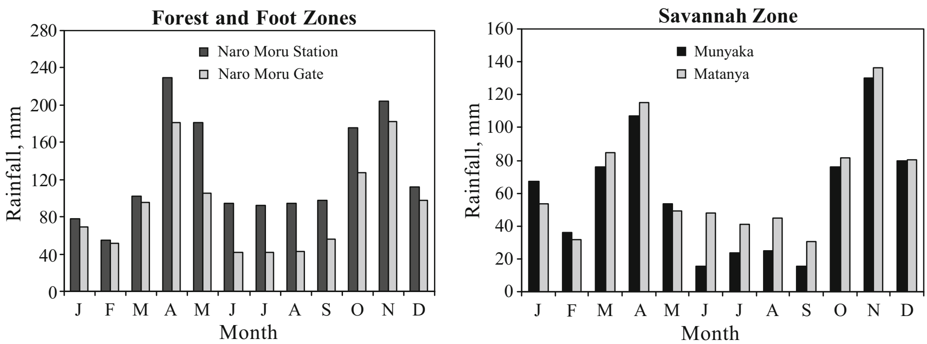

Fig. 3 Rainfall distribution in *Naro Moru* sub-basin at different river reaches (1984–2004)

Falkenmark (2007) also noted that the food security dilemma is largest in arid climate regions, a situation constituting a formidable challenge.

The sub-basin has many and diverse land uses as presented in Table 1. Current settlers practice a combination of rainfed and irrigated agriculture, mainly on subsistence basis growing crops such as maize, beans, cabbages and potatoes. Irrigated agriculture takes a more commercial perspective mainly targeting horticultural crops, which have ready markets—out-growers for existing large-scale export oriented companies. Some farmers in the savannah zone have adopted rainwater harvesting and management (RHM) systems such as conservation tillage, on-farm runoff storage (farm ponds) and flood storage in earth dams/water pans for irrigation and livestock.

Other water sources with limited exploitation in the river basin are groundwater and water pans mainly in the lower zones. There are five boreholes (for domestic water and livestock) and seven water pans (for domestic, livestock and irrigation) (NRM 2003). The allocation and control of diminishing water supply within the catchment is a major challenge due to related hydrological, environmental and socio-economic implications. This calls for proper water management to ensure that this resource is used in a sustainable way for the benefit of all users. In the past, emphasis has been on using river water to meet demand but there is an urgent need to devise sustainable options to manage the increasing demand. Some of the options include improving water use efficiency, soil moisture conservation in rainfed agriculture, restricting water use during critical dry periods and wet season flood storage for use during the dry seasons. However, sustainable solutions to addressing ensuing conflicts over water among different users rely on formulation of adaptive policies and strategies that promote promising interventions such as integrating RHM in the land use systems.

Flood storage and management can reduce water abstractions and related water conflicts. For instance, harvesting 30% of runoff in semi-arid parts of the upper *Ewaso Ng'iro* river basin can triple the available water supply (Gichuki et al. 1998). This potential if exploited would minimize dry season water demands and river abstractions. The paper demonstrates that flood storage and management can substantially reduce dry seasons' irrigation water abstractions, which is the major cause of reduced river flows and conflicts among downstream and upstream users. Flood storage and management would not only reduce negative environmental effects such as soil erosion through reduced runoff, but also reduce water pressure and direct stream flow abstractions during the dry seasons. High abstraction and over-irrigation during dry season is used as a risk management measure due to low reliability of river flows. Farmers tend to abstract more water due to fear and risk of

Table 1 Types of land use and their coverage in *Naro Moru* sub-basin

Type of land use	Area (km^2)	Proportion of sub-basin (%)
Ice cover	1.25	0.72
Natural forest	35.83	20.71
Planted forest	2.24	1.29
Cropland[a]	39.22	22.67
Grassland	94.35	54.54
Urban	0.04	0.02
Water body	0.07	0.04

Adapted from Niederer (2000) and NRM (2003).

[a] Rainfed agriculture account for 24.22 ha (i.e. 61.75%) and irrigated agriculture 15.0 ha (i.e. 38.25%).

extended dry spells and anticipated crop failure. With flood storage such risks will be reduced due to increased reliability of water supply.

Although the paper relies substantially on analysis of historical data and findings of past research, it goes beyond identifying the extent of river flows reduction due to water abstractions by upstream farmers. It assesses one of the feasible options for reducing dry season irrigation water abstractions without compromising both upstream and downstream water uses and users. The intervention focuses on redistribution of available annual river flows through flood storage and management, with the aim of reducing dry seasons' irrigation water abstractions without compromising agricultural production and environmental sustainability. Falkenmark (2007) cautions on the consequences of upgrading agriculture without better handling of issues of environmental sustainability.

2 Methodology

2.1 River Flow Measurement

The *Naro Moru* is the best documented river in upper *Ewaso Ng'iro* basin and has a long term record spanning back to six decades i.e. since 1931 (Leibundgut 1986). It has a hydro-meteorological monitoring network consisting of 6 river gauging stations (A1–A6), eight rain gauges and four evaporation pans (Decurtins 1992), which have been effectively managed by the Natural Resources Monitoring, Modelling and Management (NRM) project based in *Nanyuki*. The six river gauging stations are distributed from the top of Mt. Kenya to the *Ewaso Ng'iro* river confluence, and divide the river basin into four sections (reaches) according to the ecological belt, i.e. moorland, forest, foot zone and savannah as shown in Fig. 2. In the past, comprehensive water abstractions monitoring was done in 1992 (Gathenya 1993), in 1997 (Gikonyo 1997) and in 2002 (NRM 2003).

2.2 Monitoring of Water Abstraction

The quantity of abstracted water was measured using cut-throat flumes and current meters for furrows, calibrated bucket and stop watch for gravity pipes and pumping rates, capacity and pumping duration (Gathenya et al. 2000; NRM 2003). For large abstraction points, river flow measurements were made by use of current meter upstream and downstream of the abstraction point. Based on the type of pumps, pumping time and/or amount of fuel used for pumping water can also be used to estimate the volume of water abstracted. Demand based estimates were used where abstraction measurements were not possible. For example, the types of crops, cropping pattern, acreage and irrigation methods were used to estimate irrigation water abstraction. This water demand estimation approach was mainly based on calculation of irrigation water requirement for the crops being grown.

2.3 Field Survey

To supplement measured data and historical records, field survey and water users' interviews were conducted to ascertain the amount of water abstracted; review the water permits, obtain details of the pumps; duration of pumping; irrigated area and type of crops. The field survey focussed on inventory of water abstraction systems, identification of points of water abstractions, use of check lists, observation of physical aspects and making some spot check measurements. The field survey was also used to authenticate the previous water abstraction records and capture new entrants or changed status of existing abstractors. The water users' interviews targeted about 100 diverse stakeholders. It used a semi-structured questionnaire and group discussions and focussed mainly on general water allocation, use and management. In the context of increasing water demand, abstraction and scarcity, the water users' views on flood storage and management were also evaluated.

2.4 Determination of Flood Storage Requirement

The volume of flood flow to be stored depends on the dry seasons' water demand and storage efficiency—anticipated water losses. Since 97% of water abstracted is used for irrigation, the required storage capacity was determined from the dry season irrigation water requirement (m^3 day^{-1}) using the method adapted from Doorenbos and Pruitt (1977) given in Eq. 1.

$$Q_i = \frac{K_c \times E_o \times A}{\eta} \quad (1)$$

where Q_i is crop water requirement (m^3 day^{-1}), K_c is crop factor, E_o is reference potential evaporation (m day^{-1}), A is area (m^2), and η is irrigation efficiency (%).

From the crop growing period, then the total seasonal flood storage capacity can be estimated. However, due to the high investment cost implications, it is not advisable to assume that all seasonal crop water requirements can be obtained from flood storage. For computation purposes, different proportions of crop water requirements were considered to be from RHM—flood storage and management system. The remaining proportion would be obtained from river water abstractions.

2.5 Data Analysis

The long term river flow data was used to determine mean monthly flow characteristics (i.e. mean, median, standard deviation and outliers) at different time period and river reaches (A3, A4, A5 and A6 as shown in Fig. 2). The naturalized flow was derived from addition of observed river flows and river abstractions at different river reaches. The impacts of flood storage on river flows was evaluated by considering different levels of flood storage efficiency and irrigation efficiencies under two reservoir management scenarios: (1) priority given to storage demand, i.e. water released downstream only after storage requirements are met, and (2) priority given to downstream flow requirement, i.e. proportioning river flows to ensure there is adequate flow for downstream users in each month.

To assess the hydrological impacts of flood storage and management, the observed flows at A6 in 2002 were naturalized by adding the monthly water abstractions to the measured river flows. Naturalization was done in order to get a better understanding of river water availability, if there were not abstractions. This means that the effects of river water abstractions are discounted against the measured values to provide an insight into what would have been available were river water abstractions not being carried out. This resources value is referred to as the naturalized river discharge representing that amount of water available for various uses including abstractions (NRM 2003). Measured river flows define the residual river water amounts after the effects of human use and abstraction. Thus the naturalized flows represent the potential water available for various uses.

The year 2002 was selected for this analysis partly due to its below average measured river flows—water shortage year—and partly due to existence of recent and complete water abstraction records. The hydrological implications of increased upstream water abstractions at the river basin level were analyzed using the historical river flow data at *Archer's Post*, which is the basin outlet (see Fig. 1).

3 Result and Discussions

3.1 Water Abstractions

Observed river flow data show that there has been a progressive decrease in river flows and increasing water conflicts, which can be attributed to increasing water abstractions, especially for irrigation during the dry seasons. The number of abstraction points has increased from 26 in 1990 (Gathenya et al. 2000) to 76 in 1997 and to 100 in 2002 (NRM 2003; Aeschbacher et al. 2005) along the settled 30 km section of *Naro Moru* river, mainly below the forest zone. Figure 3 shows some of the water abstraction points along the river. The increase in water abstractions can be attributed to many small-scale farmers using portable pumps. However, community irrigation projects and large-scale horticultural farmers have also increased the quantity of water abstraction. Surprisingly, about 80% of the total abstraction volume is carried out by five abstractors—three community irrigation schemes and two large horticultural farms (NRM 2003). Table 2 presents the types of abstraction and quantity of water abstracted. Most of the abstracted water is used for irrigation (97%), while the rest is for livestock (2%) and domestic (1%) use (Aeschbacher et al. 2005). The area under irrigation is about 15 km^2, i.e. 8% of the total *Naro Moru* sub-basin area.

Water abstraction assessment revealed that about 62% of the dry season flows and 43% of the wet season flows are abstracted from *Naro Moru* River before its confluence with the *Ewaso Ng'iro* River. Although the river is perennial, over-abstractions leads to drying up of the lower reach (downstream of A5) during the driest months of February and March, and under extreme conditions from July to September. According to Aeschbacher et al. (2005) about 80% is abstracted illegally during flood flows and up to 98% during low flows. Gathenya et al. (2000) reported 70% and 92% illegal abstractions during flood and low flows respectively. The proportions of unauthorized or illegal abstractions have been increasing over the years. Illegal abstraction here refers to either abstracting without a permit or abstracting above the permitted limits. Moreover, out of a total of estimated water abstractions of 0.74 m^3 s^{-1}, existing permits indicate that only 0.16 m^3 s^{-1} and 0.014 m^3 s^{-1} are allowed during flood and normal flows respectively (NRM 2003). A similar study conducted in 1997 revealed that total river water abstraction was 0.45 m^3 s^{-1}, and hence a 64% increase over a period of 5 years. The situation is expected to worsen as agricultural water demand continues to increase and more land is put under irrigation without due consideration of water availability. Hence the need to regulate river flows and water distribution and management through flood storage and improved governance system.

Table 2 Types of abstraction and quantity of water abstracted in 2002

Type of abstraction	No. of abstractions	Abstracted quantity (m^3 s^{-1})	Quantity (%)
Furrows	6	0.28	38
Gravity pipes	7	0.27	37
Fixed pumps	8	0.03	4
Portable pumps	79	0.16	22

Adapted from NRM (2003) and Aeschbacher et al. (2005).

3.2 Trends in River Flows

The total water abstraction from *Naro Moru* river shows a significant correlation with the river discharge (correlation coefficient of 0.91, R^2=0.83, a=5) while abstraction points above the foot zone (A5) are not significantly dependent on river flows (Aeschbacher et al. 2005). Figure 4a shows that the average river flows on the lower river reach has gradually been decreasing, while the upper reach indicates no significant decline. The specific river flows (or yields) in l^{-1} km^{-2} give an overview of the spatial distribution of the water quantities which are available in the river basins and allows the direct comparison between the discharges of the individual watersheds (Leibundgut 1986). River flow during the dry season is only enough for domestic and livestock water needs and for minor irrigation on a kitchen garden scale. Thus, increasing irrigation water demands can only be met if RHM systems (on-farm storage and construction of reservoirs along the river) are considered.

River flow analysis at the lower zones (foot zone and savannah), i.e. downstream from A3 and A4, indicates high variability and temporal fluctuations as shown in Table 3. In general, Table 3 shows the same pattern as Fig. 4a. However, Fig. 4a shows a recurrence of extreme conditions of low flows in cycles of 3–5 years, i.e. on average once in every 4 years. Figure 4b shows that the river exhibits a bimodal pattern, with peaks corresponding with the two main rainy seasons (see Fig. 2). During the dry season, river flows are maintained by melting glaciers and groundwater (Gichuki et al. 1998).

Monthly flow data analysis (Table 4) shows that there is a high variability in flows with the highest flows occurring in the months of April and November, while 3 months—January, February and September records no flows—river dries up in these months. Though the rainfall pattern is bimodal, continental rains (July to September) sustain river flows. Table 3 shows a decline in river flows at A6, which can be attributed mainly to increasing water abstraction and drought cycles. Fig. 4a supports this argument since decline in flows is not significant at the upper river reaches over the same period.

Comparison between discharge parameters at A5, shows that although the mean flows have remained constant, Q_{50} and Q_{95} have respectively changed from 0.74 and 0.29 m^3 s^{-1} in the period 1960–1984 to 0.51 and 0.11 m^3 s^{-1} in the period 1985–2002 (Aeschbacher et al. 2005). Coincidently, low flows correspond with the dry season, when irrigation water demand is highest, which leads to over-abstraction to the extent that the river dries up at

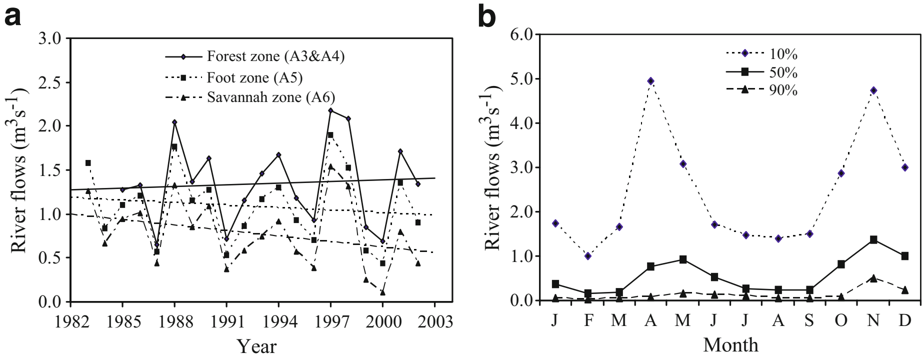

Fig. 4 Annual and monthly river flow characteristics of *Naro Moru* sub-basin: **a** flow trend at different reaches; **b** A6 flows at different probabilities

Table 3 Mean flow ($m^3 s^{-1}$) at different time period and river reaches of *Naro Moru* river

River gauging station	Catchment area (%)	Period							
		1983–1985		1986–1990		1991–1995		1996–2000	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
A3 and A4	28	1.28	1.15	1.40	1.84	1.25	1.09	1.35	1.35
A5	70	1.17	1.16	1.21	1.71	0.98	1.74	1.14	1.16
A6	100	0.92	1.04	0.92	1.45	0.66	1.56	0.75	2.01

A6. *Naro Moru* River is reported to experience over 80% over-abstraction (Gichuki et al. 1998). This in essence means even the little water that may be available is not adequate for different uses. This is made clearer by the flow duration curves at different river reaches as shown in Fig. 5. This water scarcity situation is similar in many mountainous catchment where river flows have steadily decreased and water resources become overcommitted resulting to serious water and environmental problems (Xia et al. 2007).

3.3 Flow Duration Curves

The flow duration curves (Fig. 5) show high water abstraction in the lower river reaches between the foot zone and savannah compared to the upper reaches. The difference in river flows between A6 and A3 and A4 indicates more abstractions in the lower reaches. Moreover, the steeper slope of the flow duration curve at A6 (Fig. 6b) indicates a higher rate of abstraction than the moderate slopes for upper zones. The high abstraction is mainly due to hydraulic advantage and settlement density. However, a proportion of water abstracted in the upper zone is used in the lower zones for irrigation and urban demand (Gichuki et al. 1998). According to NRM (2003), the proportion of water abstraction as a percentage of available river flows increase from 22% in the forest zone, to 43% in the foot zone and to 61% in the savannah zone. The situation is worse in low flow years. In Table 5 we see that in 2002, which was a low flow year, the average abstractions were 40%, 50% and 77% of available river flows at forest zone, foot zone and savannah zone respectively.

Table 4 Monthly flow characteristics at *Naro Moru* sub-basin outlet (A6)

Month	Monthly flow parameters 1983–2002 ($m^3 s^{-1}$)				
	Mean	Median	SD	Lowest	Highest
January	0.81	0.38	1.53	0.00	17.4
February	0.40	0.15	0.73	0.00	9.18
March	0.57	0.19	1.01	0.03	10.03
April	1.81	0.76	2.50	0.03	17.75
May	1.38	0.91	1.58	0.03	13.86
June	0.83	0.52	1.03	0.03	8.00
July	0.55	0.27	0.66	0.03	5.84
August	0.56	0.24	0.86	0.03	8.67
September	0.60	0.24	0.94	0.00	8.03
October	1.25	0.81	1.51	0.03	10.88
November	2.07	1.38	2.13	0.05	17.87
December	1.52	1.00	1.88	0.03	15.87

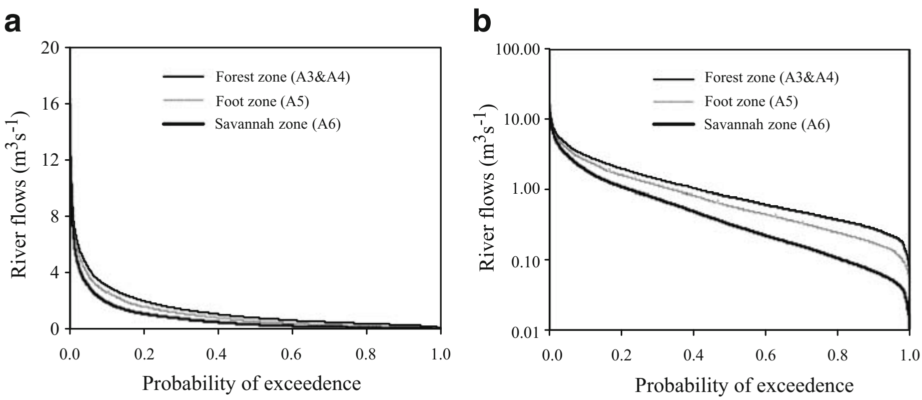

Fig. 5 Flow duration curves for different reaches of *Naro Moru* River (1985–2002): **a** normal plot; **b** log-normal plot

3.4 Flood Storage and Dry Season's Irrigation Water Abstractions

According to Hedelin (2007), in order to manage water resources in a more sustainable manner, new planning methodologies/processes for river basin management need to be developed. This is true for *Ewaso Ng'iro* where we have proposed flood storage and management as one of the sustainable options. The potential of RHM systems to reduce water crisis in *Ewaso Ng'iro* basin has been documented (e.g. WRAP 1987; Thomas et al. 1997; Gichuki et al. 1998; Gichuki et al. 1999; Gichuki 2002). The effect of flood flows storage was assessed from naturalized flows at the sub-basin outlet (A6). The unaccounted for flow (i.e. Δflow) can either be attributed to losses (positive values in Table 5) (mainly infiltration to groundwater, limited evaporation and undetected abstractions) or groundwater seepage (negative values in Table 5). Apparently there is some groundwater recharge during wet months, which releases some flow in dry months.

Flood storage is possible during the months of high flows, i.e. April/May and November/December. This can be ensured by only considering off-stream flood storage structures since on-stream reservoirs will affect dry seasons' river flows. The stored amount can be used for irrigation during the following dry seasons of say 90–120 days, i.e. January–March and June–September, which are adequate for most vegetables and

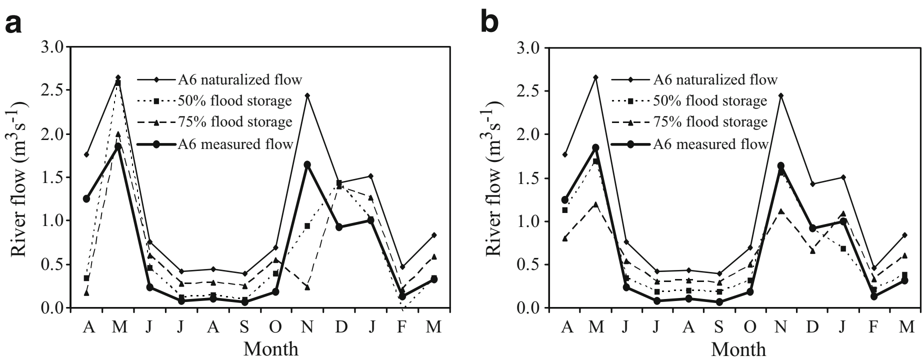

Fig. 6 The effects of flood storage on *Naro* Moru river flow at A6 in 2002: **a** scenario 1; **b** scenario 2

Table 5 *Naro Moru* monthly flows, abstraction and naturalized flow in for 2002

Month	Observed river flows, abstraction and naturalized flow ($m^3\ s^{-1}$)					
	A3 and A4	A5	A6	Abstraction	Naturalized flow (A6)	ΔFlow (A6)
January	1.80	1.52	1.00	0.51	1.51	0.29
February	0.53	0.33	0.13	0.34	0.46	0.07
March	1.02	0.72	0.32	0.51	0.83	0.19
April	2.20	1.84	1.25	0.51	1.76	0.44
May	2.89	2.42	1.85	0.80	2.65	0.24
June	0.81	0.53	0.24	0.51	0.75	0.06
July	0.42	0.26	0.08	0.34	0.42	0.00
August	0.38	0.28	0.10	0.34	0.44	−0.06
September	0.30	0.18	0.06	0.34	0.40	−0.10
October	0.85	0.58	0.18	0.51	0.69	0.16
November	2.32	2.00	1.64	0.80	2.44	−0.12
December	1.51	1.34	0.92	0.51	1.43	0.08
Mean	1.25	1.00	0.65	0.50	1.15	0.10
Abstraction (%)	40	50	77	–	–	–

horticultural produce. Irrigation water requirements can be reduced by staggering cropping pattern to ensure the crops take advantage of the wet periods. Management of cropping patterns can also ensure good market prices. By considering various options of meeting irrigation water demand, the proportion of river flows that can be allowed downstream was determined.

Increasing flood storage reduces river water abstractions during the dry seasons, and hence increase dry season river flows. Thus, farmers should be encouraged to meet most of their dry season irrigation demand through flood storage. Construction of communal flood storage structures should be considered to reduce construction cost and enhance water management. This is possible since the farmers are already socially cohesive through a marketing cooperative and *Naro Moru* water users' association. Moreover, the water users' association will enhance communal water management and maintenance of the water reservoir. The need to reduce dry season water abstraction notwithstanding, flood storage should not affect the water needs of downstream users and hydro-ecological functions such as sustenance of natural ecosystems and recharging of groundwater reservoirs. *Ewaso Ng'iro* river support many pastoral communities and a number of wildlife sanctuaries downstream before draining into *Lorian* swamp, which feeds *Habaswein* groundwater reservoir—source of water for many pastoral communities in North Eastern province.

It is widely accepted that water resource management demands an integrated assessment of resource use options, including local and regional impacts on the environment and stakeholders (Croke et al. 2007). Therefore, balancing flood storage and dry season river abstraction is a prerequisite for socio-economic development and environmental management—environmental flow requirements. Environmental flow means enough water is left in the river to ensure downstream ecosystem, social and economic benefits (Smakhtin et al. 2004; Tharme 2005; IWMI 2005). There are many methodologies since environmental flow is multi-disciplinary and integrative in nature. For instance, in the most recent review of international environmental assessments, Tharme (2003) recorded 207 different methods in 44 countries. Hence, quantification of environmental flow is beyond the scope of this study.

Eq. 1 gives an irrigation water requirement of about 1.40 $m^3\ s^{-1}$ over the total irrigated area of 1,500 ha for E_o=5 mm day^{-1}, K_c=0.8, and η=50%. If this amount (i.e. no dry season water abstraction, i.e. 100% flood storage) is stored during three high flow months to be used during the next dry season of 3 months, then each high flow month will, on average store 1.40 $m^3\ s^{-1}$. Assuming 50% storage efficiency, this translates to 2.8 $m^3\ s^{-1}$ per wet season. Thus for 3 months, on-farm storage of about 14,500 (2.8×86,400×30×3/1,500) $m^3\ ha^{-1}$ is required, or 7,250 $m^3\ ha^{-1}$ if losses are controlled.

The storage capacity can further be reduced to 4,830 $m^3\ ha^{-1}$ if irrigation efficiency is improved from 50% to 75% by adopting high water efficient technology such as cost effective low-head drip irrigation (Ngigi et al. 2005a; Ngigi et al. 2005b and Ngigi et al. 2000). Table 6 shows flood storage requirements at different irrigation and storage efficiencies. Moreover, smaller flood storage structures would suffice if supplementary, instead of full irrigation is practised. Reduced flood storage means less investment costs, and hence a compromise can be attained depending on socio-economic and hydrological implications. After determining the flood storage requirements, the main concern is social, technical and environmental feasibility for constructing such huge flood storage reservoirs. However, we are not advocating for the construction of large reservoirs, but a series of small off-stream reservoirs—farm ponds, either for individual household or a few neighbouring farmers, whose size will depend on specific irrigation water demand.

A comparison between average abstractions (0.5 $m^3\ s^{-1}$ from Aeschbacher et al. 2005) and computed net irrigation water demand (0.7 $m^3\ s^{-1}$) shows that only 71% of the irrigable land could be irrigated at 100% irrigation efficiency in 2002. This could either be due to low flows or overestimation of actual irrigated area. Otherwise the crops would be under severe moisture stress, which could lead to low production, despite the high cumulative water abstraction. Inadequate water would force farmers to either reduce their irrigated area or reduce amount of irrigation water. This could affect production and investments. Therefore, assuming that farmers abstracted all the available flow, the actual abstracted amount (i.e., 0.5 $m^3\ s^{-1}$) was hence used in flood storage analysis.

Flood storage analysis shows that it is possible to maintain average downstream river flows and increase irrigation water supply—ensuring adequate downstream water flows while meeting the irrigation needs of upstream farmers through flood storage. However, it is not possible to store adequate flood flows to meet the required irrigation water demand during low flow years. It appears already the irrigation water demand is beyond what the river flows can supply. Hence, the need for both technical solution (flood storage for water regulation and distribution) and improvement of water governance system. This means as Berger et al. (2007) proposed, that an approach that take into account technical innovation and policy change is necessary. Figure 6 presents the balance between two reservoir management scenarios for flood storage described in section 2.5, and shows the river flow patterns for naturalized flows, observed flows and simulated flows for different proportion

Table 6 Flood storage ($m^3\ s^{-1}$) at different irrigation and storage efficiencies

Irrigation efficiency (%)	Flood storage efficiency (%)			
	25	50	75	100
25	11.20	5.60	4.20	2.80
50	5.60	2.80	2.10	1.40
75	4.20	2.10	1.40	1.05
100	2.80	1.40	1.05	0.70

Table 7 Impacts of flood storage on *Naro Moru* river flow ($m^3\ s^{-1}$)

Month	Naturalized flow	Measured flow	Scenario (1)		Scenario (2)	
			50%	75%	50%	75%
January	1.51	1.00	1.01	1.26	0.68	1.09
February	0.46	0.13	0.00	0.21	0.21	0.33
March	0.83	0.32	0.33	0.58	0.38	0.60
April	1.76	1.25	0.34	0.17	1.12	0.80
May	2.65	1.85	2.58	2.00	1.68	1.19
June	0.75	0.24	0.45	0.6	0.34	0.54
July	0.42	0.08	0.12	0.27	0.19	0.30
August	0.44	0.10	0.14	0.29	0.20	0.32
September	0.40	0.06	0.10	0.25	0.18	0.29
October	0.69	0.18	0.39	0.54	0.31	0.50
November	2.44	1.64	0.94	0.24	1.55	1.11
December	1.43	0.92	1.01	1.39	0.91	0.65
Mean	1.15	0.65	0.65	0.65	0.65	0.65

(50% and 75%) of flood storage at A6 based on the two strategies. Table 7 presents the results of flood storage analysis for the two scenarios: (1) the storage is allowed to fill at first opportunity, and (2) proportionate filling is allowed depending on monthly flows based on long term flow patterns.

The two reservoir management scenarios operate under the following strategies are: (a) during the wet season, flood flow is stored for use in the dry season, with the percentage storage based on a set amount to be supplied from storage e.g. 50% flood storage means adequate flood flow will be stored to meet 50% of irrigation water supply during the dry season; (b) during the dry season, no flow is stored and the amount of naturalized flow released downstream is a function of flood storage level e.g. 75% flood storage means that only the 25% of irrigation water demand will be abstracted from river flows.

Figure 6a and b show the distinction between the two reservoir management scenarios. As a result, the downstream hydrographs in Fig. 6a show less of a shock and do not suffer from the very low flows during the months of the two rainy seasons (i.e. April and November). However, it may not be possible to store all the initial flood flows because between A6 and the reservoir, which hydraulically can be located above A5, there will be substantial runoff contributing to flow downstream. The lower zones contribute substantial surface runoff during the rainy season; hence the situation in Fig. 6a will allow flows equivalent of the difference of naturalized flows at A5 and A6.

Similarly, scenario 2 also allows for progressively increasing flow from downstream catchments. This may be hidden in monthly flows, but daily flows show the contribution of the lower catchments, i.e. there are higher flows at A6 than A5 and A4 and A3 for high rainfall events in the savannah zone near the sub-basin outlet (see Fig. 7). Figure 7 shows daily river flows superimposed on daily rainfall of *Matanya*, which is in the savannah zone as shown in Fig. 2. The monthly averages may not show clearly what happens during high storms, especially in the savannah zone.

The flood storage analysis also assumes that one big reservoir will be constructed to regulate the river flows, but the storage system will consist of a series of individual and communal storage reservoirs spread along the river course. Hence scenario 2 is more in agreement with reality than scenario 1. Nevertheless, both scenarios show similar redistribution of river flows, which allows more downstream flows during the dry season.

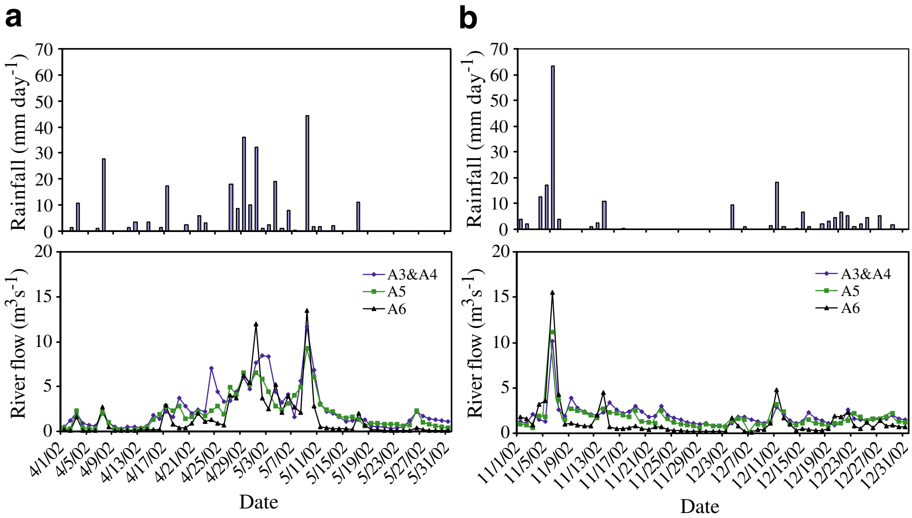

Fig. 7 Comparison of river flows and daily rainfall at *Matanya* for the two rainy seasons: **a** daily rainfall and river flow for April/May 2002; **b** daily rainfall and river flow for Nov/Dec 2002

Therefore, flood storage may reduce dry season water abstractions, without significantly reducing flood flows which are important in sustaining natural ecosystems and groundwater recharge downstream. For example, if only half of the crop water requirement is to be supplied from RHM system, i.e. 50% flood storage, then 50% of dry season abstraction will be released to downstream users. Flood storage does not affect the overall average flows, but distribute it without reducing the cumulative flows. Thus the gains in reducing dry season's abstractions would supersede the impacts of reduced flood flows.

The amount of flood storage can be reduced by improving storage efficiency, irrigation efficiency (currently at 25–40%), minimizing unproductive water losses, allowing minimal dry season abstractions and in-situ soil moisture conservation, which will reduce irrigation water requirement being met by stored flood. Since 2002 was a low flow year as shown in Fig. 4a, the positive impact of flood storage will be less in years with above normal river flows. Other benefits of flood storage are groundwater recharge, reduced cost of pumping and improved crop management. Some of the losses, especially seepage, may eventually contribute to groundwater recharge. The cost of pumping can also be reduced by locating flood storage structures where water can be delivered by gravity to the farms if adequate land is available, accessible and feasible for reservoir construction and maintenance.

Technically, besides the high capital cost of storage facilities, flood storage for dry season irrigation is feasible. Although capital/investment cost may constrain many smallholder farmers, the expected high returns from increased agricultural production would encourage them to apply for credits or financial assistance from development partners. The financial and hydrological implications should however, be considered in the formulation and implementation of a sustainable sub-basin water resources management strategy. The option of flood storage has already been adopted by some large-scale horticultural farms; for example, *Homegrown*, which has more than 300 ha of irrigated horticulture in *Timau* for export, stores up to 742,000 m^3 of flood flows in four earth dams to sustain its irrigation water demand (Ngigi 2003).

3.5 Implications on Upper *Ewaso Ng'iro* River Basin

The water crisis experienced in *Naro Moru* sub-basin is typical of what is happening in the other sub-basins. The excessive water abstractions for irrigation upstream have resulted in diminishing river flows, which are finally reflected by discharge of the entire upper *Ewaso Ng'iro* basin. Recent studies on three sub-catchments (*Burguret*, *Likii* and *Timau*) revealed similar hydrological trends (Liniger et al. 2005). The overall hydrological implication is reduced river flows, increased conflicts over water among stakeholders and negative impacts on natural ecosystems that thrive on sustained flows and periodical flooding. Figure 8 shows a decreasing trend of *Ewaso Ng'iro* river at *Archer's Post* over the last four decades.

The 10-year running average indicates that the flow has been decreasing since 1970. The months with the lowest flows correspond with those at the sub-basins; hence activities at the upper reaches affect the total river basin discharge. River flows at *Archer's Post* are lowest in February of which the mean has decreased from 9.0 $m^3 s^{-1}$ in the 1960s, to 4.6 $m^3 s^{-1}$ in the 1970s, to 1.3 $m^3 s^{-1}$ in the 1980s, and to 1.0 $m^3 s^{-1}$ in the 1990s (Liniger 1995). A section of *Ewaso Ng'iro* River dried up completely in 1984, 1986, 1991, 1997 and 2000 (Gichuki et al. 1998; Gichuki 2002). The trend line (Fig. 8) shows that the annual mean has decreased from 25 $m^3 s^{-1}$ in 1960 to 18 $m^3 s^{-1}$ in 2002, which is about 30% reduction in river flow. Besides ensuing upstream–downstream conflicts among surface water users, reduced river flows have negative environmental implications on downstream natural ecosystems. According to UNESCO and WMO (2001), increasing water withdrawals threaten the natural environment, and the biodiversity it contains. Another negative implication will be reduced groundwater recharge which sustains the lives of many pastoral communities and settlements downstream. Therefore, the impacts of reduced river flows due to human activities upstream will be felt either directly or indirectly in the entire river basin.

The cause of the decreasing river flows is mainly induced by human activities around the slopes of Mt. Kenya and *Nyandarua* Ranges since there is no corresponding decline in

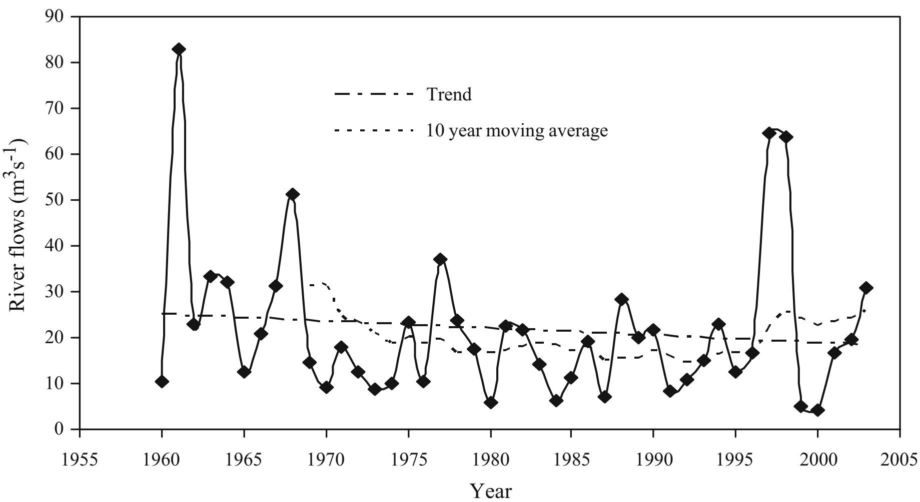

Fig. 8 Decreasing trend of observed *Ewaso Ng'iro* River flows at *Archer's Post*

rainfall amounts over the same period (Gichuki 2002). The trend is alarming and water scarcity related conflicts among different groups are increasingly becoming common. Although not all reported conflicts are related to water scarcity, the majority is water related. Water scarcity and associated conflicts have been compounded by lack of good understanding of the nature and extent of water shortage, failure to take action required to address water scarcity issues, inequity in resources access, poverty, lack of alternative sources of livelihoods, high cost of water resources development and technologies that use water efficiently, political interference, stakeholders' diverse perceptions on water availability, their entitlements and needs of other water users (Gichuki 2002), and inadequate policy, legal and institutional framework. However, despite these challenges, our interest here is how we can manage the limited water resources for socio-economic development and ecological needs. Berger et al. (2007) note that it a considerable challenge to manage water resources in an efficient, equitable and sustainable way. We believe that this challenge can be addressed through feasible technical options and improved governance.

Therefore, flood storage and management can be one of the sustainable solutions if supported by responsive policies and institutions that will adopt integrated water resources management principles and embrace direct and indirect actors and stakeholders. The problem of poor water governance is aggravated by low reliability of water supply, and we hope by improving water reliability (through flood storage), the farmers will collectively manage their common resource the through water users association. It is clear that enforcing the existing law to stop or regulate water abstraction during the dry season will not be economically feasible. This is because the farmers need an alternative since without irrigation their main source of livelihood will be jeopardized. Irrigation ensures crop production, food security and farmers' income.

4 Conclusions and Recommendations

The decreasing river flows in upper *Ewaso Ng'iro* river basin is alarming and urgent attention is required to reverse the trend. The cumulative effect of water abstractions in sub-basins is reflected by flow characteristics at the river basin outlet. The case study of *Naro Moru* sub-basin, which is representative of water crisis in other sub-basins, was used to demonstrate this scenario. The sub-basins have experienced increased immigration of settlers from the adjacent high potential districts since the early 1970s. This explains the decreasing trends of river flows (about 30% reduction over 40 years at *Archer's Post*) against an ever increasing water demand and pressure on other water resources. This has led to high proportions of unauthorized water abstractions. The *Naro Moru* case study shows the socio-economic and hydrological challenges and impacts in a water-scarce river basin, and a feasible option of addressing the ensuing water crisis.

The water crisis is aggravated by poor water governance system, which has led to over-abstraction of irrigation water and low water use efficiency. For instance, out of the 100 current water abstractors in *Naro Moru* sub-basin, only 25 have water permits out of whom, only 12 have been authenticated by the ministry of water and irrigation. The following are some of the reasons that have been attributed to high unauthorized abstractions: inadequate and ineffective water abstraction monitoring systems; high financial returns from irrigated agriculture; low fines for illegal abstractions; lack of floodwater storage facilities; and low water use efficiency for irrigation (25–40%) for smallholder irrigation schemes. Despite the high water abstractions, river flows cannot meet irrigation water demand, even at 100%

irrigation efficiency. It seems either only part of the irrigable land is irrigated or if available irrigable land is irrigated, crops are under severe moisture stress. The available water can only adequately irrigate about 40% of irrigable land at 50% irrigation efficiency. More land can be put under irrigation by either improving irrigation efficiency and/or incorporating flood storage. However, improving agricultural water management through adoption of water-use efficient technology such as drip irrigation can increase crop production with the available water resources.

The results show that flood storage can provide a feasible water management option, which may reduce the demand on river flows and over-abstraction during dry seasons. Flood management systems can either be small to medium on-farm storage structures such as farm ponds or large communal off-stream dams. This means that excess runoff and flood flows would be stored and used for irrigation during low flows. The emphasis here is on off-stream storage structures since the conventional on-stream storage structures also retain river flows during the dry season, and hence reduce flows downstream.

Besides reducing dry season's water abstraction, flood storage ensures water availability throughout the year—even distribution of water. This will reduce periodic conflicts between irrigation and other water users downstream. Another positive impact of flood storage is runoff reduction, which would reduce land degradation related to soil erosion. Soil erosion depletes agricultural lands of fertile top soil (i.e. loss of nutrients) and also leads to sedimentation of water bodies. Therefore, the positive impacts outweigh the associated negative impacts: reduced river flows during high floods, high capital costs, increased social burden in reservoir management and conflicts resolution, increased health risks (children drowning and environment for breeding of water related diseases vectors such as mosquitoes and snails), and increased human–wildlife conflicts. However, river flows reduction would be insignificant compared to the ensuing over-abstraction during following the dry periods if no storage is provided, while community capacity building will address most of the social conflicts. Human–wildlife conflicts can be minimized by ensuring adequate river flows downstream and location of the flood storage reservoirs outside the game reserve—not to affect upstream river flows.

Despite the positive socio-economic and hydrological impacts of flood storage and management, it requires substantial investment costs, which may hinder its consideration by the resource-poor smallholder farmers. This situation can be circumvented by strengthening sub-basin water users' associations, which will also assist farmers to acquire technical support, credit facilities and improve water governance. Water user's association will enhance catchment-based integrated water resources management and socio-economic development. The effectiveness of water users' association would be compromised if measures to reduce water demand and increase flood water storage are not incorporated. Such measures include provision of alternative sources of water and efficient demand management mechanisms to reduce over-abstraction. The government can facilitate formulation and implementation of catchment based integrated water resources management action plans, similar to the success stories in India (Agarwal and Narain 1997; Agarwal et al. 2001). The government facilitation can be in terms of responsive policies and incentives to private and public sector investors in water resources development and management, and provide credit to resource-poor farmers to construct off-stream and on-farm rainwater storage systems. Subsidies may lead to inefficient water use (UNESCO 2005); however, they can be considered as incentives to encourage farmers to construct flood storage structures.

To consolidate the positive socio-economic and hydrological impacts of flood management in upper *Ewaso Ng'iro* river basin, a number of restricting policies, legal and institutional issues should be addressed. Thus an integrated and multi-sectoral approach would be a prerequisite towards formulating sustainable water management strategies—sustainable solutions for addressing increasing irrigation water demand and diminishing water resources. For example, irrigation permits should stipulate that abstractions only take place during flood flows and that adequate water is stored for use during low flows. This requires legal backing to ensure compliance with Water Act and subsequent legislation (GoK 1972, 2002), which make it mandatory for permit applicants to first construct a 90-day flood storage structure. Inadequate adherence to legal requirements is a manifestation of a weak water governance system and the high returns associated with irrigated agriculture in an environment with high risk of crop failure under rainfed agriculture.

Nevertheless, technical issues should be addressed first to demonstrate their viability to policy- and decision-makers. In our case, we have demonstrated that flood storage has a potential of reducing dry seasons' water abstraction while sustaining adequate river flows for downstream water uses and users. This provides some insights to the question "how to increase water productivity in a river basin without significantly reducing river flows to affect downstream water uses and users?" The challenge is to understand how to regulate and use available water in different parts of a river basin and time of the year in order to improve overall river basin water resources management. This calls for both improved water distribution over the hydrological year and adequate water governance system that will ensure equitable allocation and efficient use of a river basin water resources.

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