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Land use changes and hydrological impacts related to up-scaling of rainwater harvesting and management in upper Ewaso Ng'iro river basin, Kenya

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Abstract

Some land use changes are driven by the need to improve agricultural production and livelihoods. Rainwater harvesting and management is one such change. It aims to retain additional runoff on agricultural lands for productive uses. This may reduce river flows for downstream users and lead to negative hydrological, socio-economic and environmental impacts in a river basin. On the other hand, rainwater storage systems may lead to positive impacts by reducing water abstractions for irrigation during dry periods. This paper presents a conceptual framework for assessing the impacts of land use changes in the upper Ewaso Ng'iro river basin in Kenya. It is based on a people–water–ecosystem nexus and presents the key issues, their interactions and how they can be addressed. The paper presents hydrological assessment of up-scaling rainwater harvesting (HASR) conceptual framework, which assesses the impacts of land use changes on hydrological regime in a river basin. The results will enhance formulation of sustainable land and water resources management policies and strategies for water-scarce river basins.

Keywords: Hydrological impacts; Conceptual framework; Rainwater management; Water abstraction; Integrated water resources management; Land use policy

Introduction

Population growth-induced agricultural intensification is taking place at an unprecedented rate in parts of Ewaso Ng'iro river basin. In semi-arid environment, where water is a major constraint to agricultural production, rainwater harvesting and management (RHM) systems are increasing in popularity (Ngigi, 2003a). The water retained by rainwater harvesting systems is part of the surface water that drains to lower reaches of the river to meet downstream water requirements. Sustainable agricultural intensification dependent on RHM requires that we address the following questions (i) How much water can be retained by RHM systems without adversely affecting the hydrologic regime, socio-economic and environmental conditions further downstream? (ii) How much would RHM systems reduce dry season irrigation demands and river water abstractions? and (iii) What proportion of the water retained in the catchment by RHM systems is used to recharge groundwater resources and sustain dry season river flows? The challenge is to identify appropriate responses to the threats of human activities on natural hydrological and ecological regimes in river basins (IAHS, 2003).

There is growing consensus for a need to improve agricultural productivity and water resources management to meet new challenges posed by increasing demand and diminishing water supply. However, the options, processes and impacts of desired change are less clear (Hajkowicz et al., 2003). Thus stakeholders are searching for a conceptual framework that can integrate policy, water users' aspirations and strategic actions to achieve the

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desired change. Hoekstra (1998) stated that the problem in integrated water resources assessment is not a lack of appropriate tools in any of the related sectors, but rather the lack of integration of these tools and the difficulty of translating analytical results into policy-relevant information. We need to support this statement by highlighting (i) the available tools, (ii) lack of integration of these tools, and (iii) difficulties in translating results into policy-relevant information. To address the most policy and management issues as perceived by users under different biophysical and socio-economic environments and taking into account needs for sustainable development, water-related physical (hydrological, climatological, ecological) and non-physical (technical, sociological, economics, administrative, law) observations are a prerequisite (UNESCO, 2005).

In an attempt to address this, conceptual framework for assessing hydrological impacts of up-scaling RHM in a river basin was developed. Up-scaling here refers to both moving from smaller to larger or improved systems (vertical up-scaling) and replication of the same systems (horizontal up-scaling or scaling out, i.e. increased adoption). The conceptual framework can be used to investigate hydrological, socio-economic and environmental impacts of intensifying agricultural production. However, the main focus is hydrological impacts related to up-scaling of RHM systems and increasing water abstraction for irrigation. The case of Naro Moru river sub-basin is used to highlight the impacts of land use change on river flows.

Description of the study area

Background information

This section presents the background of Ewaso Ng'iro river basin, anticipated land use changes, persistent water crises, opportunities and constraints, hydrological processes and production systems. The upper Ewaso Ng'iro basin, which constitutes a drainage area of 15,251 km^2, is part of the Juba basin, which covers parts of Kenya, Ethiopia and Somalia (see Fig. 1). It is situated between latitudes 0°20′ south and 1°15′ north and longitudes 35°10′ and 38°00′ east. It drains from Rift Valley escarpment to the west, Nyandarua ranges to the southwest, Mt. Kenya to the south, Nyambene hills to the east, Mathews range to the north while the downstream outlet lies at Archer's Post.

The topography of the basin is dominated by Mt. Kenya, Nyandarua ranges and Nyambene hills. Altitude ranges from 862 m at Archer's Post to about 5200 m at the peak of Mt. Kenya. The river basin is divided into three zones based on topography: mountain slopes, lower highlands and lowlands. The mountain slope is the forest zone of Mt. Kenya and Nyandarua ranges. In the upper mountain slopes elevations range from 2500 to 4000 m. The extensive gently undulating Laikipia plateau at an elevation of 1700–1800 m occupies most of the central region. The lower highlands constitute the area adjacent to the lower mountain slopes and the immediate Laikipia plateau between 1800 and 2100 m. The lowlands to the north and northeast have elevations ranging from 1000 to 1700 m.

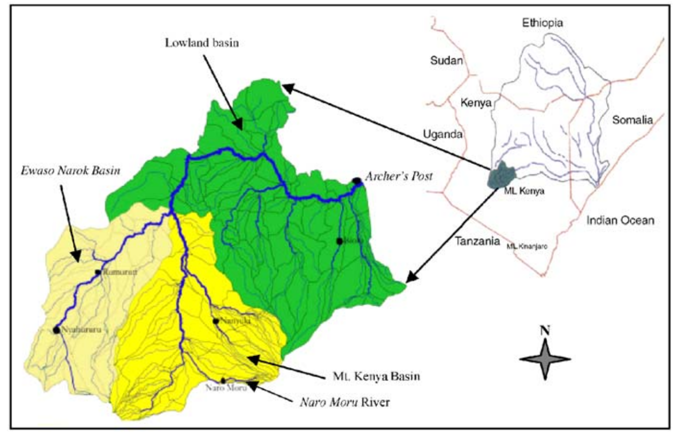

Fig. 1. Location and main sub-basins of the Ewaso Ng'iro river basin.

The river basin has diverse soil types, which include stony *mollic Cambisols* and *mollic Andosols* of medium depth, deep *mollic Andosols,* deep *humic Alisols,* volcanic *Phonolites,* well drained, deep, dark red to dark brown friable clay (*Luvisols* and *Phaeozems*), imperfectly drained, deep grey to black firm clay (*Vertisols* and *Planosols*) (Mbuvi and Kironchi, 1994).

The elevation gradient, which determines the rainfall pattern, gives rise to various climatic zones ranging from humid to arid. Long-term rainfall analysis shows high spatial and temporal variation ranging from 300 to 2000 $mm\,yr^{-1}$, with a mean of about 700 $mm\,yr^{-1}$. The rainfall pattern indicates a recurrence of wet-dry cycles of 5–8 yr (Gichuki, 2002). Rainfall variation affects river discharge, which since 1960 has varied from 0 to 1627 $m^3\,s^{-1}$ at Archers' Post. Rainfall intensities are usually high averaging about 20–40 $mm\,hr^{-1}$ while higher intensity storms of up to 96 $mm\,hr^{-1}$ have been recorded (Liniger, 1991). There are three main rainfall seasons, namely long rains (March–June), continental rains (July–-September), short rains (October–December). The long rains and short rains contribute 30–40% and 50–60% of annual rainfall, respectively. The average temperature range from 10 °C to 24 °C. The mean potential evaporation ranges from 2000 to 2500 $mm\,yr^{-1}$. However, despite the relatively high rainfall, its poor distribution and high potential evaporation affect crop production in most parts of the basin. Water deficit increases drastically with distance from Mt. Kenya (see Fig. 2).

The elevation gradient also gives rise to different climatic and ecological zones, from humid moorlands and forests on the slopes to arid acacia bushland in the lowlands, with a diverse pattern of land use (Decurtins, 1992). Natural resources are under pressure due to dynamic land use changes, migrating farmers, inappropriate land management practices, agricultural intensification and marginalization of pastoral community resulting in resource

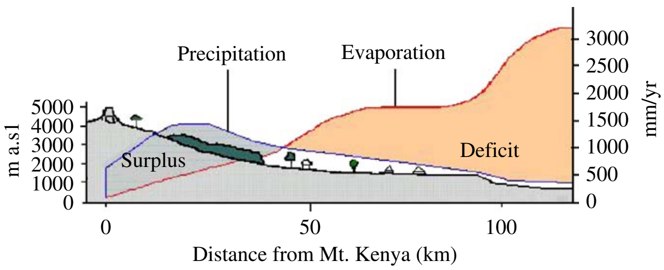

Fig. 2. Variation of annual water deficit with altitude and distance from Mt. Kenya.

degradation. The diversity in land use and land management practices range from mechanized and modern farming systems on large-scale farms to small-scale farming systems characterized by low technology and farm inputs.

Situational analysis

Population has increased from 50,000 in 1960 to 500,000 in 2000. The growth rate is estimated at 5–6% per annum (GoK, 1999) mainly due to immigration from the adjacent densely populated and high agricultural potential areas. Population in the river basin averages about 60 persons km^{-2}, but the distribution ranges from 212 persons km^{-2} on the highland small-scale farming areas, to less than 24 persons km^{-2} in the lowland pastoral areas (Huber and Opondo, 1995). Population densities are related to the diverse land-use systems. The current situation can be described as land use in transition, mainly related to conversion of semi-arid pastoral environments into agricultural lands.

The land use changes have put pressure on the fragile environment, resulting in a dilemma on how to sustain production while at the same time conserving natural resources and managing upstream–downstream water conflicting (Liniger et al., 2005). The conflicts can be considered at different spatial scales: between farmers at different agro-ecological zones; between farmers and pastoralists; between sedentary and nomadic pastoralists and between farmers/pastoralists and wildlife. Land use changes have been accompanied by reduction in river flows, environmental degradation and declining agricultural production.

Poor distribution of water is the most limiting factor to socio-economic development in the river basin (Kithinji and Liniger, 1991). Excess water during the rainy season is followed by severe drought during subsequent dry season. The situation is aggravated by unsustainable land use changes. River flow has progressively decreased by about 30% since 1960 mainly due to increasing water abstraction upstream and drought cycles, since there is no corresponding decline in rainfall trend. Water abstraction has increased from 20% in the wet season to over 70% in the dry season (Aeschbacher et al., 2005).

Water scarcity, particularly in the lower reaches of major rivers, has increased over the years and has resulted in conflicts between upstream and downstream water users (FAO, 2003; Gichuki, 2002). However, the adoption of RHM systems can reduce water abstractions and related conflicts. Exploitation of the potential of RHM systems would minimize dry season water demands and river abstractions. Some of the RHM systems are farm ponds for micro-irrigation and water pans and earthdams for livestock, in situ rainwater conservation and flood diversion and storage (Ngigi, 2003a). There is a growing realization that RHM can improve food production and livelihoods in water-scarce river basins. Despite the anticipated socio-economic impacts, up-scaling of RHM, may beyond a certain limit, lead to hydrological and environmental impacts (Ngigi, 2003b).

The anticipated land use changes and water crisis can be attributed to increasing farming activities in water deficit areas where rainfed agriculture is not sustainable. The farmers are forced by harsh climatic conditions to improve their livelihoods through intensification of rainfed agriculture, in particular adoption of RHM and irrigation to increase crop yields or stabilize yields that are normally affected by low and poorly distributed rainfall. This means increased retention of runoff on agricultural lands, which may reduce river flows during the rainy seasons. Water abstractions for irrigation also reduce river flows during the dry periods. The natural environment, and the biodiversity it contains, is threatened by both water withdrawals and water pollution (UNESCO, 2005).

The winners–losers and opportunities–constraints analysis show that upstream farmers stand to gain if they are allowed to continue retaining and abstracting more water for agricultural production. Some of the viable options are reduction of water retention upstream, reducing water demands and construction of storage and flow regulating reservoirs, improving water use efficiency, shifting from full irrigation to deficit and/or supplemental irrigation, reducing cropped area and shifting to lower water consumption crops. The disadvantaged downstream users could address water scarcity by construction of storage structures, improving water use efficiency, conjunctive use of groundwater and surface water, and demand management-oriented systems. The current demographic, socio-economic, institutional and technological transition and ensuing land use changes means that a good knowledge base is required to inform the policy and decision-making processes. The conceptual and analytical framework attempts to provide the required information and interactions, which are prerequisite in the formulation of sustainable water resources management strategies.

Conceptual and analytical framework

The conceptual framework is designed to assist water users, researchers and policy-makers to address complex problems of natural resources planning at the river basin scale (Hajkowicz et al., 2003). A conceptual framework, based on a systems approach, should consider and integrate hydrological, socio-economic and environmental aspects (Jakeman and Letcher, 2003). By considering only hydrological aspects, one would ignore important socio-economic processes, which determine water demand and hence constitute actual pressure on the physical system (UNESCO, 2005; Hoekstra, 1998; Meigh, 1995).

The conceptual framework for hydrological assessment of up-scaling RHM (HASR) was developed to incorporate hydrological and agricultural production systems with the aim of maximizing land and water productivity while minimizing negative hydrological and ecological impacts. The framework translates information on different adoption levels of RHM systems into simple hydrological indicators, which can be easily understood by multi-sectoral policy makers and the general public. Some examples of such hydrological indicators are the relative reduction of runoff and river flows and/or irrigation water demands due to adoption of RHM systems. The conceptual framework also explicitly brings to the fore the uncertainties and risks involved in making future predictions using inadequate and sometimes inaccurate data. It focuses on the impact of socio-economic development led land use changes on water resources management at a river basin. The assumption here is that in water-scarce river basins, more water on the farm will lead to increased agricultural productivity and improved livelihoods. The framework presents different scenarios that need to be considered in the assessment of hydrological impacts of land use changes in a river basin. These scenarios consider various combinations of adoption rate of RHM and river flows regime; high, average and low flows.

HASR is expected to inspire stakeholders to take necessary actions to address anticipated hydrological impacts and ensuing challenging water resources and livelihood issues. It will assist the stakeholders in addressing the complex process of determining the impacts of increased water retention upstream due to land use changes on downstream water users. HASR will give clarity to seemingly intractable problems, not only in Ewaso Ng'iro river basin, but other water-scarce basins that are bound to experience similar problems. However, it would not provide simple answers to complex questions, but guide the process of formulating viable options. It is a tool to aid thinking and assist in decision-making for those responsible for developing and implementing policies. HASR would contribute to policy and institutional reforms that promote participatory approaches to integrated water resources management (IWRM), which according to Merrey et al. (2004) are the foundations of effective river-basin level institutions.

Agricultural production systems

Understanding of the influence of farmers on the hydrological regime cannot be achieved without integrating their socio-economic activities and agricultural production systems that influence their decisions and actions. Intensification of rainfed agriculture is driven by the need to improve agricultural production and livelihoods. Improved agricultural productivity is measured in terms of biomass and crop yields, while livelihood is reflected in increased incomes. Besides increased yields, RHM is also aimed at stabilizing variations in crop yields and ensuring food security. However, increased production may reduce market prices and hence lower incomes, which may then either lead to a decline in adoption rate of RHM or to crop diversification. Investment in high yielding crop varieties and soil fertility improvement may also lead to increased crop yields.

The RHM production systems to be considered by HASR are soil storage systems (in situ water conservation, micro-catchment (overland flows) and macro-catchment (diversion of ephemeral stream into cropland–spate irrigation)) and runoff storage systems (small farm ponds, medium and large storage systems such as earthdams/water pans). It is against this background that the conceptual framework for addressing the impacts of up-scaling RHM in a river basin was developed. Though Merrey et al. (2004), Hajkowicz et al. (2003) and Vincent (2003) proposed a paradigm shift from focusing on water to people who derive their livelihoods from it, the proposed conceptual framework argues for a middle ground where both water and people are the focus of IWRM strategies.

Understanding the people–water–ecosystems nexus is a prerequisite for developing sustainable IWRM strategies. This will ensure that the concerns of other people relying on the same resources and the environment are integrated. This will be needed to reduce conflicts among winners (upstream users) and losers (downstream users) in a water resources management system. While the upstream users may justify their actions of retaining more water for productive use, the downstream users and natural ecosystems too have a right to the same water and their needs are as important. IWRM is about addressing these diverse and conflicting needs. The challenge is to support technologies that improve livelihoods of upstream farmers without compromising livelihoods of downstream users while minimizing negative hydrological and environmental impacts.

Spatial mapping of RHM systems

The location and distribution of various RHM systems in the river basin can be identified using spatial mapping based on biophysical characteristics. Spatial mapping criteria can be based on a number of factors. However, to reduce the number of combinations and complexity, soil characteristics (infiltration rates) and topography (land slopes) were used as the main factors that determine the type of RHM system and hence the amount of runoff retained on agricultural lands. Land use and vegetation/crop cover are taken as the management factors, in our case, for agricultural and non-agricultural lands. Agricultural land is further categorized into traditional (no RHM systems) and improved (with RHM systems). Three sub-categories of soil characteristics and topography were used giving a total of nine combinations (see Table 1).

The spatial mapping criteria can be used to sub-divide the catchment and/or river basin based on soil infiltration rate (S) and land slope (T) and hence assign different RHM systems to a mapping unit as shown in Table 2. Mapping unit (i.e. hydrological response unit) is defined by the pixel sizes, which vary for different RHM systems. The three RHM systems are in situ RHM (e.g. conservation tillage, bunds and micro-basins), small on-farm storage RHM systems (30–100 m^3 farm ponds for micro-irrigation) and medium to large storage RHM systems (earthdams and water pans mainly for irrigation and livestock water supply).

For example, if $S = S_H$ (high) and $T = T_L$ (low), then in situ RHM system is viable. However, such a spatial mapping criterion is simplistic and the decision on which RHM technology to adopt would depend on farmer's preference. Therefore, biophysical characteristics of RHM systems would be subjected to socio-economic constraints to delineate suitable land for agricultural production. The pixel sizes of each RHM system are based on the multiples of Landsat images pixel size (30 m × 30 m), catchment area and heterogeneity land use pattern and farm sizes.

Spatial hydrological scale

To understand the hydrological processes and impacts of land use changes in a river basin, one needs to analyse a river basin at different spatial hydrological scales, which forms the basis of hydrological modelling. However, hydrological data at these spatial scales are in most cases inadequate or inaccurate. Hydrological monitoring is also expensive and time consuming, hence reliance on hydrological models may be necessary. Nevertheless, hydrological models are only as good as the data used (Merrey et al., 2004) and hence the main task in hydrological modelling is data acquisition, verification, analysis and validation. The different spatial scales for hydrological impact assesment are field/farm (0–5 ha), medium catchment (100–200 ha), sub-basin (20–500 km^2) and basin (> 500 km^2). However, there is an increasing degree of uncertainty and complexity from field scale to river basin posing a challenge of extrapolating or interpolating results from one scale to another. Thus the need for increasing assessment from field (and runoff plot) to river basin scale to capture actual hydrological processes and agricultural production systems. Hydrological monitoring is required at field and medium catchment scales while hydro-meteorological records, where available, can provide data for sub-basin and river basin scales.

The fundamental problem related to the spatial scale issues in hydrological modelling is that hydrological systems consist of the following: spatial and temporal variations in climatic condition in terms of spatial and time scales; spatial variability of soil characteristics and impacts of human activities; spatial variation in vegetation cover due to different land uses; and diverse topographic features.

This results in non-linear hydrological responses with different physical laws, which emerge and dominate at different space and time scales, of all which hydrological models try to encapsulate, often by simple and lumped calibration procedures (Schulze, 2002). Therefore, the most critical question in hydrological modelling is how best one can integrate and up-scale knowledge of micro-scale hydrological processes. Measurements at point, plot or field scales form a causal chain in order to facilitate hydrological modelling at catchment and river basin scales. More often than not, different hydrological scales would require different models (Kite et al., 2001; Droogers and Kite, 2001) due to diverse parametric variability, and hydrological conditions and processes.

Quantification of hydrological impacts

The primary objective of RHM is to improve crop yields (ΔY) by increasing the transpiration component (ΔT) and reducing soil moisture stress, among other agronomic

Table 1
Spatial mapping units based on soil infiltration rates and land slopes

Soil characteristics (infiltration rates)	Topography (land slope)		
	T_L (low slopes)	T_M (medium slopes)	T_H (high slopes)
S_L (low)	S_L/T_L	S_L/T_M	S_L/T_H
S_M (medium)	S_M/T_L	S_M/T_M	S_M/T_H
S_H (high)	S_H/T_L	S_H/T_M	S_H/T_H

Table 2
Spatial mapping of different RHM systems and hydrological response unit

RHM system	Suitable sites	Pixel size	Pixel size selection criteria
In situ RHM systems	S_H/T_L, S_H/T_M, S_H/T_H, S_M/T_H	30 m × 30 m	• Landsat image pixel size • Heterogeneity of land use
Small storage RHM systems	S_L/T_M, S_M/T_M, S_L/T_H	60 m × 60 m	• Minimum catchment area • Multiple of Landsat size
Medium–large storage RHM systems	S_L/T_L, S_L/T_H, S_M/T_L	420 m × 420 m	• Minimum catchment area • Multiple of Landsat size

practices. Fig. 3 shows the three points of interventions for improving water productivity in rainfed agriculture in semi-arid environment as follows:

(A) maximizing plant water availability (maximize infiltration of rainfall, minimize unproductive water losses (evaporation from interception, soil and open water), increase soil water holding capacity and maximize root depth),
(B) maximizing plant water uptake capacity (timeliness of operations, crop management and soil fertility management), and
(C) dry-spell mitigation using supplementary irrigation (runoff storage and management).

The water balance analysis at these three points (A, B & C) is the basis of understanding the role of RHM in improving water productivity and food production in rainfall deficit areas. RHM may lead to: change in evaporation, $\Delta E = f$(water surface area, interception, soil moisture); change in surface runoff, $\Delta Q_r = f$(water retention, infiltration); change in base flow, $\Delta Q_g = f$(deep percolation, subsurface flow, seepage); and change in soil moisture storage, $\Delta S = f$(soil water holding capacity, rooting depth, depth of groundwater table). The hydrological and ecological impacts are reflected in change in river flow, $\Delta Q_s = f(\Delta Q_r + \Delta Q_g)$, while socio-economic impacts are reflected in change in crop yields, ΔY. Thus quantification of hydrological impacts of up-scaling RHM is based on estimation of the components outlined in Fig. 3.

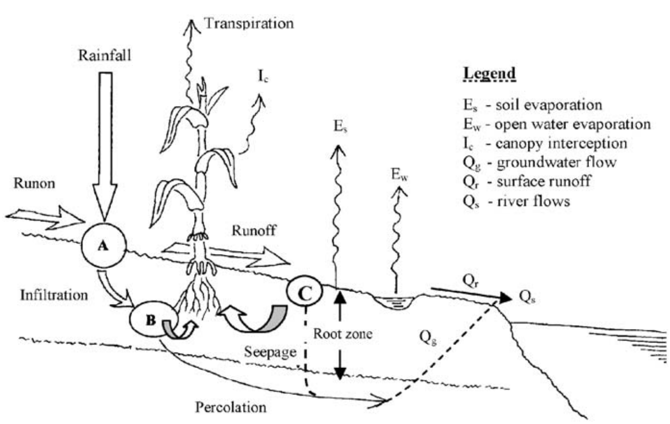

Fig. 3. Rainfall partitioning and intervention points (A, B and C) through RHM systems.

Rainfall–runoff relationship

Analysis of rainfall–runoff relationships in a catchment forms the basis of hydrological modelling. The relationship determines how much of the net precipitation (after subtraction of interception) is partitioned into runoff (i.e. overland flow from a catchment), some of which eventually becomes river flows, while the remainder either infiltrates into the soil on its way to the stream or is captured and stored on-farm for agricultural and domestic use. Rainfall–runoff relationships at each spatial scale indicate the amount of runoff generated by various land uses and farming systems. It shows the percentage of generated runoff that is retained on agricultural lands due to RHM—reduced catchment runoff yields—and consequently the reduction in river flow and water availability downstream. Fig. 4 shows linearized rainfall–runoff relationship and the effect of RHM on runoff yields at field scale. This is a typical rainfall–runoff relationship in many semi-arid areas (Ngigi et al., 2005; Gichuki et al., 2000). The intercept on the horizontal axis ($6.1/0.46 = 13\,\mathrm{mm\,day^{-1}}$) is the amount of minimum rainfall that can generate runoff. The angular coefficient (46%) is the percentage of net rainfall that becomes runoff. The complement of the angular coefficient (54%) is the infiltration (Savenije, 1997, 2004). For modelling purposes, the angular coefficient (runoff coefficient) would vary for different soil types and land slopes.

The relationship in Fig. 4 was developed from observed runoff data from farms with and without RHM systems over four rainy seasons (2002–2003). It shows the amount of runoff generated and the proportion retained due to RHM systems and hence the reduction of runoff at field scale. Different RHM systems influence catchment hydrological processes at different spatial scales.

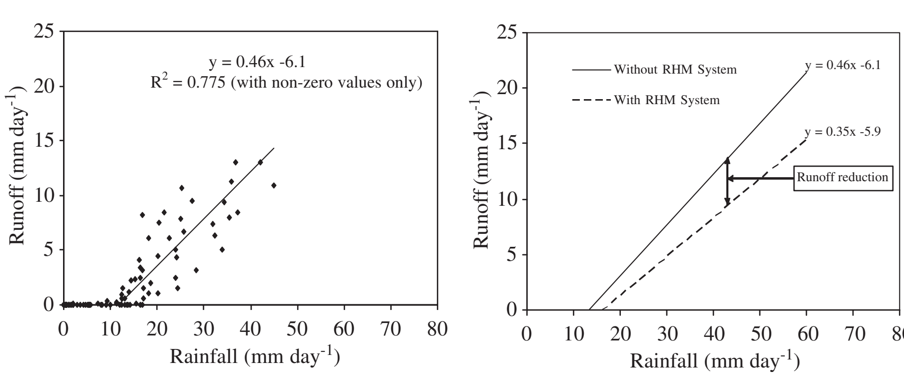

Fig. 4. Rainfall–runoff relationship and effect of RHM on runoff yield at farm scale.

Hydrological modelling

A hydrological model should capture both negative and positive hydrological impacts related to adoption of RHM upstream. The effects of different levels of adoption will be simulated in terms of incremental water "retention" and/or "release" during rainy and dry seasons, respectively. The hydrological model considers water retention/storage during rainy seasons and water "release" due to reduced abstraction, during dry season. The water "release" during dry seasons is very important because this is the time when direct water abstraction for irrigation would drastically reduce river flows. Cases of water not reaching Archer's Post are increasing, and the situation is bound to get worse if adequate measures are not taken to balance upstream and downstream water needs at both spatial and temporal dimensions. According to IAHS (2003), wise stewardship of water and environment requires a variety of predictive tools that can generate predictions of hydrologic responses over a range of space–time scales and climates, to underpin sustainable management of river basins, integrating economic, social and environmental perspectives.

Fig. 5 presents the conceptual framework, HASR, which is an explorative model meant to explore the hydrological implications of up-scaling RHM in a river basin. HASR analyses the amount of runoff retained by farmers upstream and hence the reduction in river flows downstream and gives emphasis on the surface runoff component that is significantly affected by up-scaling of RHM. The conceptual framework also integrates production systems on agricultural and non-agricultural lands.

HASR presents a simplified conceptualization of hydrological interactions between water retention through RHM during the rainy seasons and irrigation water abstraction during the dry seasons. However, in reality the hydrological processes may not be that simple because different hydrological processes occur at different spatial scales. This notwithstanding, hydrological processes at farm/field scales influence and determine, though not directly, what happens at the larger catchment or river basin scales. In our case, hydrological monitoring at different spatial scales showed that runoff coefficient varied from 46% at field scale to 12% at basin scale.

The amount of runoff retained by RHM system is computed using the rainfall–runoff relationships and adjusted to cater for the actual percentage of potential runoff that would be retained by each type of RHM systems (see Fig. 4). The decisions on the limit of up-scaling RHM are based on the amount of water available for downstream users and downstream flow requirements (DFR). If the river flow is below DFR, decisions will be made to reduce the amount of runoff retained upstream and thus a limit of up-scaling RHM for that production system.

From spatial mapping of RHM systems in the river basin, the effects of each system can be quantified from the runoff reduction ratio—proportion of runoff retained on agricultural lands. Then the runoff yields reduction ratio by a RHM system ($\Delta Q_{r(S)}/Q_{r(S)}$) is calculated from Eq. (1) and the total runoff reduction ratio in a catchment or river basin ($\Delta Q_r/Q_r$) is computed from Eq. (2). Up-scaling of RHM is reflected by an increase in area under RHM (ΔA_S) and the intensification of RHM leading to more runoff retention per unit area ($\Delta q_r/q_r$). The runoff reduction is computed per unit area based on the spatial scale (i.e. 1 ha for in situ and small storage systems and 1 km^2 for medium to large storage systems).

$$\frac{\Delta Q_{r(S)}}{Q_{r(S)}} = -\left(\frac{A_S}{A_R}\right)\frac{\Delta q_r}{q_r}, \tag{1}$$

$$\frac{\Delta Q_r}{Q_r} = \sum\left(\frac{\Delta Q_{r(SS)}}{Q_{r(SS)}} + \frac{\Delta Q_{r(IS)}}{Q_{r(IS)}}\right), \tag{2}$$

where A_S = area under a RHM system (ha), A_R = total area of the catchment or river basin (ha), $\Delta q_r/q_r$ = runoff retention per unit area, $\Delta Q_{r(S)}/Q_{r(S)}$ = runoff reduction ratio by a RHM system (%), $\Delta Q_{r(SS)}/Q_{r(SS)}$ = runoff yield reduction ratio by storage RHM systems (%), $\Delta Q_{r(IS)}/Q_{r(IS)}$ = runoff yield reduction ratio by in situ RHM systems (%), and $\Delta Q_r/Q_r$ = total catchment/river basin runoff reduction (%).

Irrigation water abstractions have been identified as one of the main contributing factors to reduce river flows, especially during the dry periods when many farmers along the streams abstract water illegally and uncontrollably without due regard to downstream water users. The irrigation–RHM interface presents a positive effect on irrigation water supply, in terms of reduced dry season river abstractions. This is based on the "released" water that would have been drawn from river flows if runoff was not harvested and stored during the rainy seasons. Medium and large RHM systems may be viable options for reducing dry season irrigation water abstraction. Thus RHM systems may reduce water scarcity related conflicts among upstream and downstream users.

Results and discussion

The case of Naro Moru sub-basin

The Naro Moru river basin (173 km^2) spreads westwards from the peak of Mt. Kenya to the semi-arid Laikipia plateau. It is situated on the southern part of the Mt. Kenya sub-basin (Fig. 1) and the altitude ranges from about 5200 m to 1800 m at the confluence of the Naro Moru and Ewaso Ng'iro rivers. The river has six river gauging stations from the top of Mt. Kenya to the point where it joins Ewaso Ng'iro river (see Fig. 6). Naro Moru sub-basin is divided into sections (reaches) according to elevation and ecological belt i.e. moorland (3500–5200 m), forest (2300–3500 m), foot zone (2000–2300 m) and savannah (1800–2000 m). Much of the river flow is concentrated within the two rainy seasons. River discharges during the

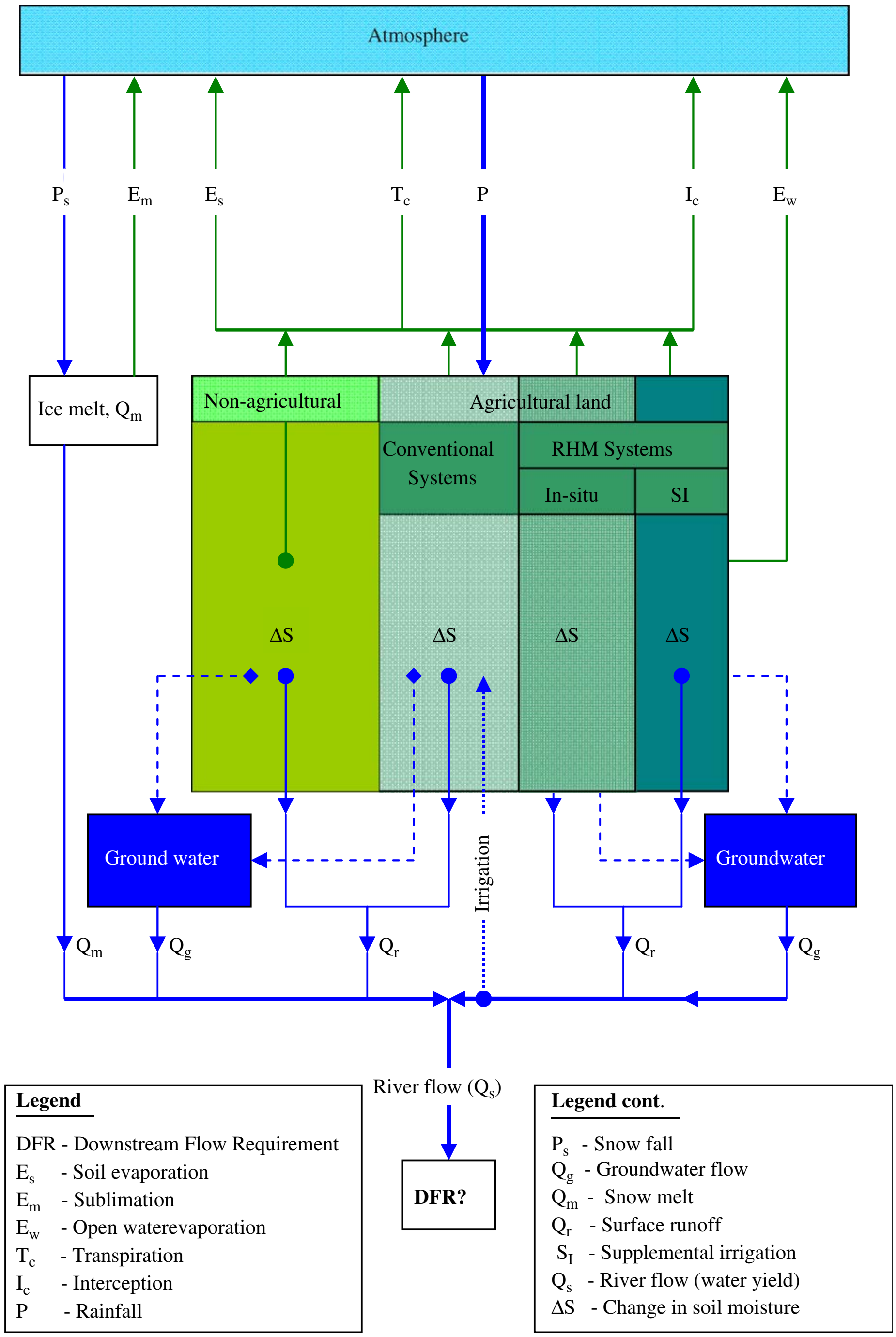

Fig. 5. Conceptual framework for HASR.

dry months consist mainly of base flow, which is derived from groundwater sources in the lower moorland and upper forest zones. The semi-arid savannah only yields runoff during the rainy season.

Water abstraction assessment revealed that about 62% of the dry season flow and 43% of the wet season flow is abstracted from Naro Moru river before its confluence with Ewaso Ng'iro river (NRM, 2003). Though the river is perennial, over-abstraction, of which more than 70% is illegal (Aeschbacher et al., 2005; Gichuki et al., 1997; Gikonyo, 1997), leads to drying up of the lower reach during the driest months of February and March, and under extreme conditions from July to September. Irrigation water demand during the dry seasons can only be met through flood storage, that is by construction of storage reservoirs. Land use changes have drastically affected river flows. Average river flows on the lower river reaches (foot and savannah zones) have gradually been decreasing (Fig. 7), while there is insignificant decline in upper reach (forest zone).

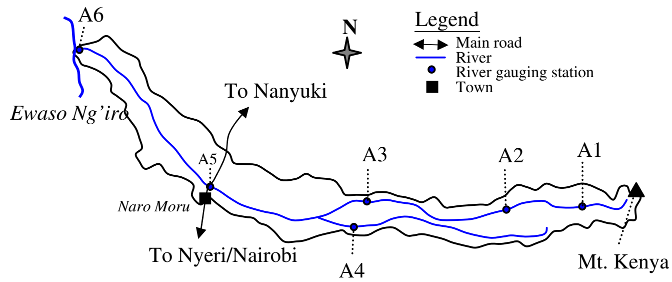

Fig. 6. The six river gauging stations (A1–A6) of Naro Moru sub-basin.

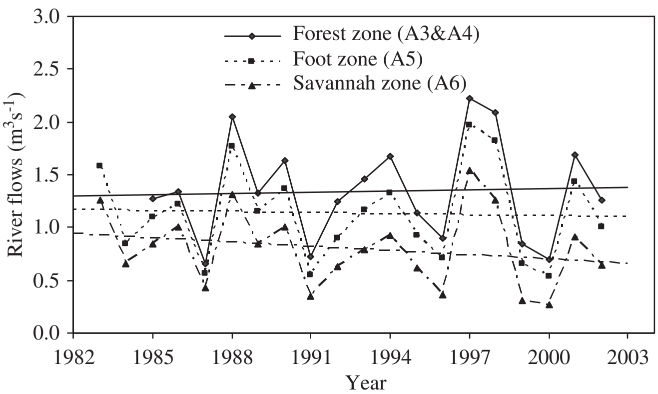

Fig. 7. Observed flows and trends along three reaches of Naro Moru river.

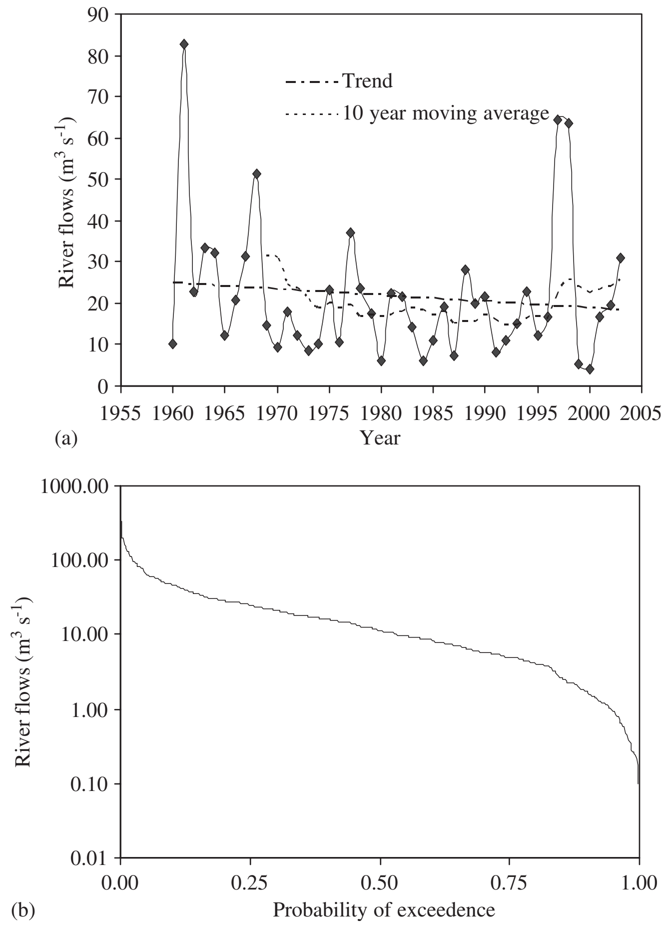

Fig. 8. Flow trend and duration curve of Ewaso Ng'iro river at Archer's Post.

The management of diminishing water supply poses a major challenge due to related hydrological, environmental and social implications. This calls for proper water management to ensure that this resource is used in a sustainable way. In the past, emphasis has been on supply of river water to meet demand but there is an urgent need to devise viable 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 storage for use during the dry seasons. However, sustainable solutions to addressing conflicts over water rely on formulation of adaptive policies and strategies.

Anticipated scenarios and hydrological impacts

Fig. 8a shows a decreasing trend of Ewaso Ng'iro river flows at Archer's Post, which can be attributed to land use changes and upstream water abstraction mainly for irrigation, since there has been no significant reduction in rainfall. This reflects what is happening at the sub-basins upstream, for example the case of Naro Moru presented in Fig. 7. Therefore, the anticipated scenarios shown in Fig. 9 are based on two hypotheses: (i) adoption of RHM will increase progressively due to its tangible benefits to farmers, and (ii) increased retention of runoff upstream will reduce river flow.

The scenarios of up-scaling RHM are based on three river flow regimes: high (upper quartile), average (median) and low (lower quartile) flows, i.e. at 25% ($Q_{25} = 25.16\,m^3\,s^{-1}$), 50% ($Q_{50} = 11.53\,m^3\,s^{-1}$) and 75% ($Q_{75} = 4.97\,m^3\,s^{-1}$) probability of exceedence, respectively. These probabilities are based on observed historical river flow data of Ewaso Ng'iro river at Archers Post (see Fig. 8b) and anticipated adoption rates of RHM systems. The y-axis on the right represents the observed long term river flow while that on the left represents anticipated rate of adoption of RHM systems. The adoption rate, currently estimated at 15%, is based on increased awareness of RHM and related impacts on agricultural productivity and household livelihoods. Adoption of RHM can also be attributed to diminishing river flows, which has prompted commercial farmers to construct runoff storage reservoirs for irrigating high value horticultural crops (Ngigi, 2003a).

The intersection point of river flows and the desired DFR indicates the limit of up-scaling RHM. Even at the present low RHM adoption rate, there are cases of water not reaching the basin outlet during extremely low rainfall years—river flows fall below the desired DFR. In general, the river flow patterns show short peak flow and long low flow periods (Gichuki, 2002; Liniger et al., 2005). This means that the river flow during dry season is some times below the minimum DFR, which for our case can be

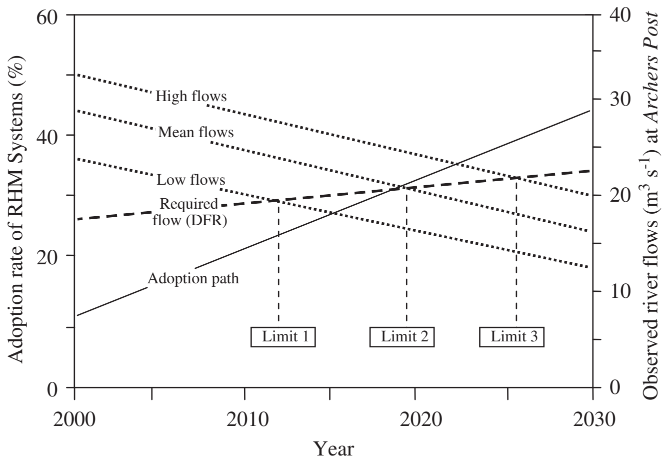

Fig. 9. Simplified presentation of anticipated scenarios due to adoption of RHM systems.

conservatively estimated as Q_{95} (i.e. $0.95\,m^3\,s^{-1}$). Reduced river flows could lead to negative hydrological, socio-economic and environmental impacts for downstream water users. High river flows during the rainy seasons are important for recharging groundwater and maintenance of natural ecosystems. These anticipated river flows reduction present a big challenge and hence the need to formulate sustainable solutions.

The long-term hydrological impacts can be assessed by simulating the HASR management scenarios using established river basin hydrological models such as the soil and water assessment tool (SWAT). SWAT is a physically based continuous-event hydrological model for predicting the impacts of land management practices on water, sediment and agricultural chemicals in large complex watersheds with varying soils, land use and management conditions over long periods of time (Nietsch et al., 2001). The SWAT model can simulate different land use scenarios related to up-scaling RHM as conceptualized by HASR (see Fig. 5) and hence hydrological impacts on downstream water resources management. Thus HASR can be integrated into complex hydrological models to enhance long-term assessment and policy formulation. However, caution should be taken as a more sophisticated model may not alone solve the impediments of data quantity and quality, uncertainty and scaling issues (IAHS, 2003). Nevertheless, with substantial data, it would be imperative to apply hydrological modelling to enhance formulation of sustainable IWRM policies.

Formulation of IWRM policies

Policy and decision makers are faced with a dilemma due to inadequate information and simple methodologies for assessing the consequences of socio-economic development, which bring about land use changes and hydrological impacts on water resources management. In the past, water has been perceived merely as a "free" resource, to be exploited in order to support socio-economic development. Impacts of human activities on water resources management are manifested in limited water supply and increasing tension between intensive water use and the functioning of natural ecosystems. Moreover, uncertainty and risks associated with forecasting future scenarios and trends on the utilization of natural resources affect policy formulation process.

HASR can address this by highlighting possible consequences of stakeholders' actions or inactions towards land and water development. The framework provides a tool for assessing hydrological impacts based on various production systems and guide formulation of IWRM policies at a river basin scale. It forms the basis of formulating policies and strategies by highlighting key issues and the process of understanding them. Therefore, the framework can enhance decision **s**upport **s**ystem (DSS) and stakeholders' dialogue. DSS would be based on optimization of production systems and hydrological impacts assessment related to land use changes. DSS provides stakeholders with options and related hydrological impacts thus feeding into stakeholders' dialogue. The dialogue focuses on trade-offs among conflicting water users' interests. The conceptual framework integrates the needs and aspirations of different stakeholders and the needs of natural ecosystems, i.e. hydrological, socio-economic and environmental aspects. It aims to maximize land and water productivity of upstream and downstream users, minimize conflicts among water uses, and maintain minimum flows for conservation of natural ecosystems and downstream users beyond the river basin boundaries. Analysis of the "best" or "acceptable" land and water management options will consider the results of optimization and evaluation of trade-offs among different stakeholders and socio-economic sustainability of production systems (Mainuddin et al., 2003). Sustainable water resources management strategies aim to improve livelihoods of downstream and upstream inhabitants and conservation of natural ecosystems.

Hydrological modelling can be used to assess impacts of upstream land use changes related to increased adoption of RHM for improving rainfed agriculture. The results can show how socio-economic activities of upstream land users can affect their downstream counterparts, and what needs to be done to address such impacts. The main stakeholders are the downstream and upstream land and water users, who strive to make maximum benefits from a resource they have always considered as free and a common good. When the resource is adequate, there is no conflict and hence status quo remains. However, more upstream water abstraction leads to water scarcity downstream. Conflicts among different water users may lead to social disruptions, which would affect socio-economic development.

Different water users perceive the problem differently. The downstream users see upstream irrigators as the problem. The irrigators on the other hand argue that it is the only way they can produce food in this semi-arid environment. The problem is bound to be more complicated if upgrading rainfed agriculture could retain more water upstream. HASR emphasizes on irrigation–RHM interface that could enhance water balance and reduce conflicts.

Conclusions

Land use changes, especially upgrading of rainfed agriculture, are unavoidable due to increased food demand and declining agricultural productivity. Such changes are bound to have positive socio-economic impacts geared towards improving livelihoods, but could lead to negative impacts downstream. This would affect downstream livelihoods and natural ecosystems that depend on sustained river flows. HASR analyses the anticipated scenarios and socio-economic, hydrological and environmental impacts on upstream and downstream reaches of Ewaso Ng'iro river basin. The socio-economic impacts are based on improved agricultural production through adoption of RHM systems, which retain and store more water for crop production. However, this may reduce runoff and hence river flows, which may lead to water scarcity downstream. HASR can be used to assess the impacts on up-scaling RHM, and hence form the basis hydrological modelling and formulation of IWRM strategies.

Up-scaling of RHM can be attributed to increased agricultural production and stabilized crop yields, and hence improved income and livelihoods. However, there is need for preparedness to address anticipated impacts and resulting water crisis. This forecast will assist stakeholders to formulate sustainable policies to avert the looming water crisis. Moreover, there is need for more detailed predictions of the possible scenarios. Application of advanced hydrological models to simulate anticipated scenarios would be one method of achieving this. Nevertheless, the preliminary results guide the process of formulating IWRM strategies to address anticipated land use changes and related impacts. Thus HASR will play a role in answering the following question "What is the limit of up-scaling RHM in a river basin scale?" Ngigi (2003b). The answers form the basis of sustainable IWRM strategies, especially for water-scarce basins.

A sustainable IWRM strategy should balance the diverse interests of stakeholders. It is envisaged that HASR would enhance understanding of various hydrological and socio-economic processes and hence support formulation of sustainable policies, legislation and institutions that focuses on the needs and socio-economic activities of water users and natural ecosystems. The policy formulation process requires an understanding of trade-off between land and water systems as well as potential impacts on other sectoral policies. This would identify sustainable options for water resources management.

The conceptual framework defines how land use changes and hydrological impacts can be integrated in a decision support system. It is an explorative tool aimed at strategic land use issues: how to satisfy the conflicting needs and objectives on economic, food security, ecological and social dimensions of land use. Its primary aim is to support and stimulate open discussion about future possibilities and limitations. HASR is simple enough, for the stakeholders to understand the hydrological impacts of land use changes, and comprehensive enough to predict possible future scenarios and trends under different land use and water management systems. Besides contributing to the ongoing restructuring of water resources management in Kenya, the paper will contribute to international policy dialogue and programs such as Hydrology for the Environment, Life and Policy (HELP) (UNESCO, 2005), Consultative Group on CGIAR Challenge Program on Water for Food (IWMI, 2002), among others.

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