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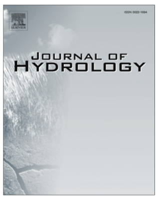

Coupling socio-economic factors and eco-hydrological processes using a cascade-modeling approach

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SUMMARY

Most hydrological studies do not account for the socio-economic influences on eco-hydrological processes. However, socio-economic developments often change the water balance substantially and are highly relevant in understanding changes in hydrological responses. In this study a multi-disciplinary approach was used to study the cascading impacts of socio-economic drivers of land use and land cover (LULC) changes on the eco-hydrological regime of the Lake Naivasha Basin. The basin has recently experienced substantial LULC changes exacerbated by socio-economic drivers. The simplified cascade models provided insights for an improved understanding of the socio-ecohydrological system. Results show that the upstream population has transformed LULC such that runoff during the period 1986–2010 was 32% higher than during the period 1961–1985. Cut-flower export volumes and downstream population growth explain 71% of the water abstracted from Lake Naivasha. The influence of upstream population on LULC and upstream hydrological processes explained 59% and 30% of the variance in lake storage volumes and sediment yield respectively. The downstream LULC changes had significant impact on large wild herbivore mammal species on the fringe zone of the lake. This study shows that, in cases where observed socio-economic developments are substantial, the use of a cascade-modeling approach, that couple socio-economic factors to eco-hydrological processes, can greatly improve our understanding of the eco-hydrological processes of a catchment.

1. Introduction

Eco-hydrological systems respond to perturbations of varying magnitude and intensity across space and time (Caylor et al., 2005). And so do socio-ecohydrological systems. Identifying mechanisms that translate these perturbations into structural and functional changes is important towards informing on socio-economic decisions of management and conservation of basins (Burcher et al., 2007). For example land use and land cover (LULC) changes mirror the impacts of human activities (Houghton et al., 1999; Schneider and Eugster, 2005).

With increasing population, human actions and associated LULC are known to increasingly affect the water quality and quantity and may compromise the integrity of eco-hydrological systems through numerous and complex pathways (Allan et al., 1997; Allan, 2004; Strayer et al., 2003; Townsend et al., 2003). There is a need to understand the main drivers of such systems and how they interact and influence the system. Without knowing how these drivers propagate through a system, we cannot identify the associated trigger mechanisms, thus limiting our ability to understand or manage such a system. However, identifying the driving factors and processes of these influences is complicated by the multitude of potential causalities and time-frames at which the processes take effect.

Pathways define the propagation of influences from an initiation phase which is then conveyed through entities in space and time to a destination (Fig. 1) where consequences are realized (Reiners and Driese, 2001). Such an organization of links or couples is described in this paper as a cascade where a series of connected links originate from a trigger that is translated through chains of interdependent elements terminating in a response (Burcher et al., 2007).

Hydrological modeling approaches for densely populated areas should factor the socio-economic influences in the hydrological processes (Loucks and Van Beek, 2005; van Oel et al., 2013). However, before we optimize and allocate water we need to know what drives water withdrawals and water diversions. Only then, we are able to formalize a river basin management plan, and design policy instruments either in the physical or in the social realm. As an

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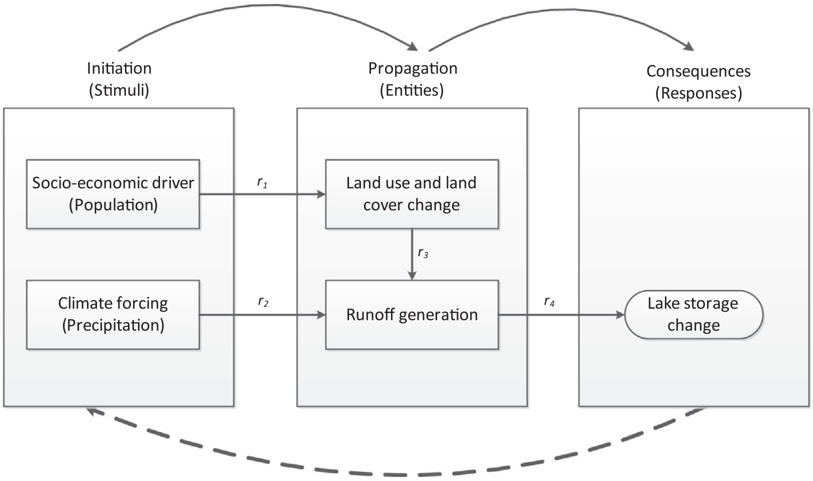

Fig. 1. A conceptual framework illustrating a path diagram of a hypothesized cascade model that predicts lake storage change. The links, r_1, r_2, r_3 and r_4 represent the pathways through which factor influences are propagated through entities and responses. Adapted from Reiners and Driese (2001).

example, an important factor is the growing human population that exerts increasing pressure on the LULC, as demand multiplies for resources such as food and water. Another example is increase in industrial production requiring water. Socioeconomic factors dictate how land is used regionally as well as locally, and how much water is needed. Therefore, it is vital to assess the major socioeconomic drivers of LULC changes (especially in developing countries) and their impact on the environment. In total, the interaction between physical and social phenomena builds up a system with positive and negative feedbacks in space and time (Kelly et al., 2013).

In this study, we focus on understanding the historical cause of events in the Lake Naivasha Basin socio-ecohydrological system. To realize this, we restrict ourselves to a less demanding model, given that we are in a relatively data poor environment. We apply a cascade model to study the case of Lake Naivasha Basin.

The economy of the basin is highly dependent on natural resources but the response of the environment due to the socio-economic influences is highly uncertain. Despite the increased socio-economic activities and LULC changes experienced in the Lake Naivasha Basin, there is limited knowledge on the impacts of these changes on the eco-hydrological regime of the basin. The magnitude of these impacts at relevant spatial and temporal scales is uncertain. Much of what is known about these impacts has only been inferred through water balance models (Becht and Harper, 2002) or sediment studies (Odongo et al., 2013; Tarras-Wahlberg et al., 2002). However, these models fail to explain the disturbance pathways involved because they do not integrate multiple scales (Burcher et al., 2007; Downes et al., 2002). No attempt has been made to integrate multiple trigger mechanisms at different scales that include socio-economic factors and LULC changes that trigger the observed responses. Therefore, there is a need to understand the main drivers of the system and how their effect propagates through the system. Without knowing exactly how the influence of these drivers propagates through the system, we cannot identify the associated processes that need to be understood in order to address them.

The cascade modeling approach using path analysis as adopted in this study enhances a holistic understanding of a complex system such as Lake Naivasha Basin amidst the cross-cutting disciplines of socio-economy and eco-hydrological processes. It might not be the best method to apply in multi-disciplinary research that involves feedback mechanisms; however, it is a better method to apply in a data scarce environment for an African country. Alternatives to cascade modeling would be process-based models (e.g. agent-based modeling (ABM) or system-dynamics (SD)) that account for relevant feedback mechanisms, explore impacts of future scenarios or compare effects of alternative measures. However, these alternatives are data intensive and complex compared to path analysis. The advantage of using path analysis is that it mirrors theories of causation and inform on which hypothesized causal models best fits the observed pattern of correlations among datasets (Burcher et al., 2007). Also the approach allows one to decompose various factors affecting an outcome into direct and indirect components. This way the method is a first step in developing clear and logical theories about processes influencing a particular response in a system (Lleras, 2005).

To our knowledge this is the first time that a basin scale integration using hypothesized cascades of events is used to asses eco-hydrological impacts by coupling socio-economic factors in a sub-Saharan tropical basin. The combined effect of these cascades has put the lake ecosystem services under pressure (Becht and Nyaoro, 2005; Becht et al., 2006; Harper and Mavuti, 2004; Otiang'a-Owiti and Oswe, 2007). This study aimed at quantifying the impacts of socio-economic factors on eco-hydrological regime of Lake Naivasha Basin using a conceptual framework based on cascade modeling.

2. Methods

2.1. Study area

The Lake Naivasha Basin is situated in the Great Rift-Valley at a latitude of 0°09′ to 0°55′S and longitude of 36°09′ to 36°24′E. The altitude ranges from 1980 m to about 3990 m above mean sea level (a.m.s.l) on the eastern side of the Aberdare ranges. The catchment area is approximately 3400 km^2 (Fig. 2).

Climatic conditions in the study area are diverse due to considerable differences in altitude and relief. Fig. 3 summarizes the monthly average precipitation and temperature variations in the Lake Naivasha Basin. The daily mean temperature ranges from 8 °C to 30 °C. The rainfall regime within the basin is influenced by local relief with the catchment being in the rain shadow of the Aberdare ranges to the East and the Mau Escarpment to the West. There are two rainy seasons experienced in this catchment. Long rains occurring in the months of March to May and the short rains experienced between October and November. The Lake Naivasha Basin experiences an average annual rainfall of 610 mm, and the wettest slopes of the Aberdare ranges receive as much as

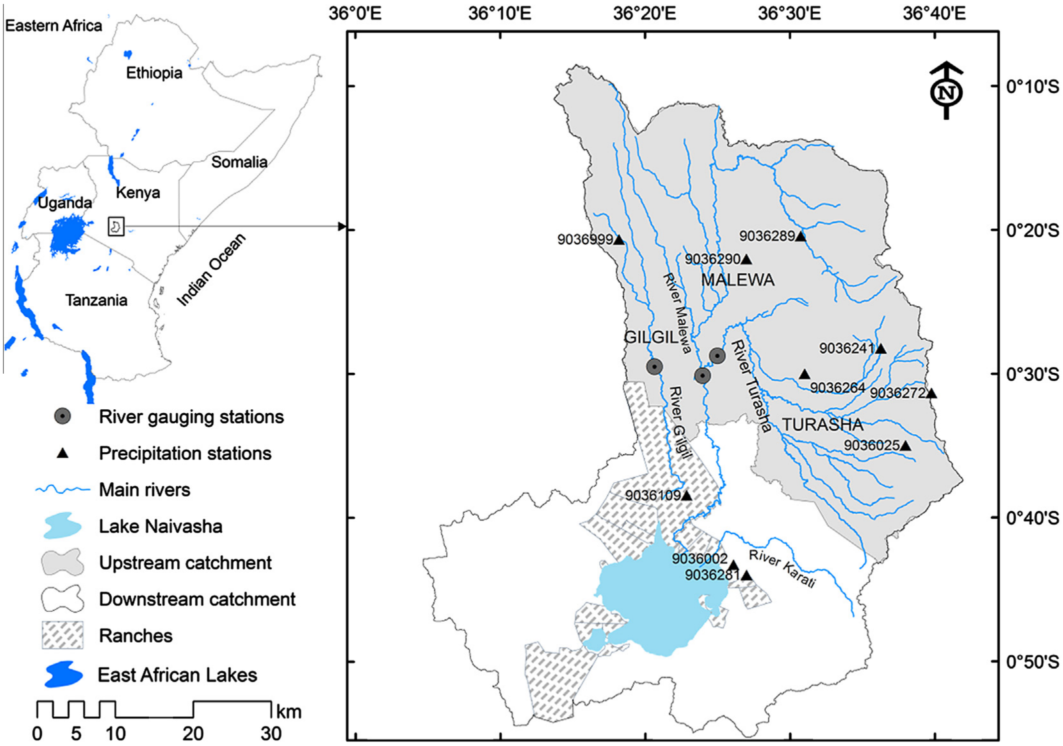

Fig. 2. Lake Naivasha Basin showing its main rivers and tributaries. The upstream area forms part of the hydrologically active area contributing majority of the flows downstream.

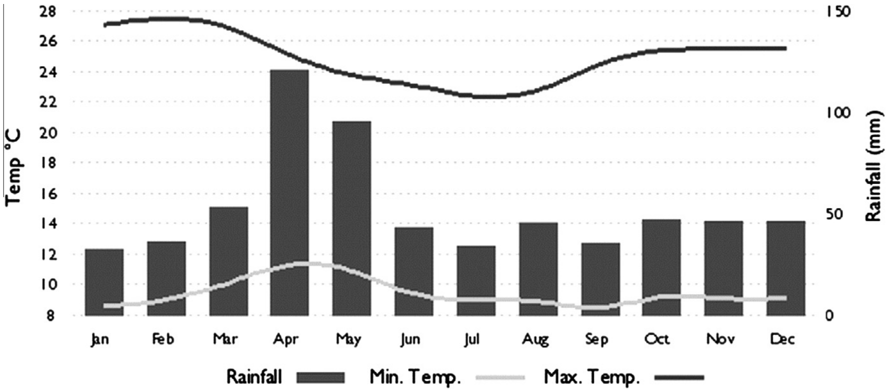

Fig. 3. Monthly average climatic conditions of temperature and rainfall for Lake Naivasha.

1525 mm. The major soils in the study area are of volcanic origin. The soils found on the mountain and major escarpments of the catchment are developed from olivine basalts and ashes of major older volcanoes.

Lake Naivasha has been subject to wide fluctuations of water levels over time and has almost dried in the past years (Abiya, 1996; Gaudet, 1977a; Verschuren et al., 2000). This natural fluctuation, combined with increasing water demand and land use change have led to occasionally strong decreases of the lake water levels (Becht and Harper, 2002; Olaka et al., 2010; Ondimu and Murase, 2007; Otiang'a-Owiti and Oswe, 2007; Trauth et al., 2010). Low lake levels made the lake ecosystem vulnerable and its fragility is a challenge to conservationists and scientists (Becht et al., 2006; Gherardi et al., 2011; Harper and Mavuti, 2004; Harper et al., 2011). The lake is a RAMSAR wetland (Ramsar, 1996) despite supporting important economic activities including fishing, agriculture, power generation, domestic water supply and tourism (Becht and Nyaoro, 2005).

Moreover, the basin has experienced increasing pressures on its land and water resources due to an increase in population majorly attracted with the rise in the horticultural industry since early 1980s (van Oel et al. 2013). The industry has supported and sustained the economy of the basin through production and export of flowers. The agriculture has encroached on previously communal grazing with significant effect on large herbivore species (Harper and Mavuti, 2004). Consequently conflicts have risen because of misunderstandings of the socio-hydro-ecological system (Becht et al., 2006).

2.2. Methods

Land use/cover was extracted from time series satellite imagery using remote sensing techniques, and consequently changes between scenes were identified in a change detection exercise. Correlation analysis was used to explore the relationship between socio-economic drivers and LULC. Path analysis (Shipley, 2000) was used to investigate the cascading impact of changes in LULC on hydrological and ecological responses. To understand the effect of the changes, these analyses were investigated using two cascade models.

The first cascade (Cascade 1) in our basin is that change from the upper catchment propagating through multiple systems, where population pressure changed the LULC, modifying the hydro-ecological system (Fig. 4). In the downstream area, around Lake Naivasha, another cascade (Cascade 2) prevails that is mostly driven by extensive horticultural production, increase in downstream population on LULC changes and changes in downstream hydrology on biodiversity (Fig. 5). The associated employment opportunities have induced rapid population growth in and around the town of Naivasha (KNBS 1979; 1989; 1999; 2009). The reason for evaluating two separate cascades is because of differences between the drivers in both parts of the Lake Naivasha Basin.

2.3. Development of the cascade model

Path analysis (Shipley, 2000) was used to test whether changes in socio-economic stimuli variables significantly affect hydrological behavior downstream. The analysis is a methodological tool that use relationships which are defined *a priori* and follow a specific causal hypothesis guided by a conceptual framework to estimate the magnitude and strength of effects (Maloney and Weller, 2011). The conceptual framework is normally represented using graphical path diagrams that infer causality as predetermined by a researcher's knowledge of the system. The requirement of *a priori* hypothesis in path analysis makes it an appropriate tool to predict important interactions in a system. The paths are then evaluated either by path coefficients or by regression coefficients. Regression coefficients provide information about the functional relationships between pairs of variables, predicting how much the dependent variable changes with a given change in any of the different causal variables (Wootton, 1994). Path coefficients indicate the strengths of association, providing a relative measure of the amount of variance explained by different causal variables, and the sign of the interaction or effect from the causal variable (Grace et al., 2010; Wootton, 1994). The analysis follows a general form of structural equation modeling (SEM) approach expressed as:

$$Y = \beta Y + \Gamma X + \zeta \tag{1}$$

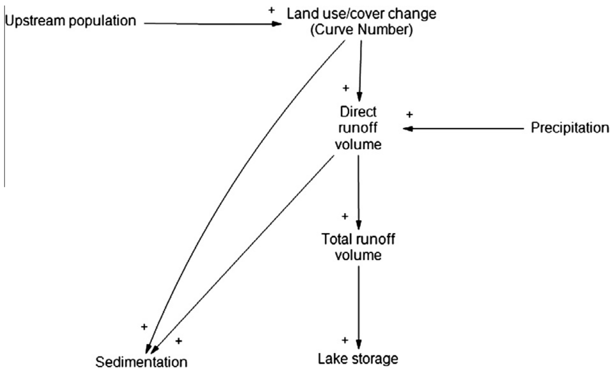

Fig. 4. Upstream population-land use/cover driven cascade impacting the hydrological system of the basin. Upstream population is the main trigger of land use/cover activities that transform the surface for hydrological changes. Precipitation is the exogenous variable that provides water to the transformed surface as runoff. Sedimentation and lake storage are the response of the system due to upstream effects. ± sign indicate direction of change of the variable or effect.

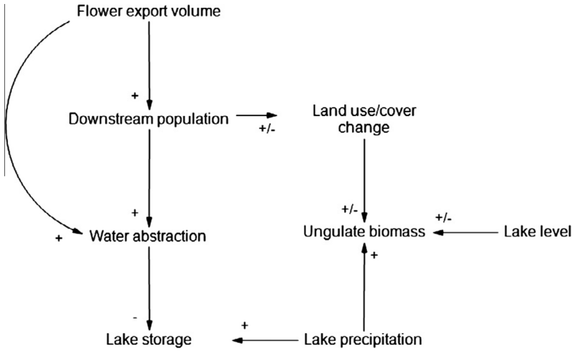

Fig. 5. Downstream cascade driven mainly by horticultural sector and population increase impacting the eco-hydrological system of the basin. Lake precipitation is an exogenous variable that contributes to the lake storage changes and ungulate biomass downstream. Lake levels are exogenous variable that influence Ungulate biomass. Lake storage is the response with flower export volume being the trigger of the system. ± sign indicate direction of change of the variable or effect.

where Y is a vector of endogenous observed variables (dependent variables) which could be response or intermediate entity variables, X is a vector of exogenous observed variables (independent variables with no causal assumptions), β is a coefficient matrix defining relationships among the endogenous variables and Γ is a coefficient matrix defining the relationship of exogenous and endogenous variables and ζ is vector of errors for the equation. In this study the cascade models illustrating relationships between stimuli, entities and responses were developed and tested using AMOS™ (Arbuckle, 2006). The estimated path coefficients and regression coefficients were standardized by the ratio of the standard deviations of the independent and dependent variables to allow relative comparison of magnitudes of effects on the different dependent and response variables (Lleras, 2005). Following Kozak et al. (2007) and adopting their notation, a standardized regression model is given by:

$$y = \sum_{i=1}^{k} p_{iy} x_i + \varepsilon \quad \text{for} \quad i = 1, \ldots, k \tag{2}$$

where y is the standardized response or dependent variable, x_i represents the standardized independent variables, p_{iy} are the partial regression coefficients for the model $E(y|x_i, \ldots, x_k)$ and ε is the residual error term of the model. Interpretation of the path analysis is then based on decomposition of the correlation coefficients between response and independent variables.

$$r_{yx_i} = p_{iy} + \sum_{j=1}^{k} p_{jy} r_{ij} \quad \text{for} \quad j = 1, \ldots, k \quad \text{and} \quad j \neq i \tag{3}$$

where r_{yx_i} are the correlation coefficient between the ith independent variable and the response variable y and r_{ij} is the correlation coefficient between the ith and jth independent variable. Details on the complete formulation and procedure of path analysis have been described in Shipley (2000).

We focused on the interpretation of the standardized partial regression coefficients to quantify the amount of variance in entities/dependent and response variables as depicted over an entire pathway or section explained by the preceding cascade model. Assessment of the cascade model fit was based on Chi-square analysis where p values >0.05 indicate no significant difference between model and the data. Values of $p \sim 1$ are indicative of good model fit (Burcher et al., 2007).

Possible causal paths that linked socio-economic indicators to land use/cover and hydrological indicators were established. Figs. 4 and 5 illustrate the upstream and the downstream cascades respectively. In the upstream parts of the basin (Cascade 1), upstream population was identified as the key socio-economic driver of land use/cover changes. The effect of these LULC changes propagate to direct runoff and sediment yield generation downstream following precipitation events since direct runoff and sediment yield generation are a function of land use/cover. Direct runoff contributes to total runoff which again contributes to lake storage volume downstream. Potential paths that fitted the sample data were then identified. This led to three sub-cascades that fitted the sample data forming the upstream catchment (Cascade 1) and two sub-cascades for the downstream catchment (Cascade 2). The potential paths that fitted the sample data from Cascade (1) were Cascade (1A) describing the effect of upstream population on land use/cover change and the relationship of the direct runoff and precipitation, Cascade (1B) describing the relationship of land use/cover change and direct runoff on sediment deposited into the lake. Cascade (1C) describing the effect of direct runoff on total runoff volume and lake volume changes.

The potential paths that fitted the sample data for the downstream cascades were Cascade (2A), which described the lake as a source of freshwater for irrigation, commercial and domestic consumption and sustains a variety of flora and fauna. The developments associated with the horticultural farms have seen an increase in flower export volumes. This has led to increased downstream population attracted by employment opportunities in the horticultural farms. As a consequence water removal from the lake and its conjunctive aquifer has increased over the last two decades (Becht and Harper, 2002). Cascade (2B) explores the impact of the downstream LULC conversions and hydrological changes (lake levels and precipitation) on the biomass of large herbivorous mammals. The next sections titled "Land use/cover variables", "image classification and accuracy assessment", "socio-economic variables and Pearson correlation", "Assessment of runoff", "sediment yield" and "Biodiversity in the fringe zone of the lake" describe data and methods used for development of the cascade models.

2.4. Land use/cover variables

Data used for image classification were Landsat MSS of 31st January 1973, Landsat TM 1st January 1986, Landsat TM 2nd February1987, Landsat TM 17th January 2011, ASTER of 14th March 2011, Worldview 2 of December 2010. A stratified random sample of 302 ground reference points of major LULC spaced at a minimum distance of 1 km were collected using a GPS. Ground photos taken with a handheld camera and aerial photos of August 2010 acquired from Department of Remote Sensing and Resource Survey (DRSRS) of Kenya were also used to support interpretation and extraction of extra ground reference data.

2.5. Image classification and accuracy assessment

Unsupervised classification was conducted on all the images using the ISODATA algorithm with an initial set of 50 classes. The 50 unsupervised classes allowed for identification of contiguous homogenous classes. Overlaying ground reference points on the contiguous homogenous classes enabled defining of regions of interest (ROIs) for use in supervised classification. For each ground reference point an ROI where the point falls were extracted. The Jeffries–Matusita (J–M) class separability test was also performed to distinguish different classes based on their spectral profiles (Thomas et al., 1987).

Ground reference points collected during the study (January to March 2012) and aerial photos of August 2010 were used to distinguish classes for supervised classification of the Landsat TM, ASTER and World View 2 images representative of the year 2011. Half of the ROIs extracted ($n = 151$ ROIs) were then used in training the maximum likelihood classifier to develop 12 main dominant land use/cover classes of Lake Naivasha Basin for the year 2011. For the 1976 Landsat MSS image, ROIs were developed by unsupervised classification using ISODATA algorithm together with vegetation map of 1976 published by the British Ordnance Survey. Forthwith, a maximum likelihood classification was conducted using the ROIs that led to 8 dominant land use/cover classes of the Lake Naivasha Basin representative for the year 1973.

The other half of the reference data ($n = 151$) were used to conduct the accuracy assessment of the classified image of 2011. The true map accuracy for 1973 could not be easily established due to a lack of field observations at that time, but a 1976 vegetation map published by the British Ordnance Survey was considered a reasonably accurate rendition of map accuracy because it was prepared from ground observations and aerial photographic interpretation. There being no ground truth data to match with the 1986 images, the LULC map of 1986 was produced using unsupervised classification in combination with known land use/cover spectral signatures derived from the 2011 LULC map.

2.6. Socio economic variables and Pearson correlation

Socio-economic variables of the basin used in this study were obtained from various government agencies in Kenya. Decadal census population data from 1969 to 2009 was provided by the Kenya National Bureau of Statistics (KNBS). Annual flower export volume from 1994 to 2010 was provided by the Kenya Horticultural Crops Development Authority (KHCDA).

Pearson correlation was used to describe the relationship between socio-economic variables and LULC. In the upstream part only population data was available for inclusion in cascade model 1. In the downstream cascade, the extent of irrigated and horticultural areas, population size and flower export volumes were identified as the main drivers for inclusion in the cascade model. Single LULC change dynamic degree (Eq. (4)) was employed to quantify the rate of LULC change between two periods. This provided estimates of annual LULC for years that had no representative LULC maps.

$$K_i = \left[\frac{LU_{bi} - LU_{ai}}{LU_{ai}}\right] \times \frac{1}{T} \times 100\% \tag{4}$$

where K is the annual rate of change of a specific LULC type i, in a fixed time period. LU_{ai} and LU_{bi} is the area of the LULC type i at the beginning and the end of the time period, respectively; and T is the time period.

2.7. Assessment of runoff

To evaluate the impact of changes in surface conditions on the runoff of Lake Naivasha Basin, runoff coefficient (Eq. (5)) was calculated to assess the evolution of surface conditions. The Soil Conservation Service Curve Number (SCS-CN) method (SCS, 1985) was used to estimate direct runoff volumes for given rainfall events (Eq. (6)).

$$C = \frac{Q}{P} \tag{5}$$

where C is the annual runoff coefficient, Q is the total runoff volume (mm), and P is the total annual precipitation (mm) received in the upper basin.

$$Q_d = \frac{(p_d - l_a)^2}{(p_d - l_a) + S} \tag{6}$$

where Q_d is the direct runoff (mm) following a precipitation event, P_d is the daily precipitation (mm), S is the potential maximum retention after the start of runoff generation (mm) which is estimated as function of curve number as follows:

$$S = \frac{25,400}{CN} - 254 \tag{7}$$

where CN is the area weighted basin curve number obtained by aggregating the individual curve number of each individual land use/cover obtained from look-up table following procedures described in SCS (1985), I_a is the initial abstraction of all losses before runoff generation and includes water retained in surface depressions, evaporation, infiltration and that which is intercepted by vegetation. Through experimental studies I_a (SCS, 1985) is approximated as:

$$I_a = 0.2S \tag{8}$$

A low CN value is suggestive of low direct runoff generation from the basin while a higher CN would suggest the opposite assuming that other determinant parameters of flow remain the same. Runoff and precipitation data were obtained from the Water Resources Management Authority (WRMA) of the Government of Kenya. Runoff data from 1960 to 2010 of the three outlet stations discharging into the Lake and seven precipitation stations within the upper basin were used for this analysis.

2.8. Sediment yield

In this study it was postulated that the sedimentation rate of the lake is influenced by the upstream LULC changes. Data of lake sedimentation rate from Stoof-Leichsenring et al. (2011) was used as response proxy indicator of water quality downstream arising from LULC changes upstream. Rate of change for years with no sedimentation rate were estimated using a similar approach as Eq. (4) with sediment for known years as input.

2.9. Biodiversity in the fringe zone of the lake

Downstream LULC and hydrological regimes can impact on biomass density of large herbivore mammals. The trend in large herbivore mammal's population was obtained from biennial (April and October) wildlife census conducted by Nakuru Wildlife Conservancy (NWC) from 1999 to 2010. The data was collected using a total count of large mammal species on all ranches between Lake Naivasha and Lake Nakuru. We selected data for the 12 most common large herbivore species on 16 ranches that are immediately adjacent to Lake Naivasha (Table 1). During the census, the ranches were divided into fixed counting blocks in each ranch divided by physical barriers such as hills, escarpments and the lake. Each block was assigned a counting team consisting of experienced Kenya Wildlife Service scientists, ranch staff and trained volunteer scouts. Counting was carried out between 0600 and 1000 h when most of species are active. This was done using vehicles or walking in some inaccessible sections. Detailed information on the survey method is outlined in Ogutu et al. (2012).

The herbivore numbers were converted to biomass density (kg km^{-2}) using units weights in (Coe et al., 1976) and the total area ($275\ \text{km}^2$) of the 16 selected ranches (Table 1). A principle components analysis (PCA) (Legendre and Legendre, 2012) was carried-out on the land cover data to obtain an orthogonal linear combination of land cover values for each year. The first PCA axis explained 99% of variance and was thus selected in the subsequent analysis to represent the LULC for each year. Path analysis was used to explore the significant of downstream population, LULC, annual downstream precipitation and lake levels changes to the total ungulates density.

3. Results

3.1. Socio-economic drivers

Pearson correlation analysis (Table 2) of the upstream sections of the basin identified population as having negative correlation with forest cover, bushland and shrubland and a positive correlation with farmland, woodland, grassland and built-up.

In the downstream parts of the basin, Pearson correlation analysis (Table 3) of socio-economic variables identified downstream population, flower export volumes and irrigation land to be positively and strongly correlated.

3.2. Cascade models

All the cascade models had chi-square p-values greater than 0.5 (Table 4) suggesting that the model outputs matched those of the sample data. Cascade (1A) indicated that 63% of upstream land use/cover changes could be explained by population growth. This explained only 40% of the observed variance in changes of land use/cover suggesting that other exogenous variables accounted for 60% of the variance. Land use/cover changes had direct effect of 36% on direct runoff generation, while upstream precipitation had 95% effect on direct runoff. The combined influence of upstream population, land use/cover changes and precipitation explained 95% of the variance in direct runoff generated from the basin (Fig. 6).

The second sub-cascade (1B) had precipitation being the main impulse triggering runoff generation. Land use/cover changes had a direct effect of 58% on sediment yield while direct runoff had a negative influence on sediment yield. The overall influence of both could only explain 30% of sediment yield deposited to the lake.

Table 1
Detail on the surveyed mammal species and the ranches/blocks.

Ranches/sampling blocks		Mammal species		
Name	Area (Acres)	Common name	Scientific name	Unit weight (Kgs)
Crater Lake/Indu/Lentolia	1000	Common Zebra	*Equus burchelli*	200
Mundui	1145	Thomsons Gazelle	*Gazella thomsoni*	15
Hippo Point/Nderit	500	Impala	*Aepyceros melampus*	40
OLERAI	500	Eland	*Taurotragus oryx*	340
Oserian wildlife sanctuary	18,000	Buffalo	*Syncerus caffer*	450
Oserian Game Corridor	3000	Grants Gazelle	*Gazella granti*	40
Cresent Island	190	Kongoni	*Alcelaphus lichtensteinii*	125
Bushy-Island/Flay/Yatch-Club/D'Olier/Higgins/Sanctuary	100	Defassa Waterbuck	*Kobus ellipsiprymnus*	160
Marula	25,000	Wildebeast	*Connochaetes taurinus*	123
KARI & Ol Magogo	9000	Common warthog	*Phacochoerus africanus*	45
Loldia	6000	Giraffe	*Giraffa camelopardalis*	1402
Manera	1600	Hippo	*Hippopotamus amphibious*	1160
DDD ROCCO FARM	200			
KWSTI ANNEX/Institute/Mirera	200			
Green Park & Brixia	1500			
Morendat	100			

Table 2
Correlation of upstream population and land use/cover.

	Forest	Bushland	Farmland	Woodland	Grassland	Shrubland	Built-up
Population	−0.43	−0.85	0.8	0.97	0.94	−0.03	0.96

Table 3
Correlation of downstream population and land use/cover.

	Irrigation	Horticulture	Population	Flower export volume
Irrigation	1			
Horticulture	0.77	1		
Population	0.78	0.99	1	
Flower export volume	0.69	0.96	0.98	1

Table 4
Chi-square measures of model fit for the significant cascades.

Model		X^2	df	*p*
Upstream cascade (1)	A	0.022	2	0.989
	B	0.071	1	0.790
	C	0.233	1	0.629
Downstream cascade (2)	A	4.632	6	0.592
	B	7.159	3	0.067

Sub-cascade model three (1C), showed direct runoff as the main trigger contributing to total runoff volume generated in the upstream parts and contributing to lake volume storage downstream. 57% of variation in lake volume storage changes could be explained by direct effects contribution of upstream total runoff (76%) and direct runoff (92%).

The downstream sub-cascade model (2A) majorly driven by the horticultural sector explained 71% of the variation in water abstracted, with flower export contributing 58% as direct effect to the overall water abstraction volumes (Fig. 7). Water abstraction had a negative direct effect of 15% on lake storage changes. Overall influence of the triggers and effects of this cascade explained 34% of the lake storage changes with precipitation falling over the lake contributing 59% to the changes.

Cascade (2B), showed that the downstream population had a strong significant positive effect (99%) on downstream LULC changes (Fig. 7). The total herbivore biomass density on the fringe zone had almost tripled over the study period (Fig. 8). This was related to a 93% positive direct effect of downstream LULC changes. Lake levels had a 4% direct effect on ungulate biomass production while precipitation over the lake had a 4% negative direct effect. The four variables in this cascade explained 78% multivariate effect of total ungulate density.

3.3. Hydrological effects

The results of basin runoff generation indicate that the runoff conditions have undulated over time with minima and maxima runoff coefficient cycles occurring between 2 and 4 years (Fig. 9).

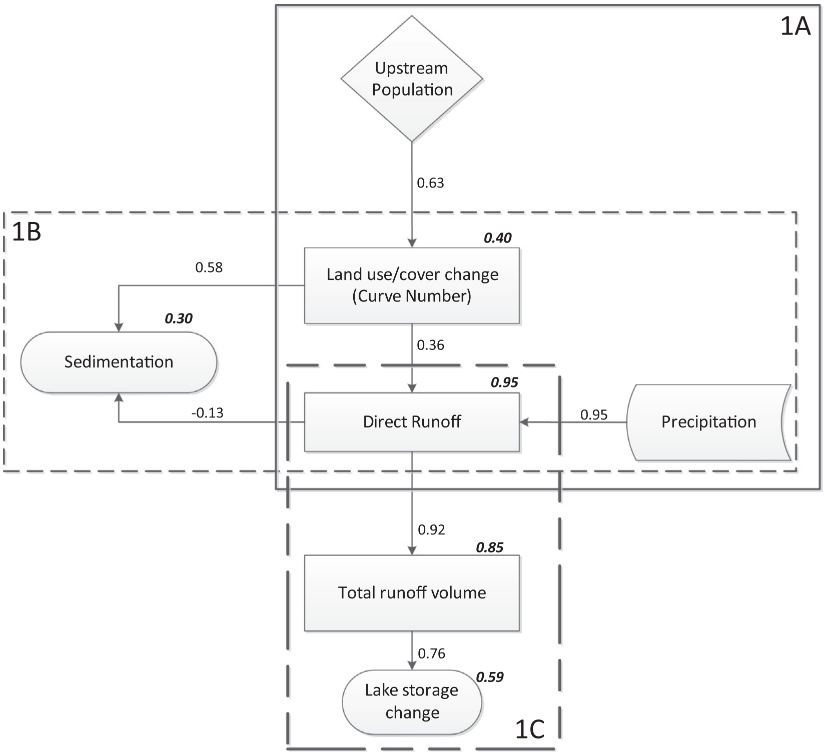

Fig. 6. Upstream path diagram quantifying the cascade effects of upstream population on hydrological variables. Numbers along the arrows are standardized path correlation coefficients and represent the direct bivariate effect of the two linked variables. Bold and italicized numbers on the edges of effect and response variables represent the multiple correlation coefficients that describe the multivariate strength of the preceding model. Bounding boxes labeled 1A–1C are the significant cascade models.

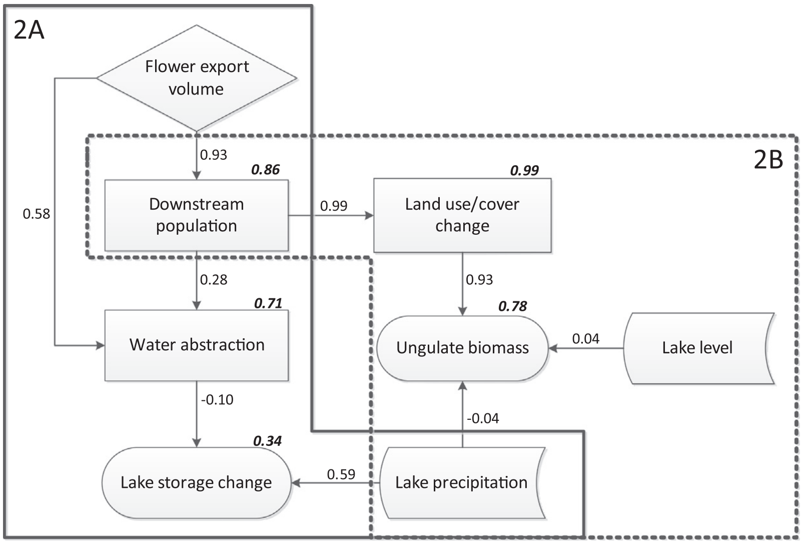

Fig. 7. Downstream horticultural/irrigation driven cascade impacting the lake storage change. The horticultural and irrigation commercial agriculture activities are the main triggers of hydrological changes. Numbers along the arrows are standardized path correlation coefficients and represent the direct bivariate effect of the two linked variables. Bold and italicized numbers on the edges of effect and response variables represent the multiple correlation coefficients that describe the multivariate strength of the preceding model. Bounding boxes labeled 2A and 2B are the significant cascade models.

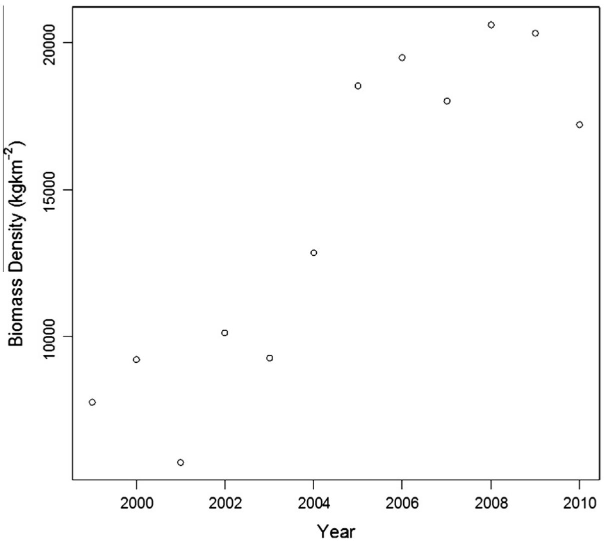

Fig. 8. Total herbivore biomass density for 12 years on ranches adjacent to Lake Naivasha.

Increased total runoff flows were observed during the period of 1986–2010 suggesting that surface changes due to LULC changes are responsible for the changed hydrological regime. The runoff coefficient for the period of 1961–1985 significantly ($p < 0.05$) differs from the one of the period 1986–2010. Over the entire period precipitation has remained fairly unchanged with a monthly average reduction of 5% (Fig. 10) while total runoff volume has significantly ($p < 0.05$) increased by 32% (Fig. 11). Direct runoff generation estimated using SCS-CN method remained fairly unchanged over the two periods (Fig. 10) even though the basin curve number showed an increase from 55 to 61 for 1973 and 2010 respectively.

Although total runoff volumes into the lake between the two periods of change have been distinct, the lake storage changes have been marginally lower (Fig. 11).

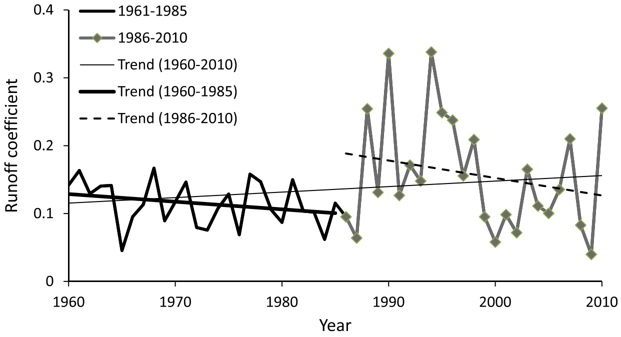

Fig. 9. Evolution of annual runoff coefficient for Lake Naivasha Basin between 1960 and 2010.

4. Discussion

4.1. Hydrological effects

Cascade models indicate that the rural population in the upstream part of the Lake Naivasha Basin determined much of the land use/cover changes impacting on the hydrology, whereas the cut-flower production and downstream population are identified as the main drivers influencing the hydro-ecological system in the lower basin. The total runoff volumes from the upstream part of the basin explain the variation of the lake volume rather than water abstractions from the lake and its conjunctive aquifer.

Our findings show that upstream land use/cover changes exacerbated by population increase over the last 25 years have increased total runoff generation even though precipitation has not changed over the same period. Runoff analysis in this study confirmed these observations since monthly total runoff volumes increased significantly ($p < 0.01$) by up to 32% even though the precipitation amount between the two periods remained significantly unchanged. The downstream effect of these upstream changes has seen a positive response in the lake storage change over the same period. The lake storage changes have been lower on average than was in the period 1961–1985.

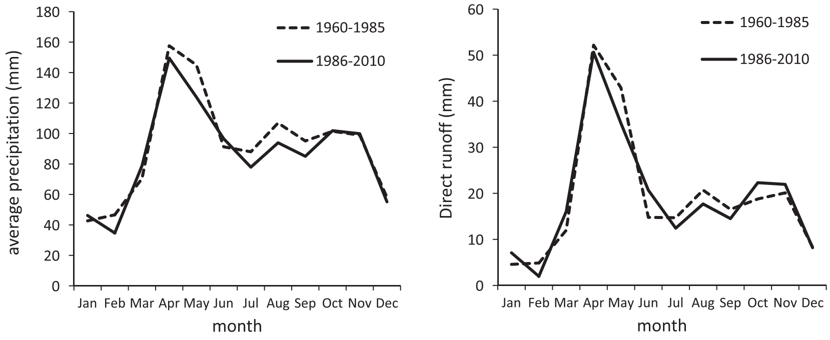

Fig. 10. Variation of monthly precipitation (left) and direct runoff (right) generation from upstream of Lake Naivasha Basin.

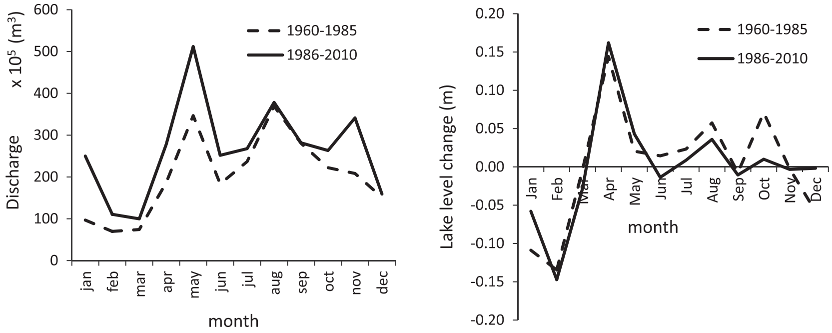

Fig. 11. Monthly total runoff (left) and lake level change (right) for periods 1 (1960–1985) and 2 (1985–2010) for Lake Naivasha Basin.

Considering that precipitation conditions in the basin have remained constant over the last four decades, intuitively, this would suggest that precipitation being an external climatic forcing was unlikely to be the cause of the observed changes in total runoff in the last 25 years. However, this could be explained by changes in land use/cover exacerbated by upstream human population increase. Our land use and land cover classification results for the upstream part of the basin (Fig. 12) suggest that the decline in forest (−5.4%) and bush land (−26.4%) between the period 1973 and 2011, have been at the expense of substantial increases in grassland (20.3%) and farm lands (5%). The grasslands may be transitional lands that might have been previously under cultivation. The grassland and farm lands typically have low leaf area that intercepts less rainfall, shallow rooting depths and even higher surface albedo compared to forests and bush land (Costa et al., 2003; Costa and Foley, 1997; Zhang et al., 2001). Moreover, pastoralism is an activity that prevails in this part of the basin with livestock overgrazing having left the surfaced exposed. Considering that the precipitation changes are insignificant, the above LULC change may have caused a reduction in the evapotranspiration (ET) and infiltration rates and subsequent increment in discharge in this part of the basin. The LULC changes may have caused the observed significant changes in runoff coefficients and land cover curve numbers between the periods 1961–1985 and 1986–2010 that resulted to the increased runoff.

Observable impacts of land use/cover changes on basin hydrology at larger catchment scales (>100 km^2) have been relatively few (e.g. Costa et al., 2003; Siriwardena et al., 2006; Zhang and Schilling, 2006). This is particularly because as the scale of the basin increases so have been the increased mixed effects of climatology and land cover changes at these scales making it difficult to discriminate the influence of land use/cover changes from that of climate (van Dijk et al., 2012). For the case of Lake Naivasha Basin which has a hydrological active contributing area of approximately 1800 km^2, our findings agree with those from large-scale studies (Cognard-Plancq et al., 2001; Costa et al., 2003; Gentry and Lopez-Parodi, 1980; Siriwardena et al., 2006; Zhang and Schilling, 2006) and from small-scale deforestation experiments (Bruijnzeel, 1990; Sahin and Hall, 1996). Much of the changes in those catchments were due to large scale land use and land cover changes despite experiencing insignificant changes in precipitation. Most previous studies including those of the Murray–Darling basin in South Eastern Australia, however, have observed decline in flows attributed to decreased rainfall, increased temperatures, increased evapotranspiration and increased water abstractions (Potter et al., 2010; van Dijk et al., 2007). Other research findings (Bruijnzeel, 1990; Wilk et al., 2001) from large scale basin that have experienced deforestation disagrees with results observed at small-scale deforestation experiments. This has been attributed to simultaneous regrowth of land cover in some parts of the basin

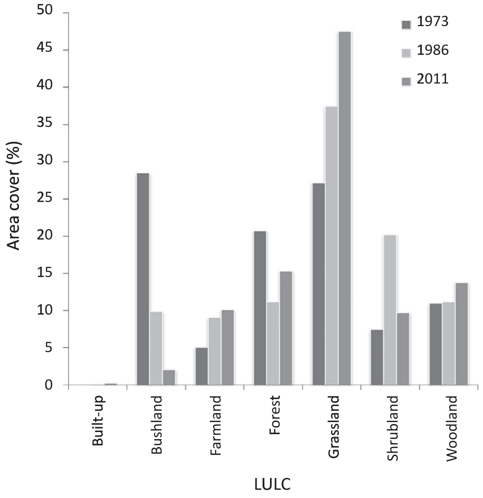

Fig. 12. Temporal changes of land use and land cover in upstream parts of the Lake Naivasha Basin.

while other parts are being deforested or cleared proportionally such that changes in runoff volumes cannot be observed.

The consequence of the increased runoff volumes from the upper catchment of Lake Naivasha caused deep channelization at the lower reaches of River Malewa that hindered the dendritic re-distribution of water on the former aquatic North swamp, leading to its eventual drying (Harper and Mavuti, 2004). The impact of drying of the swamp was that the lake water quality was compromised due an excess of sediment and nutrients transported by upstream runoff. Before the drying of the swamp, the swamp acted as filter that improved the water quality of the lake by trapping sediments and nutrients (Gaudet, 1977b; Kitaka et al., 2002). The cascade model in this study explained 30% of the variation in sediment yield from the upper basin. Most important was the impact of upstream land use/cover changes which contributed 57% of the total variation in sediment yield.

4.2. Biodiversity effects: total biomass density of large herbivores mammals

The downstream LULC explained the highest variation on herbivore biomass density on ranches adjacent to Lake Naivasha. The observed LULC on formerly communal grazing lands surrounding Lake Naivasha resulted to loss of habitats and grazing land eventually leading to aggregation of high ungulate biomass along a riparian zone. The LULC progressively converted the riparian zone into a high ungulate biomass island. This contrast with earlier studies that observed that increased LULC caused a decline in herbivore biomass density (Mundia and Murayama, 2009; Western et al., 2009). However our results concur with (Harper and Mavuti, 2004), who observed that the ungulates biomass especially the buffaloes in the riparian zone had tripled compared to mid-1990's. This increase was attributed to land cover conversions especially in the deforestation of Eburru forest, to the west of the Lake. The increased ungulates density can induce continuous intense grazing that can alter plant composition and productivity (Morrison and Harper, 2009; Muthoni et al., 2014).

Moreover the low variance explained by the annual precipitation on the herbivores biomass contradict earlier observations that ungulates density is dependent on annual precipitation (Coe et al., 1976; East, 1984; Georgiadis et al., 2003; Ogutu and Owen-Smith, 2003). The changes in lake levels was also expected to have significant impact on ungulate biomass since decline in levels increase the area of the highly productive riparian grazing land. However these riparian grasslands experience frequent and prolonged flooding even in the dry seasons in response to upstream precipitation regime. However prolonged flooding especially during the dry seasons reduces grazing area during the scarcity when it is supposed to subsidize the forage. Prolonged flooding due to increased lake levels has been observed to reduce herbivores population in the nearby Lake Nakuru as it reduces the foraging area (Ogutu et al., 2012). Since the lake levels are largely dependent on streamflow from upper catchment (see discussion section "Hydrological effects"), the results therefore highlight the impact of the upper catchment rainfall on the ecological integrity of downstream ecosystem.

Overall, our cascade modeling approach offered insight on the contribution of socio-economic factors on the eco-hydrological regime of the Lake Naivasha Basin. Thus, our method could potentially be used to show the influence of eco-hydrological variables on socio-economic developments.

5. Conclusions

This study shows that, in cases where observed socio-economic developments are substantial, the use of a statistical cascade-modeling approach, coupling socio-economic factors to eco-hydrological processes can greatly improve our understanding of the eco-hydrological system.

Lake Naivasha Basin has experienced substantial land use and land cover (LULC) transformations predominantly caused by socio-economic drivers. Accounting for the implications of socio-economic drivers of LULC is vital to the understanding of hydrological and ecological functioning of a river basin. This study investigated the cascading impacts of socio-economic drivers of LULC changes on the hydro-ecological regime of Lake Naivasha Basin. The findings show that socio-economic factors have exacerbated LULC transformations leading to increased flow regimes over the last 25 years. The upstream cascade model revealed that population has contributed about 63% to the land use/cover transformations in that part of the basin. Water abstractions from the lake and its conjunctive aquifer influenced the lake storage changes less than the contribution from upstream runoff volume. Upstream runoff volumes directly affected the lake storage change by up to 76% whereas water abstractions had 10% negative effect. The lower cascade further showed that downstream population and the flower export volume accounted for 71% of water abstraction. The downstream LULC conversions explained the large aggregation of high biomass density of large herbivore mammal species.

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Corrigendum

Corrigendum to "Coupling socio-economic factors and eco-hydrological processes using a cascade-modeling approach" [J. Hydrol. 518 (Part A) (2014) 49–59]

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