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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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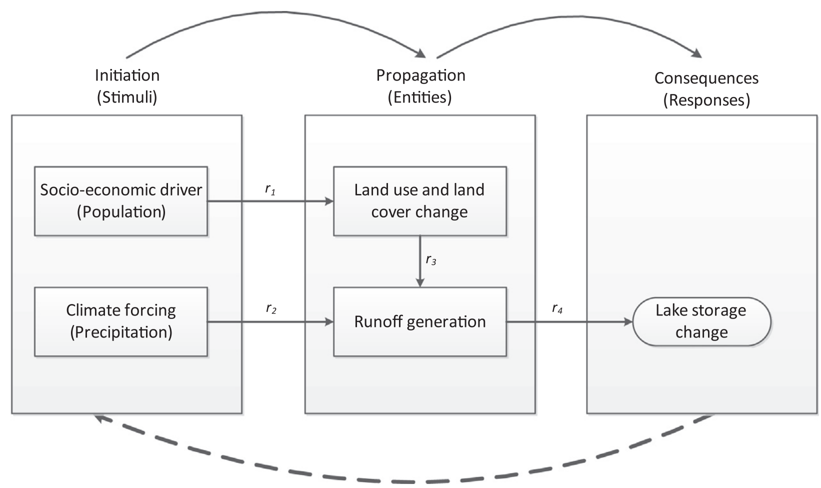

Fig. 1. A conceptual framework illustrating a path diagram of a hypothesized cascade model that predicts lake storage change. The links, r_1, r_2, r_3 and r_4 represent the pathways through which factor influences are propagated through entities and responses. Adapted from Reiners and Driese (2001).

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