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Relative contribution of land use change and climate variability on discharge of upper Mara River, Kenya

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ABSTRACT

Study region: Nyangores River watershed, headwater catchment of Mara River basin in Kenya.
Study focus: Climate variability and human activities are the main drivers of change of watershed hydrology. The contribution of climate variability and land use change to change in streamflow of Nyangores River, was investigated. Mann Kendall and sequential Mann Kendall tests were used to investigate the presence and breakpoint of a trend in discharge data (1965–2007) respectively. The Budyko framework was used to separate the respective contribution of drivers to change in discharge. Future response of the watershed to climate change was predicted using the runoff sensitivity equation developed.
New hydrological insights for the region: There was a significant increasing trend in the discharge with a breakpoint in 1977. Land use change was found to be the main driver of change in discharge accounting for 97.5% of the change. Climate variability only caused a net increase of the remaining 2.5% of the change; which was caused by counter impacts on discharge of increase in rainfall (increased discharge by 24%) and increase in potential evapotranspiration (decreased discharge by 21.5%). Climate change was predicted to cause a moderate 16% and 15% increase in streamflow in the next 20 and 50 years respectively. Change in discharge was specifically attributed to deforestation at the headwaters of the watershed.

1. Introduction

Changes in watershed hydrology may have far reaching impacts on a catchment water balance. The changes may be observed through change in water input (precipitation), water distribution into evapotranspiration and runoff, and in the short term, change in catchment water storage (i.e., soil storage and groundwater recharge). Climate variability and human activities are the main drivers of changes in watershed hydrology (Tomer and Shilling, 2009; Ye et al., 2013). At a local scale, change in precipitation may only be caused by changes in climate, while changes in streamflow, evapotranspiration and

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watershed storage may be caused either by climate variability, human activities or both. Changes in streamflow (either total water yield or seasonal discharge) have a major implication on water resources management and especially water supply (Döll and Schmied, 2012; Farley et al., 2011; Charlton and Arnell, 2011). Human activities can alter streamflow through changes in land use, reservoir operation and direct abstraction of surface water or groundwater (Carpenter et al., 2011; Biemans et al., 2011). In absence of reservoirs and inconsiderable water abstractions, land use change and climate variability are the main drivers of change in streamflow (Carpenter et al., 2011). Separation of the impacts of the drivers is helpful in better understanding of the watershed hydrology as well as in developing sound water resources management strategies (DeFries and Eshleman, 2004; Arnell and Delaney, 2006). However, separation and quantification of the drivers' impact is challenging (Zhang et al., 2014; Li et al., 2009; Tomer and Schilling, 2009) because of the complex linkage between climate, human activities and the individual hydrological processes (Falkenmark and Rockström, 2004).

A number of studies have proposed approaches to separate the impacts of land use change and climate variability on streamflow (Li et al., 2012; Wang, 2014). The approaches can be broadly categorized as empirically-based and process-based. Proposed empirical methods are based on climate elasticity (Schaake, 1990) and test the sensitivity of streamflow to changes in climatic factors (Ma et al., 2010). Elasticity-based methods can further be categorized into non-parametric and water balance based methods (Sun et al., 2014). Non-parametric elasticity-based methods are empirical approaches that use linear relationships derived from long-term historical data (Schaake, 1990; Sankarasubramanian et al., 2001; Zheng et al., 2009; Ma et al., 2010). Most of the water balance-based elasticity methods (Dooge et al., 1999; Arora, 2002; Wang and Hejazi, 2011; Roderick and Farquhar, 2011) are based on the concept of the Budyko framework (Budyko, 1974) of catchment water-energy budget (Sun et al., 2014). Process-based methods use distributed physically-based hydrological models where separation is done by alternatively varying and fixing (holding constant) the meteorological inputs and land use/cover conditions (Xu et al., 2014). Process-based methods are more sophisticated, require more data as input and have high uncertainty in parameter estimation whereas non-parametric elasticity methods have weak or no physical meaning (Xu et al., 2014; Wang and Hejazi, 2011). Approaches based on catchment water-energy budgets are easier to use and also have better physical background (Sun et al., 2014; Roderick and Farquhar, 2011).

In this study, we used the catchment water-energy budget approach to separate the contribution of climate variability and land use change on discharge of Nyangores River; the river is a tributary of the trans-boundary Mara River in East Africa. Over the watershed of Mara River, competing land uses and socio-economic activities in the headwaters have been blamed for changes in its hydrological regime (Gereta et al., 2009; Mati et al., 2005, 2008; Dessu and Melesse, 2012). There has been significant deforestation and conversion to agriculture in the upstream regions of the Mara River basin (Mutie et al., 2006). Other studies have also linked observed high level of sediment yield and sedimentation in the Mara River to land degradation following deforestation (Kiragu, 2009; Defersha and Melesse, 2012). A land use change analysis study by Mati et al. (2008) found that the forest cover of 1973 in the Mara basin progressively decreased by 11% and 32% in 1986 and 2000 respectively. For the same periods, open forest increased by 73% and 213% respectively based on the 1973 land cover—a clear indication of the massive deforestation that was taking place in the area immediately after Kenya's independence in 1963. At independence, almost the entire upstream area of the Mara River basin including the Nyangores watershed was covered by dense natural forest and pockets of montane grassland (Government of Kenya—GoK, 1969). Cultivation was limited and strictly controlled by the colonial government (Kanogo, 1987). Mati et al. (2008) used the 1973 and 2000 land use maps to simulate the effect of land use change on hydrology of the Mara River. They found an increase in peak flow during the long rainfall season (March–May) between 1973 and 2000 which they attributed to deforestation in the basin. Mango et al. (2011) simulated deforestation in Nyangores watershed and likewise reported that further deforestation in the watershed may increase peak flows and reduce dry season flows. Based on the findings of these two studies, it can be deduced that deforestation (past or future) lead to increase in peak flows in the watershed. Change in streamflow, however, is not only caused by human activities (particularly land use change) but also by climate variability. Information on how much of observed change in streamflow is separately caused by land use change and climate variability is important for water resources management planning including simulation of informed future land use and climate change scenarios. Analysis of measured historical streamflow data gives valuable evidence-based information of watershed response to past changes in land use and climate variability either individually or in combination. Such information is however lacking for the Mara River basin.

Separation of the contribution from drivers of change in observed streamflow i.e., land use and climate variability is important for integrated watershed management in the Mara River basin. Herein, we focus on Nyangores watershed, one of the headwater catchments of Mara River basin where there has been a major competition between forest conservation and agriculture. The objectives of the study are: (i) to statistically test the presence of a trend in measured streamflow data, (ii) to empirically separate hydrological impacts caused by changes in land use and climate variability from historical streamflow data, (iii) to further partition the contribution of climate variability into that caused by changes in rainfall and potential evapotranspiration respectively, and (iv) to predict the future relative contribution of climate change to streamflow.