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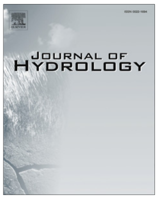

Identifying sources of temporal variability in hydrological extremes of the upper Blue Nile basin

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SUMMARY

It is known that changes in catchment runoff variability are a function of changes in climate as well as catchment behavior. For proper management of a certain watershed it is important to have a good understanding of the main causes of variability. Specifically, changes in extreme conditions of water resources are imperative as their consequences are far reaching. This paper attempts to identify the cause of hydrological extremes variability in the upper Blue Nile basin of Ethiopia. A method is proposed to utilize conceptual hydrological models to simulate long term (41 years) hydro-meteorological data and analyse the outputs using the Quantile Perturbation Method (QPM) specially designed for investigation of the temporal variability of extreme values in time series over multi-annual to (multi-)decadal time scales. Two conceptual hydrological models were calibrated and evaluated for their performance to simulate extreme high flows and changes in these flows for corresponding changes in rainfall conditions. The temporal variability results show similar patterns for simulated and observed extreme flows. This indicates the major influence of climate variability in extreme flows as demonstrated by the rainfall input in the models. There is no discernible change in the catchment response, e.g. quick runoff coefficient as a function of soil saturation state, between periods of the 1960–1970s, the 1980s and the 1990–2000s, which are attributed to land policy changes. This shows the influence of changes in catchment characteristics is minimal. (Multi-)decadal climate variability is identified as the main cause of temporal variation in hydrological extremes of the Blue Nile basin.

1. Introduction

Changes in catchment runoff variability are a function of changes in climate as well as the catchment behavior. Catchment characteristics changes can be caused by land use or land cover modifications and different water management practices such as abstraction, irrigation and/or constructed dams and others. Although detecting the impact of land use/cover changes on catchment runoff is intricate, it is important to evaluate the impact considering the ultimate effect on a given catchment system. Different studies described that the upper Blue Nile basin, located in northwestern Ethiopia, has been undergoing considerable change in terms of land use/cover and soil degradation over many decades (Gete and Hurni, 2001; Hurni et al., 2005; Zegeye et al., 2010; Asmamaw et al., 2011). Other studies attempted to find the influence of these changes on water resources of the region. For instance, Betrie et al. (2011) reported soil erosion is an immense problem in the upper Blue Nile region and consequently excessive sedimentation occurs in the downstream part of the Nile basin, particularly in Sudan and Egypt, leading to excessive operation cost of irrigation canals desilting, and sediment dredging reservoirs, e.g. in front of hydropower turbines. On the other hand, inside the upper Blue Nile basin, Gebrehiwot et al. (2011) showed that watershed characteristics influence the spatial variation of the basin's hydrology with a special focus on low flows. For a region whose population is massively dependent on rain-fed agriculture, changes in water resources as a result of changes in either climate or land use/cover deserves a substantial attention. Specifically, changes in extreme runoff or river flow conditions are imperative as their consequences are far reaching both at the upstream and downstream parts of the (Blue) Nile basin.

Previous studies reported varying influence of land use/cover change on different sub-catchments of the upper Blue Nile basin. To mention few examples Rientjes et al. (2011) reported forest cover decreased in the Gilgel Abay catchment from 50% to 16% during 1973–2001 period due to expansion of agricultural land and resulted decrease in low flows and increase in high flows. Bewket and Sterk (2005) reported on the Chemoga catchment in which during the period 1957–1998 the cultivated area increased at the expense of open grazing area while slight increase in forest cover was observed. As a result low flows declined significantly with time while there is no discernible trend for high flows. Gebrehiwot et al. (2010) reported no change in the hydrology of Koga

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catchment during 1960–2002 while the forest cover decreased from 16% to 1% during the period 1957–1986. These and other studies described the presence of considerable land use/cover change in the different sub-catchments although the effect on water resources is sub-catchment specific. The present study concentrates on the entire upper Blue Nile basin to get a better idea on the causes of the Blue Nile flow variability with a specific focus on the extreme high flows.

Earlier time series analysis of the Blue Nile flow at El Diem, outlet from the Ethiopian highlands, showed temporal variability of extremes to have a multi-decadal oscillation pattern (Taye and Willems, 2012). Subsequently, a question was raised whether the observed variability can be explained solely as a result of rainfall anomalies or if other land and water use activities contributed to the change. Hence, an investigation was done with the hypothesis that land use change had significant influence on the temporal variability of extreme flows of the upper Blue Nile basin. Statistical analysis and hydrological modeling techniques are among the most commonly suggested methods in terms of understanding the effect of change in climate and land use/cover on water resources. In this paper, to investigate the cause of extreme flow variability, a method was proposed to utilize conceptual rainfall–runoff models and subsequently investigate the variability of the outputs. Rainfall–runoff models can implicitly be used for testing whether observed changes or trends in hydrologic time series can be explained entirely by experienced climate variability (Refsgaard et al., 1989). Various types of models can be used for simulating land use changes, some examples from different categories are mentioned in Breuer et al. (2009). Complex models such as fully distributed process-based models or physically-based semi-distributed models usually require large amount of data and might encounter difficulty in estimation of large number of model parameters commonly known as the model over-parameterization or equifinality (Beven and Freer, 2001). Conceptual lumped models on the other hand have simple model structure and small number of model parameters. They are advantageous due to their minimum input data requirement which makes them applicable in areas where data scarcity is common similar to the case of the upper Blue Nile. Two conceptual lumped models are considered in this study; namely NAM, which is the precipitation–runoff-model implemented in the MIKE11 modeling software of DHI Water and Environment (DHI, 2008), and VHM, after implementation of the generalized lumped conceptual and parsimonious model structure identification and calibration procedure developed by the Hydraulics Division of the KU Leuven (Willems, submitted for publication). The output of these models is analyzed using the Quantile Perturbation Method (QPM), a method proposed to detect the hydrological changes and/or variability in extremes. This method has been applied in previous studies in relation to variability detection of rainfall, temperature and river flows (Ntegeka and Willems, 2008; Taye and Willems, 2012; Mora and Willems, 2011). Brief explanation of the method is provided in the subsequent sections including how conceptual rainfall–runoff models are utilized. But primarily description of the study area and the data used is provided.

2. Study area and data

2.1. Study area description

The upper Blue Nile basin contributes more than 60% of the Nile's flow at Aswan, Egypt. It has an approximate area of 176,000 km^2 located in the north-western part of Ethiopia (Fig. 1). The highlands of the basin reach maximum elevation of over 4000 m in the headwaters and about 500 m in downstream parts. The river flows starting from Lake Tana a length of around 940 km to the outlet at the Ethiopian–Sudanese border at El Diem (Elshamy et al., 2009). The climate in the Blue Nile is governed by north–south seasonal migration of the Inter Tropical Convergence Zone (ITCZ). The basin receives considerable amount of rainfall ranging between 800 and 2200 mm (Melesse et al., 2010). The largest contribution of this high rainfall occurs during the main rainy season from June to September. The period October to May is usually a prolonged dry period with short rainy season between March and May. During the main rainy season considerable amount of land is eroded from the entire basin causing frequent agricultural drought in the Ethiopian highlands and excessive sedimentation in the downstream countries (Betrie et al., 2011). Rain-fed agriculture is the dominant way of life in Ethiopia and therefore the most common land use feature of the basin is cultivated land.

2.2. Meteorological data

The minimum data requirement for rainfall–runoff modeling using conceptual models is both meteorological and hydrological historical records averaged for the entire basin. Thus, weighted average rainfall and evapotranspiration were calculated using the Thiessen polygon method making use of 11 and 7 stations in and around the catchment respectively. The meteorological data were obtained from the National Meteorological Agency in Ethiopia for the period 1964–2004 at daily time step. Some of the missing gaps that are present in the meteorological records were dealt with inverse distance weighting method from neighboring stations. The method used to obtain evapotranspiration for each station is the Hargreaves method (Eq. (1)) which requires basic (minimum input) data, i.e. maximum and minimum temperature. The Hargreaves method reported to have some limitations in literature compared to the standard FAO Penman Monteith method, but it is widely used in cases of data limited areas and still provides acceptable results. This method was applied in previous studies conducted in the upper Blue Nile basin for example in Tekleab et al. (2011) and Setegn et al. (2008).

$$ET_o = 0.0023 * (T_{max} - T_{min})^{0.5} * (T_{mean} + 17.8)Ra \tag{1}$$

where ETo is the reference evapotranspiration (mm/day), $T_{mean} = (T_{max} + T_{min})/2$, the average daily air temperature (°C) and Ra is the extra-terrestrial radiation (MJ m^{-2} day^{-1}).

2.3. Hydrological data

Daily river flow data at the outlet of the upper Blue Nile (at El Diem) is used for this analysis. The data acquired is for the period 1964–2009. Nevertheless, since the meteorological data ends in 2004, the data used for the hydrological modeling is limited until the same period. This river flow data was reported to have a good quality compared to other upstream gauging stations within the Blue Nile basin (Conway, 1997, 2000). Few of the missing gaps were completed using linear interpolation from a downstream station at Roseires.

3. Hydrological modeling

3.1. Conceptual rainfall–runoff models description

The two lumped conceptual hydrological models implemented for the basin upstream of El Diem are NAM and VHM model. These hydrological models simulate the rainfall–runoff processes on a (sub) basin scale based on catchment averaged rainfall and evapotranspiration inputs. Generally lumped conceptual rainfall–runoff models constitute two main components: the reservoir-based