FLOOD AND DROUGHT MANAGEMENT BY PROPOSED DAMS AND RETARDING BASIN: A CASE STUDY OF THE UPPER EWASO NGIRO NORTH BASIN, KENYA

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ABSTRACT

The Ewaso Ngiro North River Basin (ENNRB), which is the largest river basin in Kenya, has been experiencing alternate incidents of flood and drought hazards that cause fatalities and economic losses. In the upper reaches of the ENNRB, heavy rains contribute to flood river flows and inundation in the downstream areas whereas the lower part of the basin is semi-arid and drought prone area. These climatic variety and frequent hazard events make the river basin management difficult and have caused a series of water conflicts between the upstream and downstream water users. In the previous ENNRB studies, the increase of water storage by constructing dams and the adaptation of water allocation plans have been selected as a viable option by Kenyan water management authorities.

National and local authorities identified four possible sites of proposed multi-purpose dams in the headwaters of the ENNRB for three main purposes: to maintain minimum river flows during droughts, to provide municipal, livestock and minor irrigation water supply and to decrease flood peak discharges at the tourist lodges in Samburu and residential areas around Archers post town located in the downstream part of the river basin.

In our study, a holistic approach of combined drought and flood assessment is adopted for the multi-purpose dam operation to maintain full storage before the start of dry season and to keep flood capacity for the flood peak reduction during flood season. For the hazard severity assessment, the long-term precipitation record has been investigated with the use of Standardized Precipitation Index (SPI) as well as Standardized Precipitation Evapotranspiration Index (SPEI).

To evaluate water infrastructure effectiveness, we utilized existing 600-arcsec (about 18-km) grid BTOP model, which was developed for the entire ENNRB as a part of the global BTOP modelling system, and focused on the catchment area located upstream of the Archers post. The BTOP model was run with the local precipitation data and calibrated to observed river discharges at the Archers post. The calibrated BTOP model demonstrated a satisfactory statistical performance and represented peak and low flows of the Ewaso Ngiro River during short- and long-term simulations. From the calibrated BTOP model, the proposed dams and retention basin were simulated to find an optimum dam location for water supply and flood control. From the results of our study, the best possible location and capacities of flow control structures (dams/retarding basin) can be selected for the implementation of a combined flood and drought risk reduction activities.

Keywords: *BTOP model, water storage, flood peak discharge, water scarcity, Ewaso Ngiro North River*

INTRODUCTION

In Kenya, the proper management of floods contributes to the realization of Millennium Development Goals (MDG) and also plays a vital role in realization of vision 2030 goals whose achievements depend on proper natural and manmade disaster management. The Ewaso Ngiro North River Basin (ENNRB) is one of the six catchment areas in Kenya and is the largest catchment with an area of 210, 233km². The study sub-basin with an area of 14,973km² is located in the upper part of the ENNRB and experiences alternate periods of droughts and floods (Figure 1). In the study area, majority of the flooding occurs near the Archers Post, which is the most densely populated area due to increasing population along water bodies for day-to-day activities such as irrigation and fishing, livestock, tourism and industry.

In the previous studies, development of water allocation plans and construction of water storage infrastructure have been recommended for the national and local authorities. Currently, there is an effort in development of water allocation plans in the study area as in the case of 5DA sub-basin (WRMA, 2014), see yellow area in Figure 1. However, the planning activity only offers regulation of surface water and groundwater takes, which have been ever increasing in the upstream parts of the study area. For example, these abstractions have already been reducing river flow downstream and resulting in no river flow during dry seasons. Therefore, the current planning needs to be complemented with the development of water storage infrastructure as a way of increasing available water and addressing water scarcity during dry seasons. Figure 1 shows the study area as well as the proposed storage locations in the study area.

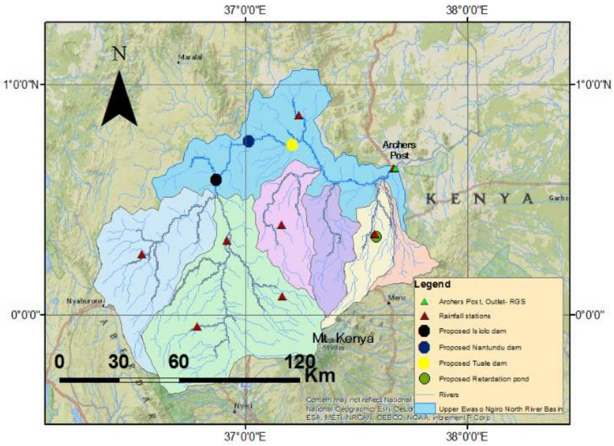

Figure 1. Location of Upper Ewaso Ngiro North River Basin with proposed dams and retardation pond locations. The rainfall and river gauging stations with available data are also demonstrated.

This study aims to analyze the possibility of applying water infrastructure structural such as a multi-purpose dam and a flood retardation basin. The multi-purpose dam is designed to reduce flood peak discharges during wet seasons and to mitigate the effects of droughts in the basin by utilizing accumulated dam water storage for water supply. This water supply can reduce the water demand deficit during water scarce periods as a way of optimizing the management of water resources in the catchment. Therefore, the specific objectives of this study are:

a) To identify historical flood and drought events and their magnitude by analyzing Standardized Precipitation Index (SPI) and Standardized Precipitation and Evapotranspiration Index (SPEI);
b) To conduct numerical simulations of the selected flood and drought events with the aim of obtaining peak and low flows to enable the proposed flow control solutions;
c) To investigate the impact of proposed dams in flood peak reduction for downstream areas, which are susceptible to flood inundation;
d) To investigate the effectiveness of the proposed dams for the water supply;
e) Optimize water resources management through water supply by dam.

THEORY AND METHODOLOGY

In this study, the methodology was divided into two parts: flood peak reduction (Part 1) and drought mitigation (Part 2). For the multi-purpose dam operation, holistic approach of combined drought and flood assessment is adopted to maintain full storage before the start of dry seasons and to keep flood capacity for the flood peak reduction during flood seasons, see detailed steps of these two parts are provided below:

Standardized indices for flood and drought assessment

In the hazard severity assessment, standardized indices of SPI and SPEI were adopted in this study. For local precipitation data, the long-term precipitation record has been investigated with the use of SPI (McKee et al.,1993). The long-term deficit of effective rainfall was investigated with global dataset of SPEI (Serano et al., 2010). The range of SPI and SPEI values indicate moderate drought from -1.0 to -1.49, severe drought from -1.50 to -1.99, and extreme drought below -2.0 (McKee et al.,1993; Serano et al., 2010).

BTOP model set up and calibration

To evaluate water infrastructure effectiveness, existing 600-arcsec (about 18-km) grid BTOP model, which was developed for the entire EENRB as a part of the global BTOP system (Magome et al., 2015), was utilized and the catchment area located upstream of the Archers post was investigated. The BTOP model conducts rainfall-runoff simulations based on vegetation, root, unsaturated and subsurface zones (Takeuchi et al., 2015). The 600-arcsec BTOP model preserved small topographical features by utilizing upscaling algorithm and utilized global datasets of land cover and soil properties due to unavailability of local data (Magome et al., 2015). For the BTOP input, the long-term average potential evapotranspiration was estimated by the Shuttleworth-Wallace model using climate forcing data CRU TS3.1 and a fortnightly Normalized Difference Vegetation Index (NDVI) (Magome et al., 2015). In the study area, the 600-arcsec BTOP model was run with short- and long-term local precipitation data and calibrated with river discharge data of the Archers post river gauging station. The BTOP model simulations were evaluated using statistical performance to represent flood peaks and low flows of the Ewaso Ngiro River.

BTOP application for dam and retardation pond simulations

From the calibrated BTOP model, the proposed dams and retention basin were simulated to choose an optimum dam for water supply and flood control operation. Each dam was simulated using the newly implemented dam operation in the BTOP model. The investigation of flood peak discharges was conducted using flood frequency analysis and was focused on dam locations. For each BTOP grid, the flood peak discharges were estimated from the long-term BTOP river discharges using the Gumbel distribution with L-moments. For the water supply, the newly developed dam operation type “33” in the BTOP model was utilized for the municipal water supply diversion from the dam. From these results, the possible location and capacities of flood control structures (dams/retarding basin) enable authorities to develop the implementation plan on a combined flood and drought risk reduction.

DATA

Hydro-meteorological data

In this study, a total of 24 rainfall stations were identified for the upper ENNRB. These rainfall stations are mostly located in the headwaters of the Archers Post and only few ones are located downstream. For the purpose of simulation and calibration, seven precipitation stations and three discharge stations that had data sufficient for the periods of simulation were used. The available rainfall data was obtained from the stations shown in Figure 1.

Details of the proposed dams

The information of the proposed dam is available from two existing studies, which were conducted by the National water conservation and pipeline corporation (NWCPC) and by the Ewaso Ngiro North Development Authority (ENNDA). NWCPC commissioned consultants to do a feasibility study for a dam to serve Laikipia, Isiolo and Samburu areas as a strategy in achieving the Kenya vision 2030 and also to supply water to the proposed Isiolo resort city. The locations and capacities of the proposed dams are shown in Figure 1.

RESULTS AND DISCUSSION

Hazard severity Assessment

From the long-term SPI and SPEI, the 3-month SPI and SPEI values are effective in analyzing short-term to mid-term soil moisture conditions and are effective in planning for farming activities. For these events, the SPI and SPEI values for the period 1950 to 2015 are indicated in Figure 2. These standardized indices of 6-month SPI and SPEI depict medium-term trends in precipitation while the 12-month SPI and SPEI indicate a drought impact on stream flow patterns. From these indices, the probability of recurrence of floods and droughts is obtained with extreme severity droughts. The probability of recurrence of moderate droughts is once in 18 months and severe dryness at once in 5 years. From this analysis the 2008/2009 droughts were represented as severe droughts. For flood incidents, the analysis showed that moderate wetness is experienced once in 7 months and severe wetness occur once in 18 months and this can be confirmed by the floods of March 2010, November 201, April 2013 and October 2014.

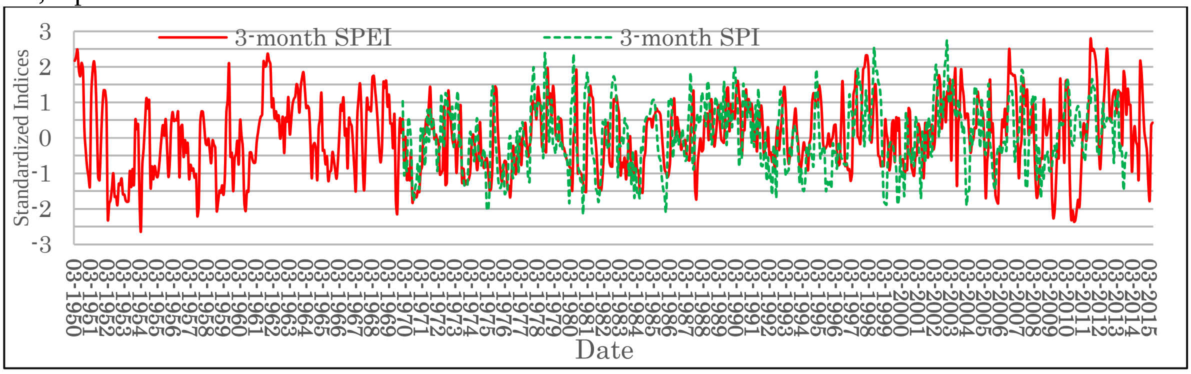

Figure 2. Standardized precipitation indices 3-month SPI and SPEI

Discharge simulation

The simulation of 600-arcsec BTOP model with local precipitation is plotted for calibration and validation periods at Archers post station (Figure 3). The Archers post station is located at the study area outlet and one BTOP block is used to represent the study area. For the calibration period, year 2011 is selected. The statistical performance indices of Nash-Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE) are found satisfactory for calibration period (NSE= 0.72 and RMSE= 33.47). From the calibrated BTOP model, the validation is conducted with the long-term simulation from 1960 to 1980 and resulted in NSE of 0.47.

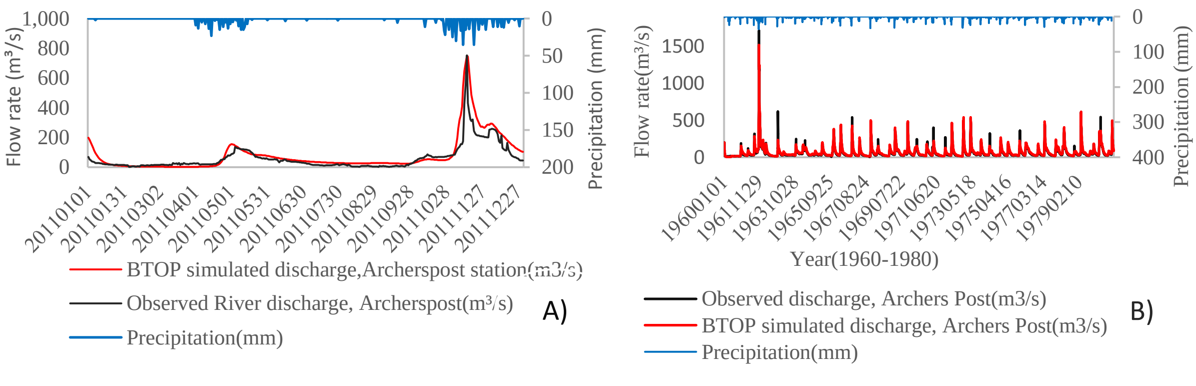

Figure 3. BTOP model simulation: A) calibration using observed data for 2011 and B) Validation using available discharge for 1960 to 1980 at Archers post station.

To obtain the long-term discharge, 21-year long-term simulation is conducted to carry out the flood frequency analysis at various locations including the dam and at Archers post. The summary of these peak discharges is provided in Table 1. Analyzed peak discharges from the ENNR's Archers post station indicate incidences of extreme flood events in the study area. The BTOP simulation analysis enabled to obtain discharge conditions for all the locations in the study area and is useful for flood risk reduction and management.

Table 1. Flood frequency analysis of long-term BTOP simulation output

BTOP simulated discharge type	ISIOLO DAM	NANTUNDU DAM	BARSALINGA DAM	TUALE DAM	RETARDATION POND	ARCHERS POST
Maximum annual discharge	866.47	1153.07	1194.44	1194.44	85.04	1651.36
Average annual discharge	226.06	305.02	311.43	311.43	24.81	434.68
Minimum annual discharge	89.26	123.57	127.54	127.54	9.4	181.75
Standard deviation of annual discharge	172.23	227.98	234.9	234.9	17.22	323.39
10-year flood peak discharge	419.15	560.53	571.23	571.23	45.42	791.97
25-year flood peak discharge	528.57	705.32	718.45	718.45	57.1	994.45
50-year flood peak discharge	609.75	812.74	827.67	827.67	65.77	1144.66
100-year flood peak discharge	690.32	919.36	936.09	936.09	74.37	1293.75
200-year flood peak discharge	770.61	1025.6	1044.11	1044.11	82.94	1442.31
500-year flood peak discharge	876.52	1162.75	1186.62	1186.62	94.25	1638.29
1000-year flood peak discharge	956.57	1271.68	1294.32	1294.32	102.8	1786.42

Dam Operation for flood control and water supply

The application of dam reservoir operation is conducted for flood peak reduction and water supply. In flood peak control, investigation is done under two scenarios: regulated and unregulated releases. The regulated scenarios is designed as a case, where prior to a major flood event like experienced in 2011, the dam volume is maintained to the normal water level to create room for the flood storage volume of the dam. In this case, both Isiolo dam and Nantundu dams satisfactorily reduce the flood peaks by almost half. The Isiolo dam reduced the simulated November 2011 flood peak from 729m³/s to 352 m³/s, which is slightly above the estimated bankfull discharge of 340 m³/s. Similar operation is observed for the Nantundu dam lowering the flood peak to normal water level; in this case, the 729 m³/s peaks of November 2011 were reduced to 220 m³/s satisfactorily below the bankfull discharge. In the unregulated release case, this operation does not consider the dam flood storage capacity and focuses on maximizing the dam storage capacity to the crest level for purely drought reduction. In this scenario, both dams do not reduce the peaks to below the bankfull discharge, which is to be expected.

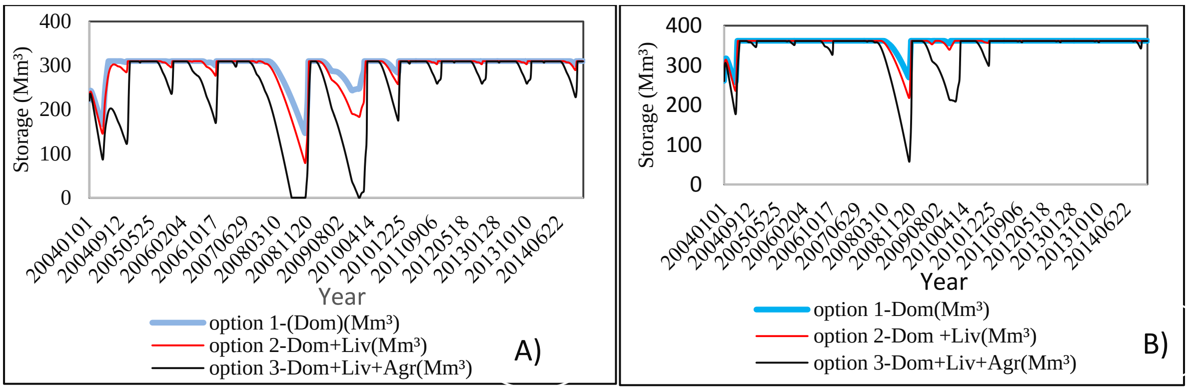

Figure 4. Change in water storage volume of the proposed dam during the 2008/2009 droughts: A) Proposed Isiolo dam and B) Proposed Nantundu dam.

For drought reduction, the change in storage volumes with the three options is shown for proposed Isiolo dam in Figure 5A and for proposed Nantundu dam in Figure 5B. The each dam operation is simulated for a period between 2004 and 2014 to monitor the decrease in dam water levels during the severe to extreme drought events with three water withdrawal options. Option 1 is designed to run the dam operation with domestic water withdrawal and maintain ecological flow and represents a minimum case for drought risk reduction. Option 2 is run the dam operation with domestic and livestock water withdrawal while maintaining ecological flow and represents an intermediate drought risk reduction case. Option 3 is designed to avoid any drought risks by dam operation and includes water withdrawals for domestic, livestock and agriculture and maintaining ecological flow.

CONCLUSION AND RECOMMENDATIONS

In this study, several tools were adopted for conducting a combined assessment of floods and droughts. For the assessment of severity and frequency, floods and droughts were investigated using Standardized Precipitation Index (SPI) and Standardized Precipitation and Evapotranspiration Index (SPEI). From the findings, the probability of recurrence of these two alternate events was obtained. For discharge simulation, existing 600-arcsec (about 18-km) grid BTOP model with local precipitation was calibrated and validated with observed river discharges at Archers post. Using the calibrated BTOP model, the proposed dams and retention basin were simulated to select an optimum dam volume and location for water supply and flood control. From the results of our study, the proposed Isiolo and Nantundu dams both showed satisfactory performance in flood control when regulated in relation to the estimated bankfull discharge. For drought reduction/water scarcity, both dams performed satisfactorily in supply of water for domestic and livestock/wildlife. Due to its advantage in capacity, the Nantundu dam with an effective volume of $363Mm^3$ showed better performance in provision of water for agriculture compared to Isiolo dam with the effective capacity of $311Mm^3$. In terms of location, the Isiolo dam located about 23km upstream of the Nantundu dam is preferable since it can supply a bigger area within the study area by gravity. This information enable as to plan on a combined flood and drought risk reduction.

The dams can supply domestic and livestock water if properly regulated to downstream users of Archers post. Future studies can consider the improvement of the BTOP resolution to 1-km or 0.5-km to enable more accurate estimation of discharge and to evaluate the effectiveness of the dams in reduction of water scarcity in the study area. In addition, the entire river basin beyond the study area can be included in the future studies.

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