

First impact assessment of hydrological cycle in the Tana River Basin, Kenya, under a changing climate in the late 21st Century

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Abstract:

This study projects the hydrological cycle in the Tana River Basin, Kenya, under a changing climate due to anthropogenic greenhouse gas emissions in the late 21st century, using a 20-km mesh atmospheric global climate model (AGCM) and a 0.5°-mesh global river-routing model. In addition, 60-km mesh AGCM ensemble experiments forced with four different projected sea-surface temperatures were performed to quantify the uncertainty in the climate projections. All four climatological annual mean hydroclimate variables: precipitation, evaporation, total runoff, and soil water storage: are projected to increase in the future climate. With the exception of total runoff and river discharge in the headwater basin, these climatological annual mean increases are generally robust. The four climatological monthly mean hydroclimate variables at Garissa are projected to exhibit different seasonal changes. The long rains season is projected to have almost the same peak precipitation amount in April with an earlier onset, while the short rains season is projected to have significant precipitation increases. River discharges are projected to increase significantly in November to March with high consistent change in sign and in June. These results should guide the awareness programs of the changing hydrological cycles in the Tana River Basin and assist in formulating mitigation and adaptation strategies to meet these challenges.

KEYWORDS Tana River; future climate projection; hydrological cycle; AGCM; Kenya

INTRODUCTION

Water scarcity is currently serious in Kenya, due to the large population and low national mean precipitation, with a large extent of semi-arid climate in 75% of the country. The amount of annual renewable water resources available per person in Kenya is 778 m³ yr⁻¹person⁻¹, which is classified as a chronically water scarce country (FAO, 2001). The Tana River is the longest river system (1000 km) and one of the largest basin areas (120,000 km²) in Kenya, supplying about 32% total national water resources (NWDR, 2006); it flows from its headwaters on Mount Kenya and in the Aberdare Range in the eastern rim of the Great Rift Valley to the Indian Ocean near Kipini (Figure 1). Most of the major tributaries, which discharge only during the two wet seasons, join the Tana River from the right-hand banks in the lower basin. In the lower basin irrigation projects

have been implemented, and the riverine forest has high conservation value as the residence of two endemic primates and the Tana River poplar (IUCN, 1978). In addition, the Tana Delta, which stretches 30 km upstream from the river mouth, has coastal lakes, a mangrove swamp, tidal creeks, and flood plains (Bouillon *et al.*, 2009) that are home to wildlife declining in number (e.g., crocodiles, hippos, and elephants). This delta contributes to significant sediment transport, estimated at 3.1 × 10⁹ kg yr⁻¹ (Syvitski *et al.*, 2005) or 6.6 × 10⁹ kg yr⁻¹ (Kitheka *et al.*, 2005). Although it does not flow directly through Nairobi, the Tana River plays an important role, since the Sasumua Reservoir in the upper catchment supplies about 12 to 20% of Nairobi's water demands. Five other reservoirs, including the largest reservoir in Kenya, are operated for electric-power generation and irrigation (Ministry of Energy, 1987).

The changing climate due to anthropogenic greenhouse gas emission is degrading the water and electric power supplies and the wildlife habitat by changing river discharge. Previous works project that river discharge late in this century will generally increase in Kenya (Milly *et al.*, 2005, M05; Nohara *et al.*, 2006, N06); however, the river discharge in the lower basin of the Tana River is projected to decrease in M05. These projections originated from coarse atmosphere-ocean coupled general circulation models (CGCMs) with a horizontal resolution of 300 km. However, this resolution is insufficient for representing the topographical features of the Tana River Basin. Recently, a 20-km mesh atmospheric GCM (AGCM) has been used for river discharge projections (Kitoh *et al.*, 2008; Nakaegawa and Vergara, 2010; Kitoh *et al.*, 2011), enabling us to project the distributions of changes in the hydrological cycle within a basin, as well as river discharge at a gauging station.

Many studies have focused on the hydrological processes in the Tana River Basin, due to the importance of the Tana River Basin in the impact of dam construction (Maingi and Marsh, 2002), sediment transport and exchange in the estuary (Kitheka *et al.*, 2005), and origin and cycle of carbon (Bouillon *et al.*, 2009). However, hydrological cycles have not yet been projected in the entire Tana River Basin, although Dyszynski *et al.* (2009) did assess water resources in the upper basin using an integrated water model. The present study first assesses future changes in the hydrological cycle in the Tana River Basin in the late 21st century using a 20-km mesh AGCM. In addition, we quantify the uncertainty in the climate projections by performing 60-km mesh AGCM ensemble experiments forced with different projected sea-surface temperatures (SSTs).

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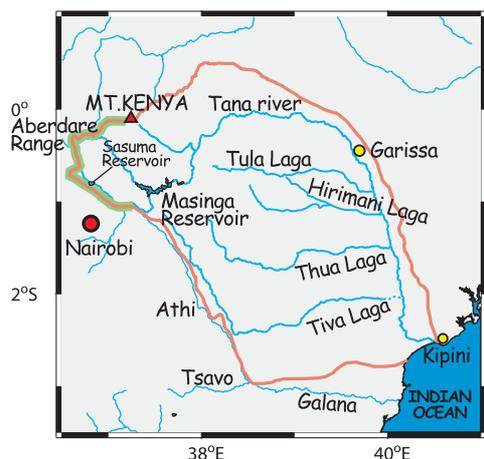


Figure 1. Tana River Basin.

MODEL, EXPERIMENT, AND DATA

Model

The model used is a global hydrostatic AGCM developed by the Meteorological Research Institute (MRI) and the Japan Meteorological Agency (JMA), with a horizontal resolution of 20 km and 60 vertical layers (MRI-AGCM3.1S) (Mizuta *et al.*, 2006). The land-surface scheme in this model is the new version of JMA Simplified Biosphere (SiB; Sellers, 1986) (Hirai *et al.*, 2007), incorporating soil-vegetation-atmosphere heat and water transfers. SiB predicts soil water storage and canopy retention water, as well as their temperatures, and diagnostically calculates the total runoff, a summation of surface and subsurface runoffs, into a river channel.

River discharge is computed in offline mode with 0.5-degree version of the Global River flow model using TRIP (GRiVET; N06) which is a digital river-routing dataset of the Total Runoff Integrating Pathway (Oki and Sud, 1998). GRiVET assumes that river discharge is proportional to river-water storage and the proportionality constant or the effective velocity is set to 0.4 m s^{-1} . This model considers only natural river flows, not lake, artificial controls such as reservoir operations and water withdrawal; however, river discharges are well-simulated in major river basins (e.g., Nakaegawa and Hosaka, 2008)

Experiment

We performed 25-year time-slice experiments for present-day and late 21st century climates with the 20-km mesh AGCM (e.g. Kitoh *et al.*, 2009). The observed monthly SST and sea-ice concentration during 1979 to 2003 (Rayner *et al.*, 2003) are used for the present-day climate simulation. The lower boundary SST data for future climate projections were prepared by superimposing three components: future change in the multi-model ensemble (MME) of SST projected under the Special Report on Emission Scenario (SRES) A1B emission scenario in the 3rd Coupled Model Intercomparison Project (CMIP3), the trend in the MME of SST, and the detrended observed SST anomalies for 1979 to 2003 (Mizuta *et al.*, 2008). Future sea-ice distribution is obtained in a similar fashion.

We also performed ensemble experiments with the 60-km mesh AGCM forced with four different lower boundary conditions, projected SST, and sea-ice distributions, in order to quantify the uncertainty in climate projections. The four different lower boundary conditions used are the same MME mean of CMIP3 as in the 20-km mesh AGCM experiment, CSIRO-Mk3.0, MRI-CGCM2.3.2, and MIROC3.2 (hires) (see Table S1 in detail). The change in global annual mean SST prescribed is 2.16 K, 1.43 K, 1.73 K, and 3.49 K in the late 21st century. MIROC3.2 (hires) indicates a La Niña-like pattern in the tropical Pacific, while the other three indicate an El Niño-like pattern. For each lower boundary condition, three member runs with different initial conditions are performed.

Data

We used two observed datasets to validate climatological mean precipitation and river discharge in the present-day climate simulation: Climate Research Unit TS2.1, which contains monthly mean precipitation over land areas with a horizontal resolution of 0.5° for 1901 to 2002 (Mitchell and Jones, 2005), and climatological monthly mean river discharges provided by the Global Runoff Data Center (http://www.bafg.de/GRDC/EN/Home/homepage_node.html). River discharge in the Tana River Basin is available at Garissa only (drainage area $42,220 \text{ km}^2$, 39.7°E , 0.45°S). The drainage area is $34,000 \text{ km}^2$ in TRIP as about 20% small as the actual one. This underestimation is tolerable in the 0.5° global river routing model.

RESULTS

Validation

The increase in climatological global annual mean surface air temperature determined by the 20-km mesh AGCM experiment is 2.73 K in the future climate, while that of the CMIP3 MME mean is 2.66 K.

Table I summarizes the validation of the present-day climate experiment with the 20-km mesh AGCM at a horizontal resolution of 0.5° . The 20-km mesh AGCM adequately captures basin-area mean precipitation in the Tana River. The annual mean precipitation in the 20-km mesh AGCM is 33% overestimated and the seasonal cycle variation is 25% overestimated, partly due to 10% overestimation of the global annual mean precipitation. The

Table I. Validation of precipitation and river discharge in the Tana River Basin in the present-day climate simulation. Annual mean ratio (simulation/observation), temporal correlation of seasonal cycles of monthly mean values between the simulation and the observation, and the variation ratio of seasonal cycles measured with standard deviation of monthly mean values (simulation/observation). All units are non-dimensional.

Variables	Annual mean ratio	Seasonal cycle	
		Temporal correlation	Variation ratio
Precipitation	1.33	0.78	1.26
River discharge	0.59	0.82	0.70

spatial distribution is also effectively captured in the 20-km mesh AGCM (see Figure S1). In Kenya, including the Tana River Basin, the intertropical convergence zone migrates latitudinally, and two rainy seasons occur: the long rains season in mid-March to mid-June and the short rains season in October to December. This seasonal cycle is well-simulated in the 20-km mesh AGCM, indicated by its high temporal correlation and by the lack of a peak phase difference between the observation and the simulation.

River discharge at Garissa is captured well (Table I), where the difference in basin area is adjusted by multiplying a factor of 1.25 with the simulated river discharge. The 20-km mesh AGCM underestimates the annual mean and seasonal cycle variation but simulates the bimodal peaks in May and November (Figure 2), corresponding to the long rains and short rains seasons in this basin, although the peak of river discharge during the short rains season is very small. The contrast between precipitation overestimation and river discharge underestimation stems from overestimated evaporation through the year from a water balance analysis for this basin.

The 60-km mesh AGCM also exhibits the same degree of reproducibility. These validations confirm that both the 20-km and 60-km AGCMs capture precipitation and river discharge in the Tana River Basin well for the present-day climate.

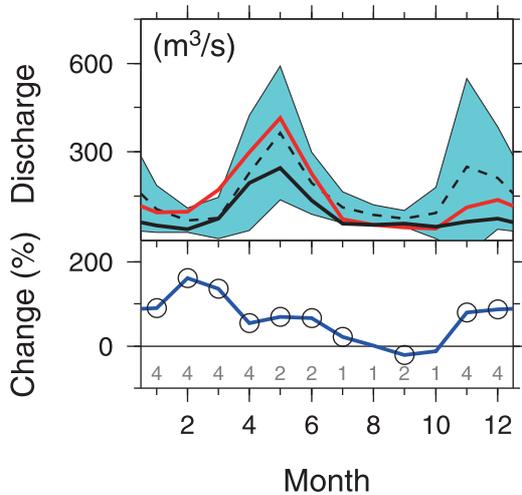


Figure 2. Upper: Observed river discharge (black dashed line) with one standard deviation range (light blue shaded area) at Garissa in the Tana River, and simulated river discharge for the present-day climate (black solid line) and future climate (red solid line) in the 20-km mesh AGCM. The simulated river discharge is adjusted by multiplying the basin area ratio of 1.25 to remove the effect of the difference in basin area between the observation and TRIP. Lower: Percentage change (blue solid line) in river discharge between the present-day and future climates in the 20-km mesh AGCM. Circles denote statistically significant changes at the 95% level. The numbers above the horizontal axis indicate the number of members of the 60-km mesh AGCM ensemble that changed in the same direction as in the 20-km mesh AGCM or that was consistent change in sign as in the 20-km mesh AGCM.

Climatological annual mean projection

Table II presents the basin-mean change in climatological annual means for three hydrological variables. Precipitation is projected to increase by 15%. This increase is mainly consumed by evaporation increase in amount. Total runoff exhibits the largest increase in percentage among the three hydrological components because of small amount in the present-day climate.

Climatological annual mean precipitation is projected to increase significantly by 10% in the entire Tana River Basin (Figure 3a). Although climatological annual mean evaporation is projected to increase significantly by at least 5%, the increases indicate geographical contrasts between eastern and western parts of the basin (Figure 3b). Significant increases in climatological annual mean total runoff are projected to exceed 50% (Figure 3c). This increase is greater than both climatological annual mean precipitation and evaporation increase; this feature is unique, since both increases generally reduce the total runoff increase in many river basins (e.g., M05; N06; Nakaegawa and Vergara, 2010). This feature stems from the fact that the absolute value of total runoff is very small compared to precipitation and evaporation, and a small increase tends to be enhanced in percent change. Insignificant total runoff increases occur in the Thua Laga River Basin. River discharge is projected to increase by more than 30% in the entire Tana River Basin in the future climate (Figure 3d). River discharge increase in the Thua Laga River Basin is also significant, probably due to the collection effect (Nakaegawa and Hosaka, 2006) that reduces the interannual variabilities in river discharges by spatially integrating total runoffs over a river basin through the river channel network.

These climatological annual mean increases in precipitation and evaporation are robust, since the 60-km mesh ensemble exhibits consistent increases in almost the entire basin (Figures 3e and 3f). In the western part, especially near Mt. Kenya, consistent increases in total runoff and river discharge are not always robust, since there are two consistent changes in signs, indicating that two of the four SST 60-km mesh AGCM experiments demonstrate decreases in the area (Figures 3g and 3h). River discharge increase projected by the 20-km mesh AGCM is significant in the area, but it is not robust, and vice versa in the Thua Laga River Basin, confirming that both statistical significance test and robustness are requisite for climate projections.

Climatological monthly mean projections

Figure 4 depicts the projected climatological monthly means of hydrological variables (precipitation, evaporation, total runoff, and soil water storage) at Garissa in the future

Table II. Climatological annual mean hydrological variables: precipitation, evaporation, and total runoff (mm day⁻¹): for the present-day and future climates and their percent changes.

Period	Precipitation	Evaporation	Total Runoff
Present-day	2.48	2.36	0.12
future	2.84	2.64	0.20
% change	15%	12%	17%

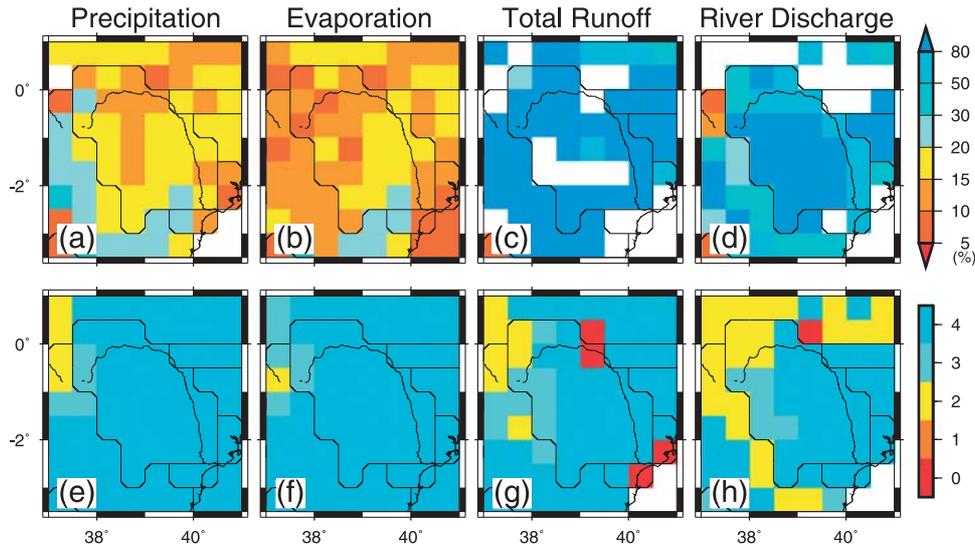


Figure. 3 Upper: Geographical distributions of projected climatological annual mean percent changes (future-present)/present $\times 100$ in the 20-km mesh AGCM. Lower: Geographical distributions of the same number as in the bottom panel of Figure 2: (a), (e) Precipitation. (b), (f) Evaporation. (c), (g) Total runoff. (d), (h) River discharge. Thin black lines denote basin boundaries.

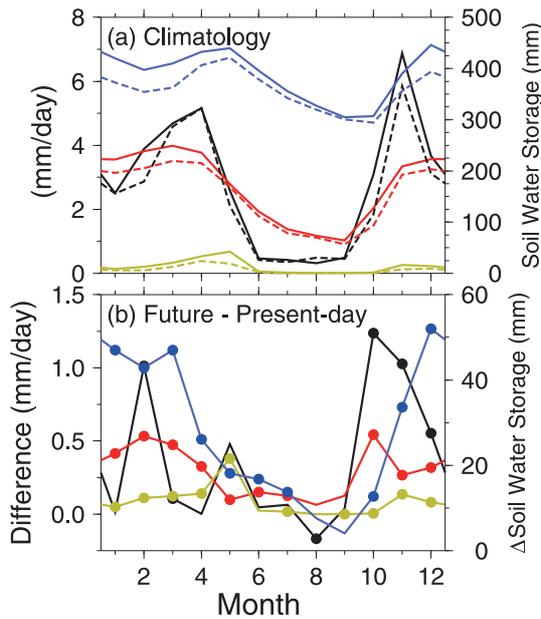


Figure 4. (a) Monthly mean hydrological variables at Garissa in the future climate. (b) Difference in the variables between the present-day and future climates. The values in both panels are basin-mean values of all grid values upstream in the sub-basin at Garissa. Black lines indicate precipitation, red lines indicate evaporation, green lines indicate total runoff, and light blue lines indicate soil water storage. In (a), the broken line denotes the present-day climate, and the solid line denotes the future climate. In (b), dots denote statistically significant changes ($P < 0.05$) compared to present-day values.

climate. The changes in this figure are basin-mean values of all grid values upstream in the sub-basin at Garissa. Precipitation in February is projected to increase in the future

climate; however, the onset of the long rains season and the peak amount in April in the future climate almost remain the same as in the present-day climate. This corresponds to a significant precipitation increase only in February. During the short rains season, monthly mean precipitation is projected to increase significantly with no phase shift in seasonal march. Monthly mean precipitation is projected to decrease significantly only in August. The climatological monthly mean evaporation is projected to increase significantly (insignificantly) from October to July (in August and September). The seasonal march of evaporation in the future climate remains the same as in the present-day climate. Climatological monthly mean total runoffs are projected to increase significantly except for June and August, and to be delayed by one month. Climatological monthly mean soil water storage in the future climate will increase significantly except for August and September. Large increases are found in a period from mid short rains season to mid long rains season. Even when the monthly mean evaporation increases more than the monthly mean precipitation (e.g., in April), total runoff increases. This is possible because soil water storage delays the peak of total runoff and concurrently supplies water for evaporation during months with small precipitation increases.

River discharge at Garissa is projected to increase significantly in November to March and in June (Figure 2). In contrast, it is projected to decrease significantly in September. During the two rainy seasons, river discharge distinctively increases in amount more in the long rains season than in the short rains season, although precipitation demonstrates opposite features in the two seasons. As mentioned above, soil water storage recharged in the short rains season contributes to river discharge in the long rains season. In Kenya, there are two low-water seasons (January to February and July to October) between the long rains and short rains seasons. In the present-day climate, river

discharges are almost the same in both low-water seasons. River discharge increases in the future climate will alleviate low flow in the first low-water season, while river discharge decrease will deteriorate low flow in the second low water season. On a monthly time scale, peak river discharges occur in May in both climates. The numbers above the horizontal axis of the bottom panel in Figure 2 indicate the number of members of the 60-km mesh AGCM ensemble that changed in the same direction as in the 20-km mesh AGCM. Highly consistent changes in sign are observed in November to April. The fact that the significant increase in June and the significant decrease in September are not robust reconfirms that both statistical significance test and robustness are requisite for climate projections.

DISCUSSION

The Tana River Basin currently faces crucial issues (FAO, 2001). Due to the skewed water distribution and lack of storage facilities, water use conflicts currently prevail within the upper catchment. Several tribes engage in flood recession agriculture along the lower parts. Projections suggest that these conflicts will be mitigated due to climatological annual increase in both precipitation and river discharge in the late 21st century (Figure 3) and that future changes in seasonal cycles of river discharge may influence agricultural practices. For example, low flow in the low-water season from July to October will decrease. These projections suggest that appropriate water resource management will enable us to adapt to river discharge in the future. Some practical mitigations and adaptations should be presented through hydrological and agricultural studies. Current estimates indicate that the Tana River and adjacent Athi-Galana basins hold one-third of the irrigation potential of Kenya (111,100 ha). Future changes in the hydrological cycle should be incorporated in the next estimate, which may increase the irrigation potential as long as appropriate water resource management is included.

We performed 60-km mesh AGCM ensemble experiments to quantify the uncertainty in climate projections. However, the ensemble size is four, which is smaller than the 24 of M05 and the 18 of N06. Comparison of projections between those two studies and the present study enhances the robustness of the projections in this study. Since M05 projected river discharges for the mid-21st century (2041 to 2060), the qualitative comparison is reasonable. Climatological annual mean river discharge increases with highly consistent change in M05 are consistent with those of this study. In contrast, quantitative comparison is possible with N06. Climatological annual mean precipitation increases are similar, but the climatological annual mean evaporation increase in N06 slightly exceeds that in this study. As a result, total runoff in this study is slightly greater than that in N06. These consistent changes reinforce change in the hydrological cycle in this study.

We projected river discharge with the global-scale models of MRI-AGCM3.1S and GRiVET, while distributed hydrological models including detailed processes with a high horizontal resolution are widely used for future projections (e.g. Ma *et al.*, 2010). The distributed hydrological models are essential for planning adaptation strategies against

hydrological disasters or extremes since the strategies distinctively depend on local features such as small-scale topography and available measures. Yet, in this study, as first assessment, we demonstrated that with the global-scale models, we are capable in projecting climatological mean hydrological changes in river basins the area of which is smaller than the continental-scale river basin areas.

CONCLUDING SUMMARY

Using the 20-km mesh AGCM and 0.5° mesh version of GRiVET, we first assess the future changes in the hydrological cycle in the Tana River Basin in the late 21st century. In addition, we quantify the uncertainty in climate projections by performing 60-km mesh AGCM ensemble experiments.

All four climatological annual mean hydroclimate variables are projected to increase in the future climate. Climatological annual mean precipitation is projected to increase significantly (by 15%) in the entire Tana River Basin. Climatological annual mean evaporation is projected to increase significantly with geographical contrasts between eastern and western parts of the basin. The largest increases of more than 50% are found in climatological annual mean total runoff and river discharge. These increases are generally robust, except for total runoff and river discharge in the headwater basin.

However, the four climatological monthly mean hydroclimate variables at Garissa are projected to demonstrate different seasonal changes. The long rains season is projected to have the same onset in the present-day and future climates and almost the same peak precipitation in April; however, the short rains season is projected to have a significant increase in monthly precipitation by greater than 15% with no phase shift in seasonal march on a monthly time scale. Climatological monthly mean evaporation and total runoff will increase for all months with no phase shift and with a one-month delay in the long rains season respectively. River discharge is projected to increase significantly in November to March and in June. Highly consistent changes in sign are confined to November to April.

We focus on the climatological mean for the first projections for the Tana River Basin. Extreme phenomena are crucial issues in climate projections (IPCC, 2012), since they distinctively affect both human and natural environments. We should address the projection of the extreme phenomena in future study.

ACKNOWLEDGEMENT

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SUPPLEMENTS

Supplement 1: This includes Group member list, Table S1, Figure S1, Document S1 and S2.

Group Member List. KAKUSHIN Team-3 Modeling Group

Table S1. The three CMIP3 models used for 60-km mesh AGCM simulations and their acronyms.

Figure S1. Climatological annual precipitation for the observation, the present-day climate simulation, and topography.

Document S1. Validating spatial distribution of precipitation

Document S2. Climatological annual mean river discharge projection in Athi-Galana River Basin

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