

Can Hydrologic Modeling Be a Solution for Transboundary Agreements?

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Abstract

Due to the colonial partition, many rivers in Africa are transboundary rivers shared by several riparian countries. Transboundary rivers in Africa have serious river basin management challenges mainly due to a lack of meteorological and hydrometric data limitations. Many African countries lack the technical knowledge and the financial resources needed to manage large river basins such as the Juba, Shabelle, Niger, Senegal, Zimbabwe, Nile, and Congo. In developed countries where meteorological and hydrometric data are available, river basins such as the Colorado and the Chesapeake in the United States are managed with hydrological models. Hydrological models require meteorological data as model input data and hydrometric data for model calibration and validation. In recent years, the acquisition of freely available global satellite data products offers model input data for developing countries with limited data acquisition capabilities. The study develops a watershed model for the Juba River Basin (JRB) shared by Somalia, Kenya, and Ethiopia. The HSPF (Hydrological Simulation Program-Fortran (HSPF) was selected for the study. Several satellite precipitation and evapotranspiration data products were evaluated, and CHIRPS precipitation and MERRA-2 evapotranspiration products gave the best model performance results. The acquisition of the satellite data products resolved the precipitation and the evapotranspiration model input data limitations. The Nash-Sutcliffe efficiency (NSE), Percent Bias (PBIAS), and coefficient of determination (R^2) performance metric ratings ranged from very good to satisfactory. The model simulated 39 years of daily flow data at selected sites in Somalia and Ethiopia. The simulated flow is suitable for addressing the river basin management solutions and establishing low flow indices and flood frequency analyses required for setting the groundwork for transboundary water management cooperations among riparian countries. The proposed solution generates daily river flow data anywhere in the basin. Given the meteorology and the hydrometric data limitations faced by many countries in Africa, applications of readily and freely available global satellite

data offer solutions to the data scarcity faced by many countries in Africa. The paper presents a cost-effective river basin management solution for developing countries with limited river basin management data.

Keywords

Juba River Basin, Transboundary Rivers, HSPF Model, Satellite Data Products

1. Introduction

The Juba River basin (JRB) originates from the Ethiopian highlands. At its upper reaches, the river is characterized by high elevation, high rainfall, and low evaporative demand. As it flows southwards to the Somali border, it passes through arid areas with low rainfall and high potential evapotranspiration. The total area of JRB is 218,114 km² [1]. However, the study watershed is 200,200 km² which corresponds to about 92 percent of the JRB area. Watershed models are essential tools for river basin management [2]. However, developing countries cannot use watershed models because they do not have the financial resources needed to establish the meteorological and hydrometric data collection. Even developed countries such as the United States of America cannot have precipitation and potential evapotranspiration data that covers large river basins such as the JRB. Lack of meteorological and hydrometric data such as river flow measurements is an impediment to developing watershed models. In recent years, daily global satellite precipitation and evapotranspiration data products became readily available for river basin development and management applications. The main challenge is to identify the most suitable precipitation and evapotranspiration data products for the study area of interest. This study selected CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) as the best satellite precipitation data product for the Juba River basin. For potential evapotranspiration data, the MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications, Version 2) data was selected for modeling the JRB. Africa has 63 international transboundary river basins that cover about 62% of the region's land area and account for 90% of the total surface water [3]. Lack of data-sharing agreements is a major challenge to achieving transboundary agreements among riparian countries [4]. Presently, there are no Juba River negotiated transboundary water agreements [5] or even arrangements of any kind between Somalia and Ethiopia. The study simulates daily river flow data of the Juba River basin from 1981 to 2019, covers all the study area of the river basin, addresses modeling related data constraints, facilitates data-sharing among riparian countries, and leads to effective transboundary agreements. The approach presented in this study allows each riparian country to model the entire river basin irrespective of the size of the area they belong to. Other specific objectives of this study are to 1) evaluate the performance of the

modeling approach, 2) simulate long-term daily flow data that covers historical droughts and flood periods, and 3) establish low flow indices and flood frequencies of the Juba River.

2. Materials and Methods

2.1. Study Area

Juba River is a transboundary river shared by Ethiopia, Somalia, and Kenya. Juba River originates from the Ethiopian highlands and flows into the Indian Ocean near Gobweyn, Somalia. It joins the Shabelle River near Jamaame. At its confluence with the Shabelle River, the total area of the Juba River is 218,114 km² [1]. The Juba River area in Ethiopia is 147,062 km² (67%), the area in Somalia is 61057 km² (28%), and the area in Kenya is 9,995 km² (5%) (Figure 1). Ethiopia is an upstream riparian state and Somalia is a downstream riparian state. The Juba River do not flow through Kenya. Given its limited land area of the Juba River, Kenya is considered as a riparian state.

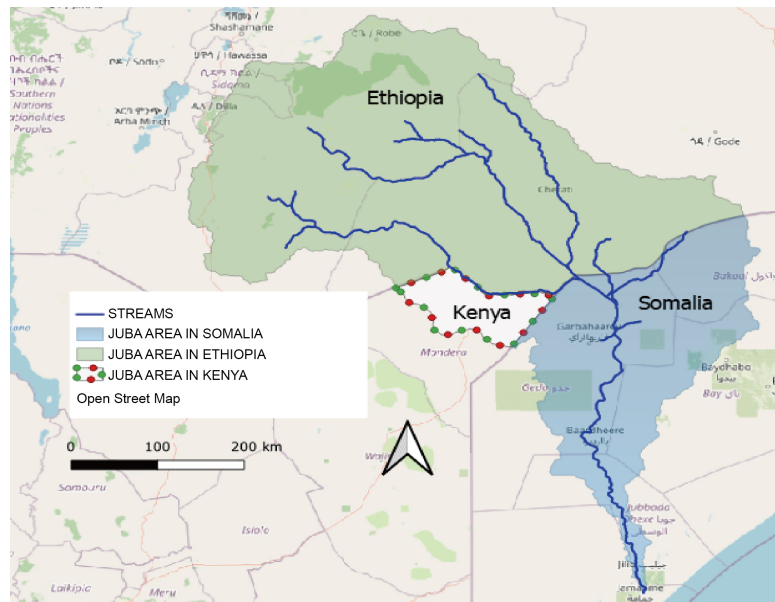


Figure 1. Juba River Basin area by country.

Figure 2 shows the four main tributaries of the Juba River basin. These tributaries are Genale 1, Genale 2, Dawa, and Gestro. Ethiopia built hydroelectric dam on Genale 1 in 2020 and proposed two other dams at the downstream of Genale 1 tributary. Ethiopia has no data-sharing nor transboundary agreement with Somalia. To establish transboundary cooperation with Ethiopia, Somalia must have daily river flow data of the Juba River basin in Ethiopia and Somalia. Hydrological modeling applications and global satellite data products allowed Somalia to simulate daily river flows from each tributary and subbasin of the Juba River basin from 1981 to 2019.

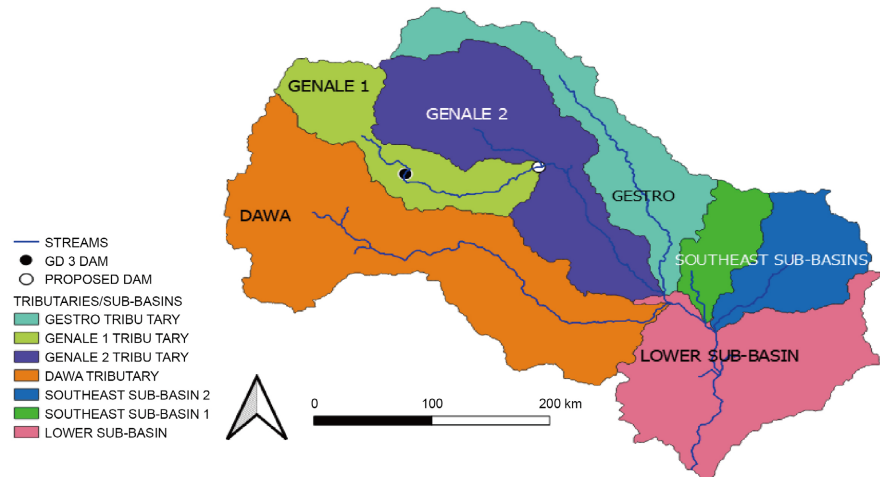


Figure 2. Main tributaries of Juba River Basin.

2.2. Global Satellite Model Input Data

Data used for the development of the watershed model comprised land cover, elevation, and meteorological data. The watershed was delineated with STRM 90-meter digital elevation model [6]. Global land cover data of the European Space Agency [7] was selected for the watershed segmentation. Daily satellite precipitation (CHIRPS-Climate Hazards Group Infra-Red Precipitation with Station) [8] was selected for model input. The CHIRPS satellite precipitation data selection criteria are based on comparisons of several satellite precipitation data products and daily observed rainfall data from the Global Historical Climatology Network (GHCN) stations in Ethiopia. GHCN-daily is an integrated database of daily climate summaries from land surface stations across the globe. GHCN-daily is available at NOAA's National Center for Environmental Information (Find a Station | Data Tools | Climate Data Online (CDO) | National Climatic Data Center (NCDC) (noaa.gov)). The GHCN stations used for CHIRPS precipitation comparisons were Moyale, Mandera, Addis Ababa, Gode, and Robe Bale. Among the satellite precipitation products evaluated, the CHIRPS data was the only product that was closely related to the GHCN network rainfall from weather stations in Ethiopia. Comparisons of monthly CHIRPS precipitation and monthly precipitation from Hagera Selam, Worka, Wadera, Kibre Mengist, and Della Menna stations in Ethiopia further supported the suitability of the CHIRPS precipitation data as model input. The ASCE Grass Reference Evapotranspiration (ET_o) of the (Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) [9] was used for model input. When simulating flow with the HSPF model, the daily precipitation and evapotranspiration data are disaggregated into hourly data. Daily rainfall and daily flow data measurements observed from gauging stations in Ethiopia were unavailable due to the lack of transboundary agreement between the two countries.

2.3. HSPF Model

The Hydrological Simulation Program—FORTRAN (HSPF) was developed in the early 1960s as the Stanford Watershed Model. It remained as a hydrology model until water quality modeling programs were added in the 1970s. The current HSPF model comprises EPA (Environmental Protection Agency) models, such as the Agricultural Runoff Management Model (ARM), the EPA Nonpoint Source Runoff Model (NPS), and a privately developed and proprietary Hydrologic Simulation Program (HSP). HSPF is a comprehensive, process-based, semi-distributed model. HSPF simulates runoff and associated water quality constituents from urban and non-urban watersheds, single and multiple rain events, temporal scales ranging from 1-min to daily, and spatial scales ranging from a small field plot to thousands of square kilometers. HSPF separates the landscape into pervious land segments, impervious land segments, and reach segments. It has different simulation modules for each land segment. Among the HSPF watershed modeling applications, the most notable application is the point and non-point source pollution control studies of the Chesapeake Bay watershed [10]. The Chesapeake Bay watershed has a drainage area of 165,760 km², which is slightly less than the JRB drainage area at Baardheere. Other notable HSPF modeling applications include river basin planning [11] and modeling reservoir operations.

2.4. Model Evaluation Criteria

Environmental and water resources management models such as the HSPF generate flow time series data at hourly or daily simulation time steps. Model prediction performance is affected by input uncertainty (e.g., precipitation input data quality), structural uncertainty related to a model's process representation, output uncertainty related to the observed runoff data used for the model calibration, and parameter uncertainty which relates to model parameterization at the model development stage or the way parameters are used for model calibration [12]. The degree to which uncertainty affects model performance is not well-established. For hydrologic modeling applications, quantitative model performance evaluations require comparisons of model-generated river flow data with observed river flow data. For a model to have high performance, the model's simulated flow must closely match the observed flow. Commonly used quantitative performance metrics include Nash-Sutcliffe efficiency (NSE), coefficient of determination (R^2), and percent bias (PBIAS). **Table 1** shows equations representing the PBIAS, R^2 , and NSE performance metrics and the acceptable ratings for each metric.

According to the acceptable performance metric ratings [13], a PBIAS value of less than 10% is considered very good, an NSE value between 0.5 to 0.65 is satisfactory, and an R^2 value between 0.5 to 0.65 is satisfactory (**Table 1**). Commonly used qualitative techniques are graphical and visual comparisons of the observed and the simulated data. A model must accurately predict the flow magnitude of each event and the sequence of each event. For instance, during rainy days, a model must accurately predict the runoff hydrograph peaks as signatures that

Table 1. Quantitative model performance ratings.

Performance metrics	Equations	Monthly Rating	Daily Rating
PBIAS	$\frac{\sum_{i=1}^n (Y_{obs}^i - Y_{sim}^i) * 100}{\sum_{i=1}^n (Y_{obs}^i)}$	±10% (Very good)	±10% (Very good)
R ²	$\frac{[\sum_{i=1}^n (Y_{sim}^i - \bar{Y}_{sim})(Y_{obs}^i - \bar{Y}_{obs})]^2}{\sum_{i=1}^n (Y_{sim}^i - \bar{Y}_{sim})^2 * \sum_{i=1}^n (Y_{obs}^i - \bar{Y}_{obs})^2}$	Satisfactory (0.5 - 0.70) Good (0.70 - 0.80)	Satisfactory (0.5 - 0.65) Good (0.65 - 0.75)
NSE	$1 - \frac{\sum_{i=1}^n (Y_{obs}^i - Y_{sim}^i)^2}{\sum_{i=1}^n (Y_{obs}^i - \bar{Y}_{sim})^2}$	Satisfactory (0.5 - 0.70) Good (0.7 - 0.80)	Satisfactory (0.5 - 0.65) Good (0.65 - 0.75)

reflect the rainfall inputs into the watershed. For periods without rain events, the model must accurately predict the baseflow component of the hydrograph.

3. Results and Discussion

Sub-basin average annual precipitation and potential evapotranspiration.

The study watershed was delineated into 27 subbasins (**Figure 3**).

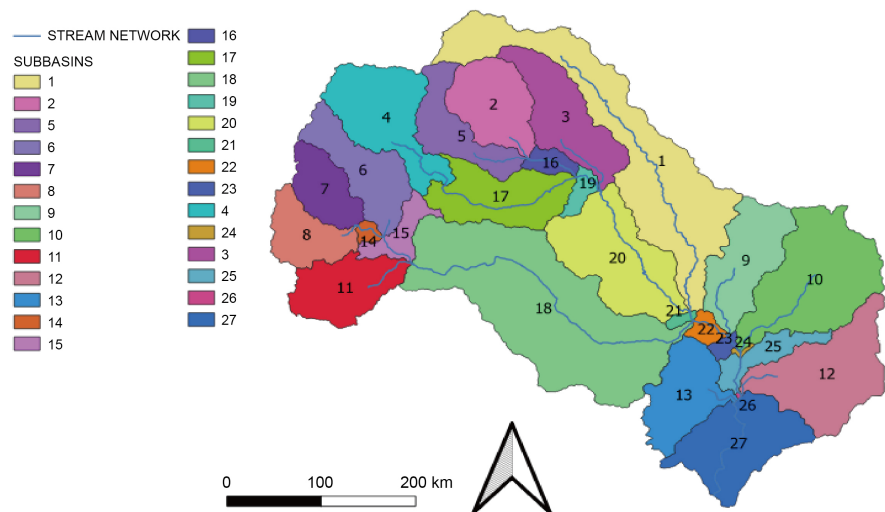


Figure 3. Juba River Basin subbasins.

The minimum annual precipitation of the study watershed is 225 mm, the mean annual is 548 mm, and the maximum annual is 1361 mm (**Table 2**). For each tributary, the highest precipitation amounts are recorded in subbasins in the highland areas in Ethiopia and the lowest precipitation amounts are recorded in subbasins near the Ethiopia-Somalia border.

Table 2 shows the mean annual potential evapotranspiration of each sub-basin. Subbasins in the highlands area have the lowest potential evapotranspiration and subbasins near the Somali-Ethiopia border have the highest potential evapotranspiration. The minimum annual potential evapotranspiration of the study

watershed is 1263 mm, the mean annual is 2455 mm, and the maximum annual is 3019 mm).

Table 2. Sub-basin mean annual precipitation and potential evapotranspiration.

Tributary/Sub-basin	Subbasin Mean annual		Mean annual potential
	Number	Precipitation (mm)	Evapotranspiration (mm)
Gestro	1	542	2243
Genale 2	2	809	2090
Genale 2	3	825	2090
Genale 1	4	1361	1263
Genale 2	5	994	2090
Dawa	6	906	1881
Dawa	7	815	1881
Dawa	8	690	1881
Southeast Sub-basin	9	266	2891
Southeast Sub-basins	10	266	2891
Dawa	11	581	2367
Lower Sub-basin	12	501	2869
Lower Sub-basin	13	314	2839
Dawa	14	704	2367
Dawa	15	704	2367
Genale 2	16	824	2090
Genale 1	17	673	2310
Dawa	18	537	2367
Genale 2	19	225	2597
Genale 2	20	236	2597
Genale 2	21	236	2870
Genale 2	22	236	2870
Lower Sub-basin	23	236	2870
Lower Sub-basin	24	254	3019
Lower Sub-basin	25	254	3019
Lower Sub-basin	26	411	2838
Lower Sub-basin	27	411	2838

4. HSPF Model Performance Evaluation

HSPF simulates surface runoff, subsurface lateral flow known as inter-flow out-flow, and baseflow [14]. Surface runoff is generated if the soil storage capacity is limited relative to the amount of precipitation input or if the soil infiltration rate is limited relative to the rainfall intensity. HSPF simulates both storage capacity-

limited and the infiltration rate-limited runoff generation processes. The dominant HSPF parameters that control surface runoff generation are LZSN, INFILT, AGWRC, DEEPFR, and UZSN (Table 3). Specifically, INFILT has a strong influence on flow magnitude, timing, and hydrograph shape. LZSN and UZSN are storage capacity parameters that set the threshold surface and subsurface storage capacities. These parameters determine runoff initiation time and surface runoff magnitude. IRC and INTFW control subsurface lateral flow processes. DEEPFR, AGWRC, LZETP, and BASETTP control the hydrograph shape.

Table 3. HSPF calibrated parameters and their values.

Parameters	LZSN	INFILT	UZSN	IRC	INTFW	AGWRC	DEEPFR	BASETTP	LZETP
Units	mm	mm/hr	mm	Per Day	none	Per Day	none	none	none
Subbasin									
1	216	14.2	10	0.9	2.75	0.78	0.3	0.01	0.01
2	216	14.2	10	0.9	2.75	0.97	0.3	0.01	0.01
3	216	14.2	10	0.9	2.75	0.97	0.3	0.01	0.01
4	216	14.2	7.6	0.9	2.75	0.97	0.3	0.01	0.01
5	216	14.2	10	0.9	2.75	0.97	0.3	0.01	0.01
6	216	14.2	10	0.9	2.75	0.97	0.3	0.01	0.01
7	216	14.2	10	0.9	2.75	0.97	0.3	0.01	0.01
8	216	14.2	10	0.9	2.75	0.97	0.3	0.01	0.01
9	165	13.0	10	0.9	2.75	0.80	0.3	0.01	0.01
10	165	13.0	10	0.9	2.75	0.80	0.3	0.01	0.01
11	216	14.2	10	0.9	2.75	0.90	0.3	0.01	0.01
12	165	14.2	10	0.9	2.75	0.78	0.3	0.01	0.01
13	165	14.2	10	0.9	2.75	0.78	0.3	0.01	0.01
14	216	12.6	10	0.9	2.75	0.96	0.3	0.01	0.01
15	165	14.2	10	0.9	2.75	0.96	0.3	0.01	0.01
16	216	14.2	10	0.9	2.75	0.97	0.3	0.01	0.01
17	216	14.2	10	0.9	2.75	0.94	0.3	0.01	0.01
18	216	13.0	10	0.9	2.75	0.88	0.3	0.01	0.01
19	216	13.0	10	0.9	2.75	0.88	0.3	0.01	0.01
20	216	13.0	10	0.9	2.75	0.78	0.3	0.01	0.01
21	216	13.0	10	0.9	2.75	0.78	0.3	0.01	0.01
22	114	13.0	10	0.9	2.75	0.78	0.3	0.01	0.01
23	114	13.0	10	0.9	2.75	0.78	0.3	0.01	0.01
24	216	14.2	10	0.9	2.75	0.78	0.3	0.01	0.01
25	216	14.2	10	0.9	2.75	0.78	0.3	0.01	0.01
26	216	14.2	10	0.9	2.75	0.78	0.3	0.01	0.01
27	63.5	14.2	10	0.9	2.75	0.68	0.3	0.01	0.01

LZSN (lower zone storage nominal), INFILT (index to infiltration), UZSN (upper zone storage nominal), IRC (interflow recession), INTFW (interflow), GRWRC (ground water recession rate), DEEPFR (fraction of groundwater inflow that goes to inactive groundwater), BASETP (fraction of potential evapotranspiration), LZETP (fraction of remaining potential evapotranspiration)

4.1. Model Calibration and Validation

Model calibration and validation are iterative model parametrization procedures required to ensure that the simulated flows closely match the observed flows both in magnitude and time sequence. Data from gauging stations in Chenemasa (Ethiopia) and Baardheere (Somalia) were used for model calibration and validation.

4.2. Model Calibration and Validation with Monthly Flows from the Chenemasa Station (Ethiopia)

Monthly flow data from the Chenemasa gauging station of the Genale 1 tributary was used for model calibration and validation. The model was calibrated with monthly flows from 1984 through 1988. The calibration performance ratings for PBIAS, R^2 , and NSE were 0.5, 0.76, and 0.76, respectively. The PBIAS, R^2 , and NSE values correspond to very good, good, and good ratings, respectively. The model was validated with data from 1999 through 2002 (**Figure 4(a)**, **Figure 4(b)**). The validation performance ratings for PBIAS, R^2 , and NSE were 6.35, 0.73, and 0.73, respectively. The PBIAS, R^2 , and NSE values correspond to very good, good, and good ratings, respectively.

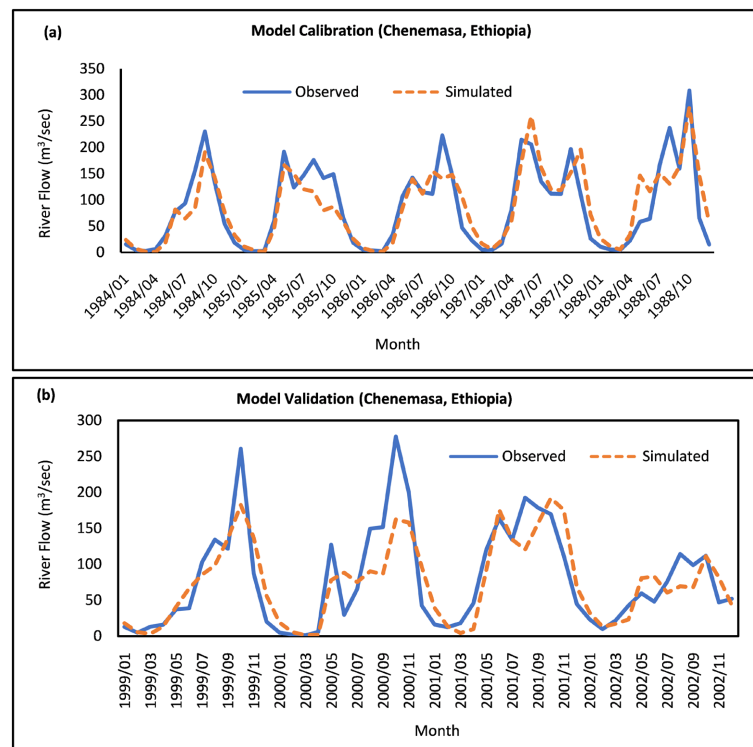


Figure 4. (a), (b) Model calibration and validation at Chenemasa, Ethiopia.

4.3. Model Calibration and Validation with Daily Flow Data from the Baardheere Station (Somalia)

The model was calibrated with 1986 through 1987 daily flow data, which corresponds to a period when the Baardheere station had superior quality observed flow data. The calibration performance ratings for PBIAS, R2, and NSE were -6.0, 0.77, and 0.76, respectively. The PBIAS, R2, and NSE values correspond to very good, good, and good ratings, respectively. The model was validated with 2006 through 2007 daily flow data (Figure 5(a), Figure 5(b)). The validation performance ratings for PBIAS, R2, and NSE were 7.0, 0.7, and 0.57, respectively. The PBIAS, R2, and NSE values correspond to very good, good, and satisfactory ratings, respectively.

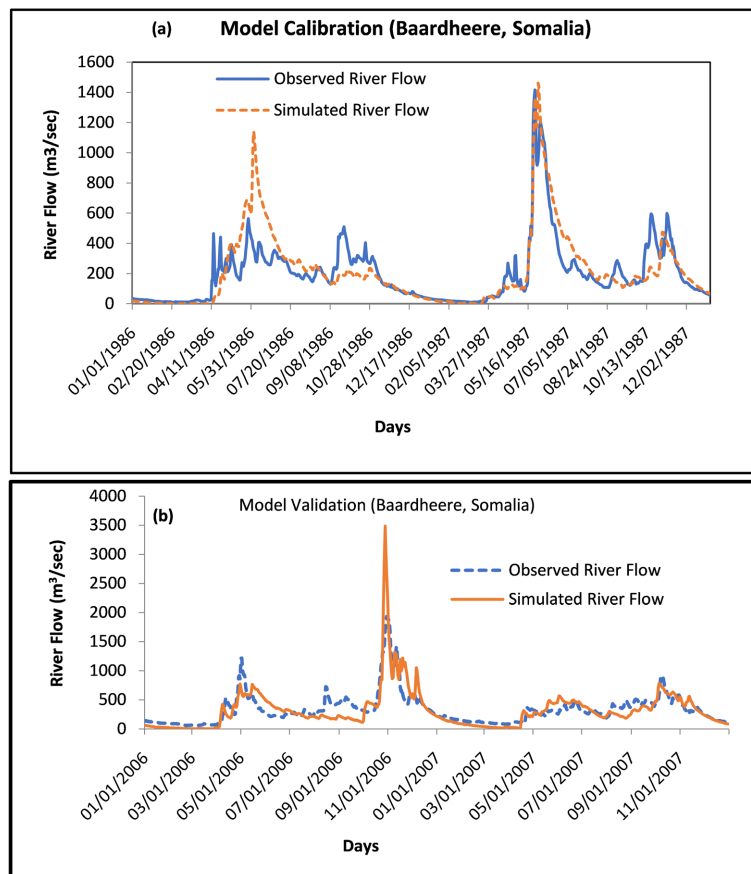


Figure 5. (a) and (b) comparisons of daily observed and simulated flows for model calibration and model validation.

5. Model Calibration

5.1. Mean Annual Flows of the Four Main Tributaries of the Juba River Basin

The model established the flow contributions of the four major tributaries of the Juba River basin and other small sub-basins of the study watershed. Before this study, relative flow contributions of the four major tributaries of the Juba River

were unavailable to Somalia. The model found that 93% of the flow at Baardheere is contributed by Genale 1, Genale 2, Dawa, and Gestro. The model simulated the relative flow contributions of Genale 1, Genale 2, Dawa, and Gestro as 47%, 21%, 22%, and 3% of the annual mean flow at Baardheere, respectively (**Table 4**). Genale 1 tributary where the GD-3 dam is located has higher flow than Genale 2, Dawa, and Gestro combined. **Table 4** shows the mean annual flow contributions of the Juba River tributaries and sub-basins.

Table 4. Mean annual flow tributaries and selected subbasins.

Tributary & Sub-basins	Mean annual flow (m ³ /sec)	Percent of mean annual flow
Genale 1	103.0	47.0
Genale 2	46.00	21.0
Dawa	49.00	22.0
Gestro	7.000	3.00
Sub-basin 9 and 10	0.000	0.00
Sub-basins within Somalia	15.00	7.00

5.2. Mean Annual Flow Contributions outside the Four Main Tributaries

Sub-basins 9 and 10, which are not part of the four major tributaries, are located to the southeast of the study watershed and near the Somalia and Ethiopia border. Sub-basin 9 predominantly lies in Ethiopia, whereas sub-basin 10 partially lies in Ethiopia and partially in Somalia. The portion of the two sub-basins that lie in Ethiopia has an area of 15,507 km², which is equivalent to 8% of the study watershed. The two sub-basins have low precipitation and high potential evapotranspiration (**Table 2**). The mean annual flow contributions from these sub-basins are less than 1 m³/sec. The area of the study watershed that lies in Somalia is about 42,317 km², which corresponds to about 21% of the study watershed area. The mean annual flow contribution from within Somalia is 15.5 m³/sec, which corresponds to 7% of the mean annual flow at Baardheere.

5.3. Data Quality Considerations for Transboundary Agreements

Establishing transboundary agreements among riparian countries requires accurate daily flow data that spans over 20 years. The simulated daily flow of the Juba River basin data spans 39 years and covers periods with severe droughts and periods with severe floods. Data measured on the Juba River basin have serious data quality that include periods with poor quality data and periods with missing data. Disparities in data quality among the riparian states can be a source of mistrust for transboundary negotiations. An alternative solution using measured flow data is to use simulated data whereby each country uses the same model and same model input data for the entire river basin. River flow data collected by the riparian countries must be subjected to rigorous quality control and should be used for

model calibration and validation. The study established the naturalized flow of the Juba River at Baardheere by reconstructing 39-years of daily flow data. These flows establish a baseline with which climate change, upstream consumptive water uses, GD 3 dam, and GD 6 dam impacts on downstream water availability are evaluated.

5.4. Comparison of Observed and Simulated Daily Flow Data at Baardheere, Somalia

Simulated data is needed for establishing low flow indices and flood frequencies for the Juba River at Baardheere under naturalized conditions (conditions without dams and consumptive water uses). The reconstructed data establishes low flow indices and flood frequencies for the Juba River at Baardheere. The reconstructed data establishes a baseline condition that does not consider the presence of the GD-3 dam, the proposed GD 6 dam, and upstream consumptive water uses [15]. The flow duration curve (FDC) of the 39-year reconstructed flows has the following exceedances and their corresponding flows (5%, 585 m³/sec), (30%, 242 m³/sec), (50%, 150 m³/sec), (70%, 70 m³/sec), (95%, 3 m³/sec) (Figure 6). The reconstructed data establishes the expected flows under the naturalized condition of the watershed.

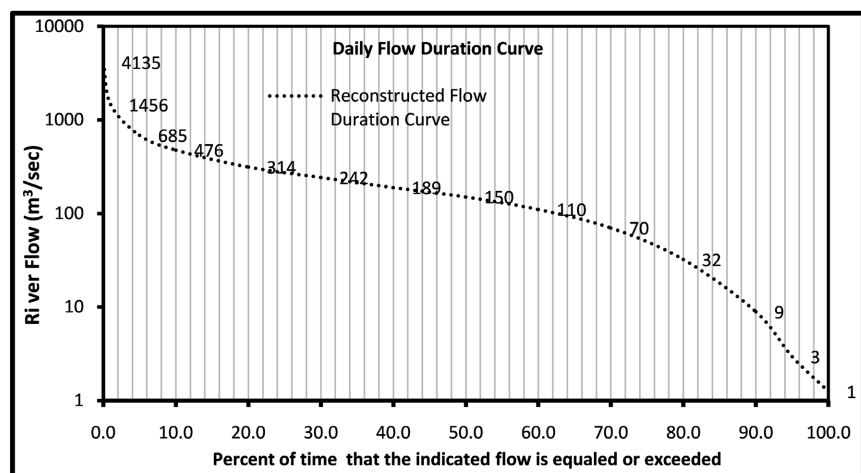


Figure 6. Daily flow duration curves at the Baardheere Bridge.

6. Juba River Basin

6.1. Low Flow Indices of Juba River Basin

The CHIRPS satellite precipitation model input data identified the following drought years (1984, 1991, 1999, 2000, 2002, 2009, and 2014) for the Juba River basin. The minimum observed and simulated daily flows at the Baardheere gauging station were 0.68 m³/sec and 1.25 m³/sec, respectively. The minimum historical observed daily flow was recorded on March 12, 1981, and the minimum simulated flow was recorded on April 13, 1986. Baseflow index, 7Q10, Q95, and R-B flashiness indices were calculated. The baseflow indices were calculated from the

39-year reconstructed data at Baardheere. Baseflow index is defined as the ratio of long-term baseflow to the total flow [16]. The baseflow index was estimated at 0.76 m³/sec. 7Q10 is the annual minimum 7-day average flow with a 10-year recurrence interval [17]. The 7Q10 was 1.86 m³/sec. Q95 is the flow equaled or exceeded 95 percent of the time. The estimated Q95 was 3.0 m³/sec. The R-B flashiness index calculates changes in short-term daily flows relative to average yearly flows [18]. The R-B flashiness index was 0.065. The four low flow indices establish baseline conditions for the impacts of future upstream water abstractions in Ethiopia.

6.2. Model-Simulated Flood Frequencies at Baardheere, Somalia

This study shows comparison of model-simulated flows at Baadheree bridge in Somalia. Model results revealed that floods observed at Baardheere originated from the Beled-Hawa-Garbaharey and Rub Dhuure-Wajid areas in Somalia. The model identified flood periods as 1981, 1989, 1997, 2006, 2011, 2013, and 2018. Because of the river's low bank elevation at the Baardheere bridge, the Juba River overflows most of the rainy seasons. As such, observed flood magnitude data measured at Baardheere are deemed unreliable. Using 39-year simulated data, this study established a relationship between flood magnitudes and corresponding return periods.

Equation A expresses flood magnitudes as a function of the return period. Conversely, Equation B, converts flood magnitudes to return periods when the flood magnitudes are known. Using Equation B, the flood magnitudes were converted to return periods. The 2011 flood magnitude of 2500 m³/sec corresponds to a return period of once every 13 years. The 2018 flood magnitude of 2567 m³/sec corresponds to a return period of once every 14 years. The 2016 flood magnitude of 3398 m³/sec corresponds to a return period of once every 29 years. The flood magnitude of the Juba River in 1981 flood magnitude was estimated at 3710 m³/sec and corresponded to a return period of once every 39 years. The 1997 flood magnitude of 4135 m³/sec corresponds to a return period of once every 58 years. The flood frequency method used is based on bulletin 17-C three-parameter log-Pearson distribution [19] [20].

7. Summary and Conclusions

This study develops a watershed model for the Juba River basin using the Hydrologic Simulation Program Fortran (HSPF) and freely available satellite data products. Model input products selected are the CHIRPS daily precipitation and MERRA-2 potential evapotranspiration. The model simulated 39 years of daily flow data that spans from January 1, 1981, to December 31, 2019. The study established baseline low flow indices and flood frequencies for the Juba River basin under naturalized daily flows of the Juba River basin. Comparisons of observed and simulated data from Chenemasa in Ethiopia and Baardheere in Somalia gave model performance ranging from very good, good, and acceptable. By applying

models, geographic information systems (GIS), freely available global satellite data, poor countries with limited financial resources and technical skills can follow the procedures presented in this study for river basin management and transboundary agreements among riparian countries. Although satellite data applications are readily available tools that facilitate transboundary cooperation among riparian countries, data-sharing among riparian countries is the only solution to achieve transboundary agreements in Africa. Given the technical and the financial challenges facing many countries in Africa, the authors strongly believe that model applications can be an effective river basin management tool for large river basins. In the absence of transboundary cooperation among riparian countries in Africa, watershed modeling applications using readily available satellite data products can facilitate data exchanges among riparian countries. If each riparian country conducts its separate modeling study on the entire river basins, data exchanges and negotiations towards transboundary agreements can be reached.

Transboundary countries in Africa have challenges in achieving transboundary agreements. The main factors restricting cooperation among riparian countries are lack of data availability and data-sharing. Upstream riparian countries often assume full river water ownership and do not see any benefit in transboundary cooperation with downstream riparian states. Methods presented in this paper use readily available global satellite data products and freely downloadable river basin modeling tools that simulate daily river flow at user-specified sites. The Juba River basin model presented herein, which covers the entire river basin was developed for Somalia. Data-sharing and transboundary cooperation among riparian countries can be achieved when each riparian country develops models of the entire river basin. Transboundary agreements among riparian countries cannot be reached when one riparian country has river flow data measured at selected sites of the river basin and the other riparian countries have no river flow data. The paper outlines technologies needed to manage transboundary river basins in Africa. Given the complexity of the modeling approach and the extensive data requirements, the authors foresee a need for extensive training by would-be tool users.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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