

Assessing Hydrological Impacts through Scenario-Based Modelling in the Bahr El Jebel Basin, South Sudan

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Abstract

The Bahr El Jebel Basin, one of the major Nile sub-basins, is a hydrologically complex system created by the extensive Sudd Wetland. It has high climatic variability, low river gradient, and high evapotranspiration. Water availability and flow stability remain at risk from continued increasing demands under climatic, land use, and population change and are leading to questions about long-term sustainability of basin operations. This research is based on a simulation scenario approach using the RIBASIM model to evaluate hydrological responses under a range of forecasting conditions. The assessment highlights the sensitivity of the basin and its implications for sustainable water management by focusing on the variations in the river discharge, wetland water balance and evapotranspiration losses. Results show that climate change is the dominant driver of hydrological variability in the Bahr El Jebel Basin. The Climate Change (+5%) scenario is the highest discharge scenario with the highest increases in the wet-season between July and October of around 25% of the discharge, indicating higher flood risk. Development scenarios involving hydropower expansion, agricultural growth, and population increase yield smaller net increases in discharge (1.5–5%), as water abstractions partially offset the effects of climate change. In contrast, the combined Development–Climate Decrease (–5%) scenario results in an annual discharge reduction of about 3.8%. The effects of climate change outweigh those of development, suggesting a highly sensitive response and enabling further growth. It has a relatively moderate hydrologic response in poor conditions, suggesting opportunities that can be achieved while maintaining environmental protection.

Keywords: Bahr El Jebel Basin; RIBASIM; Hydrological modelling; Climate change Scenarios; Water resources management; Sudd Wetland

1. Introduction

The Bahr El Jebel Basin is one of the most critical, strategic, and hydrologically important sub-basins of the Nile Basin's system due to its extensive wetlands, complex rainfall–runoff processes, and strong hydroclimatic variability. The Bahr El Jebel River flows out of Lake Albert at the extreme north corner of the lake under the name of the Upper White Nile River or Bahr El Jebel Basin. From the outlet of Lake Albert down to the city of Nimule, 225 km downstream, Bahr El Jebel River is rather broad, sluggish, stream fringed with swamps and lagoons. The area occupied by swamps and open water is estimated at 40,000 km², making the Bahr El Jebel Basin one of the most critical and strategic, as well as hydrologically important, sub-basins of the Nile Basin's system. Its large wetlands, intricate rainfall-runoffs, and high climatic variability make it especially susceptible to climate change. The

growing water demands of upstream and downstream riparian states, along with changes in climatic conditions and land-use trends, have gradually made the basin increasingly vulnerable over the past few decades. These changing circumstances highlight the need for reliable, scientifically based scenarios to forecast hydrological responses across a range of likely future conditions (Nkwasa et al., 2024).

Previous studies on the Bahr El Jebel Basin –Sudd Wetland have largely focused on specific aspects of the basin, including water balance estimation and the hydrological implications of wetland losses and canal diversion (Kudagama et al., 2025), spatial variability of evaporation and moisture storage using remote sensing techniques, and the hydroclimatic role of the Sudd Wetland in regional moisture recycling and flow regulation (Mohamed et al., 2005). Other studies examined floodplain morphology, mechanisms of flooding and drying, and seasonal inundation dynamics along the Bahr El Jebel Basin and within the Sudd Wetland (Petersen and Fohrer, 2010; Rebelo et al., 2012). More recent research has addressed long-term hydroclimatic variability and the influence of climate change on the Sudd Wetland (Mohamed and Savenije, 2014; Zeleke et al., 2024), while satellite-based hydrological modelling studies have also attempted to improve understanding of wetland hydrology under data-scarce conditions (Di Vittorio and Georgakakos, 2021). Although these are significant contributions, the literature remains limited and scattered, with the majority of studies focusing on historical hydrology, inundation of wetlands, evaporation or climate variability, but none of these studies were able to assess their combined effects in an integrated framework of scenario-based analysis in the Bahr El Jebel Basin. In addition, limited observational data, uncertainty in wetland processes, and sparse gauging networks continue to constrain basin-scale hydrological assessment. Therefore, there is still a clear need for scientifically based scenario analysis to forecast hydrological responses under future climate and development pressures in the Bahr El Jebel Basin.

This study fills a clear gap in the previous studies by offering an integrated, model-based assessment of the Bahr El Jebel Basin under combined climate and development scenarios. Although earlier studies have described the hydrological significance of the basin and the vulnerability of the Sudd Wetland system, few have quantified how future changes in climate and water resources development may jointly affect flow behaviour, wetland losses, and downstream water availability in this specific sub-basin. The present study adds to the literature by applying a scenario-based modelling approach to evaluate basin responses under a range of plausible future conditions, thereby providing a more systematic understanding of hydrological sensitivity and uncertainty. The novelty of this work is that its emphasis on the Bahr El Jebel Basin as a unique and highly strategic Nile sub-basin, and its production of evidence relevant to decisions that can assist in adaptive planning, basin management, and inter-regional water cooperation.

Although the Bahr El Jebel Basin is hydrologically significant, the understanding of its potential response to the cumulative impacts of climate change, land-cover change, and future interventions is limited. This knowledge gap creates uncertainty for water resources planning, climate-resilient management, and transboundary decision-making in the Nile Basin. To address this gap, the present study applies the RIBASIM model within a scenario-based simulation framework to assess the hydrological response of the Bahr El Jebel Basin under a range of plausible future conditions. The main objective of the current study is to quantify the impacts of these drivers on catchment water balance, river basin flows, and overall system behavior.

More specifically, the study aims to: (i) simulate the hydrological behavior of the basin under alternative future scenarios; (ii) evaluate the effects of climate, land-surface, and development changes on water availability and flow regimes; and (iii) identify the main hydrological risks and management implications for sustainable and cooperative water resources planning. In this respect, the previous studies adopt an integrated scenario-based modelling approach to support water resources assessment and decision-making in the Nile Basin, discharges upstream of Lake Nasser and assess climate change impacts, the present study extends this approach to the Bahr El Jebel Basin by explicitly examining the

combined effects of climate change, land-cover change, and development interventions at the sub-basin scale (Booij et al., 2011).

2. The Study Area

There is an exceptionally low gradient along Bahr El Jebel Basin between Nimule and Malakal, as shown in Fig. 1, reflecting its wandering through the expansive Sudd Wetland. Along the riverbed, the elevation at Nimule (620 m above sea level) to that at Monglla (460 m) increases over a distance of some 200 km. A relatively steep gradient in the upstream reach, which increased the flow (Sutcliffe and Parks, 1999).

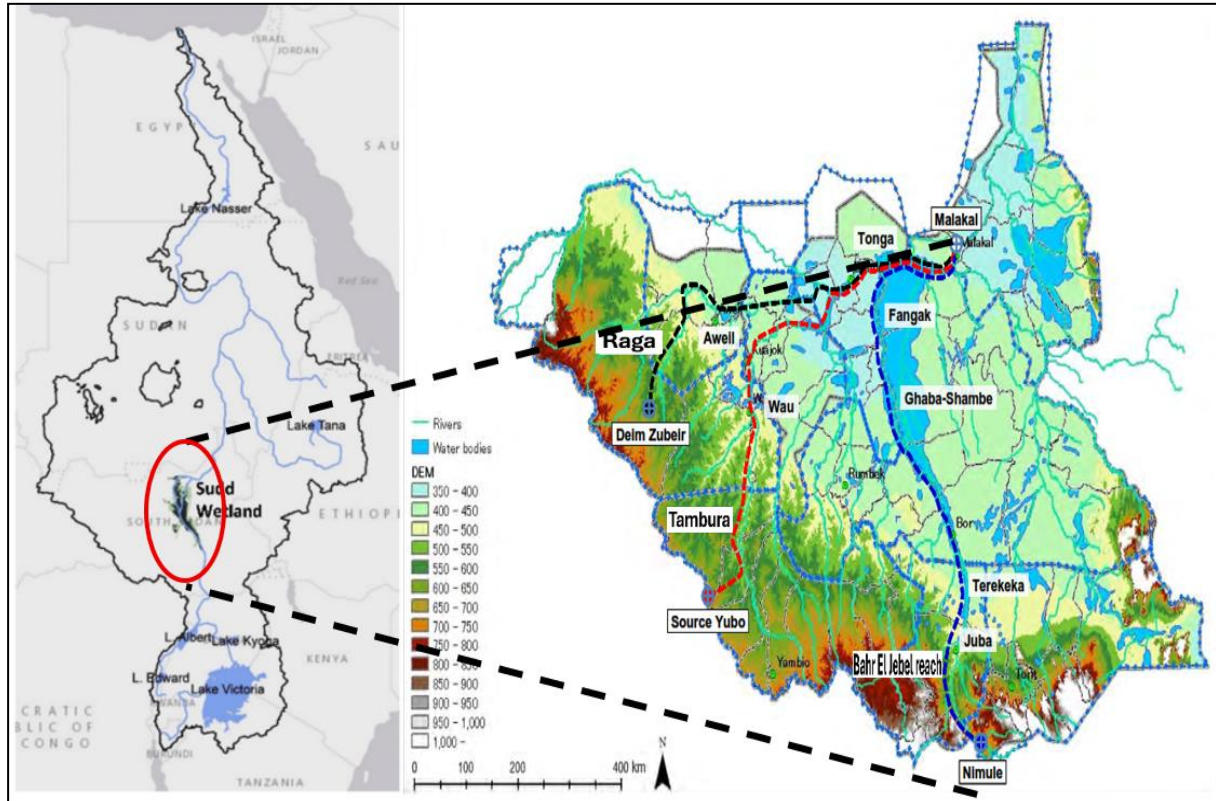


Fig. 1. Location of the Bahr El Jebel Basin in the Nile River's Basin (MEDIWR, 2015)

Below the Monglla, where the Bahr El Jebel River drains into the Sudd Wetland, the longitudinal gradient becomes very flat. The total decline in elevation, over a distance of above 500 km (Mongella to Malakal), is about (30-40) m (Sutcliffe and Parks, 1999). The very low gradient, combined with thick water cover and large floodplains, causes prolonged flooding, widespread water spread, and significant diminution of streamflow. Consequently, the Hydrodynamics of this segment are controlled by the Sudd Wetland, which serve as an important natural storage basin through which the river basin discharge is accumulated, rechanneled, and significantly reduced by evaporation and evapotranspiration.

The Digital Elevation Model (DEM) of the Bahr El Jebel Basin (Fig. 1) shows that the area, particularly across the Sudd Wetland, is characterized by very flat topography with only slight elevation differences over a wide extent. The low relief of the land present the surface is very gentle, revealing an overall low gradient, with water moving more slowly than usual, encouraging the spread of water beyond the riverbed. This causes the region to be characterized by large wetlands, swamps and floodplain areas. This flat and poorly drained terrain is one of the main physical features controlling the hydrological behavior of the Bahr El Jebel Basin.

The Bahr El Jebel Basin has a capacity of 1350 m³/sec. Flows that are above this value are expected to end up in the Sudd Wetland. The assumption is that about 50% of the volumetric flow is wasted by evapotranspiration, with the remaining 50% used downstream along the White Nile River. It is therefore

believed that approximately 50% of the Bahr El Jebel Basin water flows to the Sudd Wetland outlet leading to the White Nile River. The percentage drops during periods of increased precipitation and rises during droughts. (Sutcliffe and Parks, 1999)

Depending on the definition of what is considered part of the (wet area of) the swamp, the average surface area is approximately 40000 km², with fluctuations depending on the discharge of the Bahr El Jebel Basin. The wetland area expands more than 4 times the size of the permanent swamps in response to seasonal flooding (Mohamed and Savenije, 2014). It is noted that the area of the permanent swamps has tripled after the large increase in Bahr El Jebel River's flows of the early 1960's, which doubled the average annual inflow into the wetland as compared to the condition before 1963 (Sutcliffe and Parks, 1999).

Rainfall over the Sudd Wetland (from April to November) varies from about 900 mm/yr in the south to 800 mm/yr in the north. The temperatures average between 30-33°C during the hot season, dropping to 18°C in the winter. For a more extensive description, the average flow in the Bahr El Jebel Basin over the period 1900-2002 is 1,130 m³/sec. The lowest average flows occur in March (930 m³/sec); the highest is in September (1854 m³/sec) (Mohamed et al., 2005).

Scientific studies of evapotranspiration in the Sudd Wetland are not new, as estimates were documented in the first half of the twentieth century, with significant variability observed. Initial experimental studies, mainly focused on measuring water losses from papyrus vegetation through tank tests, yielded a wide range of annual evapotranspiration rates, ranging from about 1533 to mm (Sutcliffe and Parks, 1999). In more recent times, Wilusz et al. (2017) used surface-energy balance models based on satellite data and data recorded at meteorological stations to derive annual evapotranspiration estimates of 1210 -1636 mm.

Evapotranspiration in the Sudd Wetland has been the subject of investigation since the early 1900s, with reported estimates exhibiting substantial variability. Early experimental studies primarily measured water losses from papyrus vegetation using tank experiments, resulting in a wide range of annual evapotranspiration rates, from approximately 1533 mm to 2760 mm (Sutcliffe and Parks, 1999). More recently, some studies applied surface energy balance models informed by satellite observations and meteorological station data, deriving annual evapotranspiration estimates from 1636 mm to 1210 mm (Wilusz et al., 2017).

Since the Sudd Wetland are extensive and seasonally fluctuate, the volumetric rate of water loss per year is 13-15 BCM. This extent of loss provides a hydrological explanation for the significant reduction in discharge between Nimule and Malakal, which underscores the importance of the Sudd Wetland as a major sink in the Nile River's Basin (Fig. 1) (Nile Basin Initiative, 2022).

The agricultural system in the study region is mostly subsistence-based and influenced by the Bahr El Jebel river's seasonal rainfall. In rain-fed areas, farmers grow "sorghum, maize, millet, and sesame" on elevated areas outside the floodplain and utilize the winter and summer rains in the region, with minimal flooding. The topographic center of the farming area, however, is the flood-recession cultivation, or so-called locally "toich". In this case, the Bahr El Jebel River banks indicate fertile, moisture-rich soils after each year of flooding, making them a good nursery for crops, particularly "sorghum". Inside the main channel of the river basin and its branches, a small variety of vegetables and fruits also grows on the farm, and they utilize the intermittent water flow. Some areas, namely "Mangalla, Aweil", the eastern plains, and the "Fula Rapids" in the vicinity of "Nimule", were selected for development into irrigated farming. However, this potential remains underexploited and has been frustrated by a long-standing conflict, the lack of infrastructure, and institutional challenges that have hindered development (FAO, 2015).

South Sudan has one of the highest population growth rates in the world, mainly due to extremely high fertility rates, with crude birth rates exceeding 40 births per 1,000 people. Though mortality rates are relatively high, the total annual population growth rate is estimated to be between 2.7 and 3.3%, and

this is adding pressure on land, water, and food security, particularly in riverine areas of the Bahr El Jebel Basin, as a result of this accelerated demographic growth (UNDESA, 2022).

3. Methodology

3.1. Model Framework

This study applies the River Basin Simulation Model (RIBASIM) to evaluate the hydrological behavior of the Bahr El Jebel Basin under Baseline and future scenario conditions. RIBASIM is a node-link, process-based river basin model that simulates water allocation, flow routing, storage dynamics, and water demands according to predefined operating rules and physical system characteristics. The model schematization was developed to represent the main hydrological features of the Bahr El Jebel Basin between Nimule and Malakal, including the main course, wetland storage areas, tributary inflows, irrigation abstractions, and proposed hydraulic infrastructure.

3.2. RIBASIM Description and Model Capability

The RIBASIM model was chosen to simulate surface water flows and distribution, taking into consideration competing water users (irrigation, domestic supply, hydropower generation, and environmental flow requirements). It is controlled by rule-based allocation procedures that create water-use priorities aligned with set management goals and institutional frameworks, thereby highlighting its applicability to complex and transboundary river basin settings (Loucks and van Beek, 2017).

In the case of river-basin systems that exhibit strong seasonal variability, e.g., the Bahr El Jebel Basin, a large area of wetlands, and are highly sensitive to changes in climate and development pressures, scenario modelling becomes a critical tool for assessing future hydrological conditions. In this framework, RIBASIM enables the evaluation of the consequences of changes in inflow regimes, water requirements, and upstream regulatory interventions on downstream flow controls, and more generally, basin water availability. The brief yet comprehensive representation of hydrological and managerial processes in the model makes it particularly appropriate for strategic-scale studies of the White Nile River's system, especially in data-limited regions (Conway, 2005).

The suitability of RIBASIM for basin-scale hydrological and water-resources analysis has been demonstrated in several complex river basins in Asia. In the Ganga Basin in India, Van der Vat et al. (2019) applied RIBASIM within an integrated and participatory modelling framework that combined hydrology, groundwater, water resources management, water quality, and ecology, showing that the model can support strategic basin planning in a large and highly complex river system.

Similarly, in the Zarrineh Rood Basin in Iran, Ahmadzadeh et al. (2022) coupled SWAT with RIBASIM to assess water-supply reliability under climate change and operational water-project scenarios, demonstrating that RIBASIM can effectively translate hydrological changes into water-allocation and management outcomes.

In addition, Basco-Carrera et al. (2017) demonstrated, through an application in the Pemali Comal River Basin in Indonesia, that collaborative modelling using RIBASIM can improve informed decision-making and support inclusive basin planning.

Together, these studies indicate that RIBASIM has been successfully used in Asian rivers' basins to simulate hydrological responses, evaluate water allocation under changing conditions, and support basin-scale planning under uncertainty.

Schematization of RIBASIM

The RIBASIM schematization represents the main elements of a river basin as a network of links and nodes. Van der Krogt (2019) argued that the model schematization involves converting and simplifying conditions in the real-world basin into a structured representation that can be simulated

directly. Therefore, the network of nodes and connections captures the spatial arrangement of basin components and integrates data describing their physical and functional characteristics. In this model structure, the nodes represent important hydraulic and water-management features, including reservoirs, dams, weirs, pumping stations, hydropower installations, water-demand centers, inflow points, natural and artificial bifurcations, intake structures, and natural lakes. The conduits that convey water between nodes are represented by links, allowing the simulation of water movement throughout the basin system.

3.3. Schematization of Bahr El Jebel Basin

In the current research, the Bahr El Jebel Basin is conceptualized on the section of the Nile River that flows to Malakal, starting at Lake Victoria. This conceptualization was developed by RIBASIM interactively on a georeferenced map of the study area. The basin is conceptualized as a network of nodes interrelated through branches, thereby describing the major hydrological and hydraulic factors that affect the water balance over this extent. The nodes in the selected reach will be the basin constituents of interest, including the outflows of Lake Victoria, natural river reaches, and swamps that are part of the Sudd Wetland, natural bifurcations, water abstraction points, and other hydraulic or water-use components where available. Branches are associated with the river basin channels that carry water between the nodes, and, as a result, flow routing and water distribution through the Bahr El Jebel Basin between upstream and downstream are simulated.

The conceptualized network captures the basin characteristics relevant to the surface-water balance of the Lake Victoria-Malakal reach. It is designed to provide a level of detail that is reasonable for the assessment. The Bahr El Jebel basin is represented as a map, with the conceptualization of the RIBASIM network overlaid as a separate layer. The background map is created using a Geographic Information System, and the attribute data for the network items are entered interactively and linked to the basin's spatial model. Checks for data consistency are also built into the conceptualization process to establish coherence between the spatial and attribute data, as shown in Fig. 2.

The basin schematization for the study area in RIBASIM was developed using a network of 21 nodes, as shown in Fig. 2, representing the main hydrological and water-use components of the Bahr El Jebel Basin –Sudd Wetland. These nodes were identified based on their hydrological and functional importance in the model and this is comprised confluences, irrigation nodes, public water supply nodes, potential reservoirs, swamp storages, and variable inflow nodes. The distribution of node types used in the model is summarized in Table 1.

3.4. Input Data and Model Setup Parameters

The model input data were obtained from the basin reports and the institutional data collected from the Ministry of Water Resources and Irrigation (MoWRI) in Egypt. These sources included the major hydrological, climatic, topographical, and socio-economic characteristics of the Bahr El Jebel Basin and Sudd Wetland. The key factors that are affecting the basin behavior between Nimule and Malakal were identified such as inflow, rainfall, evapotranspiration, wetland storage, topographic slope, and water use as shown in Table 2.

The RIBASIM model was set-up to match the physical layout and operating conditions of the Bahr El Jebel basin system including specifying node–link relationships, inflow time series, rainfall and evaporation inputs, irrigation requirements, abstraction priorities, and operating rules for reservoirs and diversions. The uncertainty of input parameters was tested by conducting a sensitivity analysis using the main parameters: inflow, rainfall, evaporation and irrigation demand, by varying the parameters by $\pm 5\%$. The findings showed that although these variations altered the magnitude of flows, the system's overall hydrological behavior remained stable.

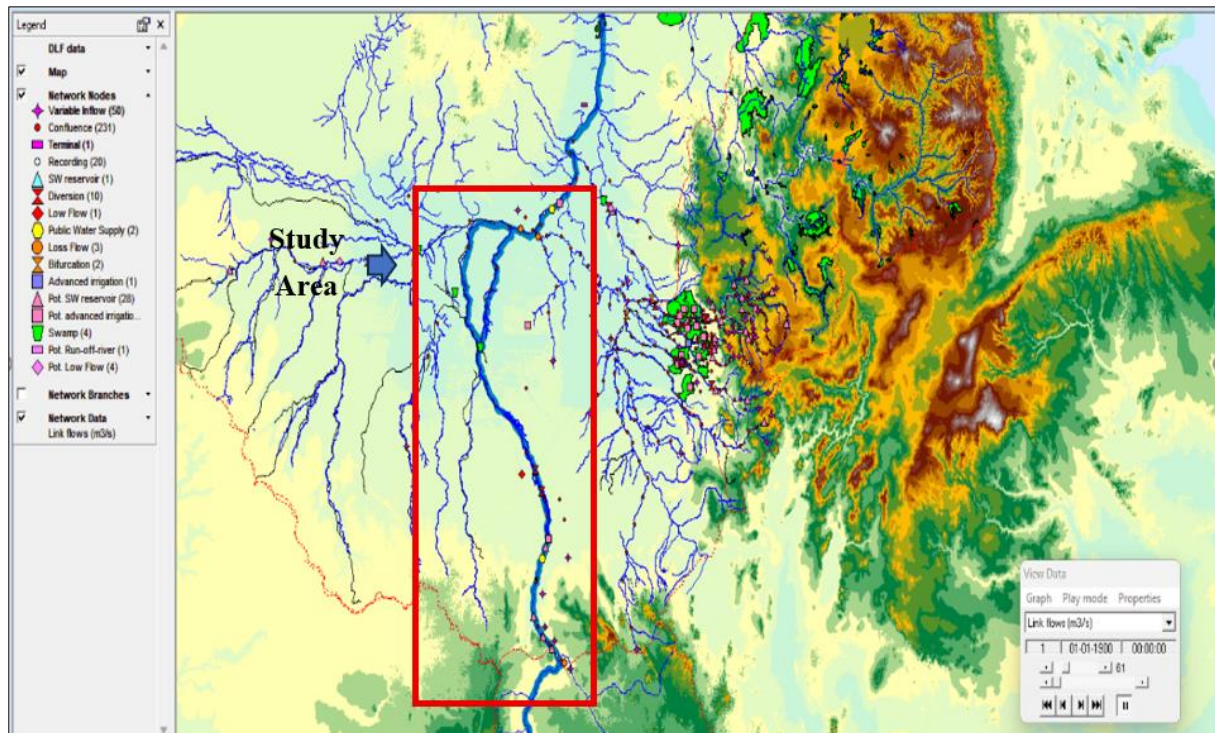


Fig. 2. River basin schematization of the Bahr El Jebel Basin

Table 1. Distribution of nodes used in the RIBASIM schematization of the Bahr El Jebel Basin

Node type	Number of nodes
Confluence	9
Potential advanced irrigation	2
Advanced irrigation	1
Public water supply	2
Potential reservoirs	4
Swamps	1
Variable inflow	2
Total	21

Table 2. Principal data sources and spatial coverage used in the analysis

Data category	Variable description	Spatial coverage
Hydrology	Average flow of the Bahr El Jebel Basin and seasonal discharge variations	Monthly averages (m ³ /sec); Bahr El Jebel Basin / Sudd Wetland, 1900–2002
Topography/river profile	Elevation and longitudinal gradient between Nimule, Mongalla, and Malakal	Static spatial information; Bahr El Jebel Basin
Climate	Rainfall distribution over the Sudd Wetland and Equatorial lakes Sub-basin	Seasonal/annual climatology; gradient across the Sudd Wetland and Equatorial lakes Sub-basin
Agriculture/irrigation	Existing and potential irrigated agriculture and development areas	Static/planning-based information: 1.83 million feddans (768.7 thousand hectares/Existing)
Public water supply/socioeconomic conditions	Main urban centres and population-related water demand pressure	Static/socioeconomic reference; Juba, Bor, Malakal and the surrounding corridor (About:1,400,000 Capita)
Reservoir operation rules	Operating rules for potential reservoirs	Assumption: applied at reservoir nodes within the study area (Table 5)

3.5. Boundary Conditions

The model boundaries in the RIBASIM were defined at the upstream and downstream limits of the Bahr El Jebel Basin between Nimule and Malakal. Upstream hydrological inputs were introduced through inflow boundary nodes using monthly time series, while the downstream boundary at Malakal was represented as the terminal outlet of the modelled system. This setup allowed the simulation of flow routing, storage in the wetland, and hydrological losses in the Sudd Wetland. Available data for discharge and water level time series are for the period 1900–2002, and are summarized in Table 3.

Table 3. Long-term discharge characteristics used for defining the model boundary conditions

Boundary location	Discharge characteristic	Unit	Value
Nimule (upstream boundary)	Minimum inflow	m ³ /s	930
Nimule (upstream boundary)	Maximum inflow	m ³ /s	2590
Malakal (downstream boundary)	Minimum outflow	m ³ /s	619
Malakal (downstream boundary)	Maximum outflow	m ³ /s	2285

Calibration and validation of the RIBASIM model was done using observed discharge data from the Bahr El Jebel Basin, and Malakal was chosen as the main downstream control point. Calibration involved adjusting parameters for flow routing, wetland storage, and hydrological losses in the Sudd Wetland, and validation was performed by simulating an independent period. The model performance was evaluated by the Root Mean Square Error (RMSE) (Moriassi et al., 2015), the Nash–Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970), the coefficient of determination (R^2) (Moriassi et al., 2007) and by a visual comparison of the simulated and observed hydrographs.

The model contained four possible hydropower dams: Fulla, Shukoli, Lakki and Bedden. The Flood Control Level, Target Level and Firm Storage Level were used to represent their operating rules. The maximum operating levels ranged from 510.00 m to 622.00 m and minimum operating levels ranged from 504.00 m to 616.00 m as given in Table 5.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Q_{sim,i} - Q_{obs,i})^2} \quad (1)$$

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^n (Q_{obs,i} - \bar{Q}_{obs})^2} \quad (2)$$

$$R^2 = \frac{[\sum_{i=1}^n (Q_{obs,i} - \bar{Q}_{obs})(Q_{sim,i} - \bar{Q}_{sim})]^2}{\sum_{i=1}^n (Q_{obs,i} - \bar{Q}_{obs})^2 \sum_{i=1}^n (Q_{sim,i} - \bar{Q}_{sim})^2} \quad (3)$$

Agriculture in the study area is primarily rain-fed and supplemental irrigation is provided to some crops in the event of inadequate rainfall. For the model, agricultural water demand was 1800 m³/feddan/year (Assumption). Further, the annual per capita water consumption was assumed to be 60 m³/person/year to represent domestic water demand in the study area.

3.6. Simulated Scenarios

The simulation system was constructed based on the long-term hydrological record (1900-2002) for 103 years. The data is a combination of basic hydrometeorological data such as runoff, evaporation, evapotranspiration, rainfall, temperature, Digital Elevation Model (DEM) and other variables of interest describing the Bahr El Jebel River system from Lake Victoria to Malakal. This data set is sufficient enough to serve as a solid foundation for the assessment of hydrological variability and the long-term dynamics of the system.

Based on this historical compilation, a set of development-conditioned scenarios was developed to address potential future conditions in the Bahr El Jebel Basin. These scenarios represent various assumptions about water-resource development, future water demand growth, and water-resource management interventions in the basin. The assessment of both scenarios is done at 103-year projection horizon (from 2003 to 2105) to ensure methodological consistency in the long-term impact assessment and allow scenarios comparison. Within all of the development scenarios simulated, four were identified and analysed in detail. The chosen scenarios are to be used to summarize salient hydrological and management conditions along the study reach between Lake Victoria and Malakal.

3.6.1. Baseline scenario

The present situation is used as a base condition and is simulated in a continuous model run for 103 years. In this instance, the cultivated land in South Sudan is reported to be 4% of the country's land area (6.7 million feddans or 2.81 million hectares). The area currently cultivated in the Bahr El-Jebel Basin is estimated to be around 1.83 million feddan (768.7 thousand hectares) in the states of Jonglei, Unity and Lakes (World Bank, 2012). Besides agricultural water utilization, domestic and other human water utilization were included in the scenario.

The three states are estimated to have a total population of about 2.64 million, with almost half of the population concentrated in the Bahr El Jebel Basin which represent the location of the settlements along the river basin (National Bureau of Statistics of South Sudan, 2014).

Estimating population within the Bahr El Jebel Basin is challenging due to displacement, migration, and the absence of recent comprehensive censuses. However, there is some evidence that Bahr El Jebel River (Nimule – Malakal) is home to several million people, the majority of them are concentrated in the urban centers of Juba, Bor and Malakal. The three cities are estimated to have a population exceeding 1,400,000 inhabitants (World Bank, 2012).

3.6.2. Climate change (+5%) scenario

The Climate Change (+5%) scenario was formulated as a simplified sensitivity scenario rather than a deterministic climate projection derived from a specific regional or global climate model. The authors acknowledge that rainfall, open-water evaporation, and reference evapotranspiration do not necessarily change proportionally under future climate conditions, and that climate models may project non-uniform responses among these variables. Therefore, the uniform +5% adjustment was adopted as a controlled analytical perturbation to evaluate the sensitivity of the Bahr El Jebel Basin under moderately wetter and warmer conditions.

The rationale for this scenario is supported by regional climate studies indicating a tendency toward increasing rainfall and temperature in South Sudan and the wider Upper Nile/East African region. For South Sudan, Chen et al. (2013) projected increasing precipitation in most seasons, together with continued increases in maximum and minimum temperatures. Similarly, Nile Basin Initiative (NBI) climate projection bulletin reported a small increasing rainfall trend in the Sudd Wetland and Bahr El Ghazal Basin, while the Sudd Wetland showed the highest increasing temperature trend within South Sudan (Nile Basin Initiative, 2023). In addition, CMIP6-based projections for Uganda, an upstream and hydrologically relevant part of the Upper Nile River's system, indicated that both precipitation and potential evapotranspiration are generally projected to increase across water management zones (Onyutha et al., 2021).

Accordingly, the main hydro-climatic inputs, including actual inflow, actual rainfall, dependable rainfall, dependable river flow, surface-water evaporation, and reference crop evapotranspiration, were increased by 5%. Other non-climatic parameters were unchanged so that the model response could be attributed mainly to the imposed hydro-climatic change.

3.6.3. Development–climate change (+5%) combined scenario

The development case and climate change are a compounded future state in which planned infrastructure development is evaluated with a moderate climate change signal of +5%. Besides the stipulated 5 % rise in the climate-related variables, as set in the climate change scenario, this case also includes operational conditions for four suggested hydropower dams along the Bahr El Jebel River. These are the Fulla, Shukoli, Lakki, and Bedden dams, with over 1,800 MW of combined installed capacity and a range of storage capacities set to assist in generating power and regulating flow (Table 4).

Table 4. Hydropower potential sites in South Sudan (Irrigation development master plan of South Sudan, December 2015)

Project	Site	Storage capacity (Bcm)	Power generation (MW)
Fulla Hydropower project	38 km from the city of Nimule	0.85	865
Shukoli Hydropower project	48 km from the city of Nimule, 14 km below the dam site Fula	0.1	150
lakki Hydropower project	72 km from the city of Nimule and 24 from the bottom of the site Shikoly	0.38	300
Bedden Hydropower project	138 km from Nimule and 66 km below the Lucky site	1.41	530

As presented in Table 5, the assumed operating rules assigned to the proposed hydropower projects in RIBASIM are based on three main control levels: the Flood Control Level, the Target Level, and the Firm Storage Level. The values of these levels reflect a simplified, nearly constant operating scheme, as the Flood Control Level and Target Level were assumed to be identical across all projects, with no monthly or seasonal variations. In addition, the relatively small difference between the Target Level and the Firm Storage Level suggests limited active storage and a narrow operating range, indicating that the proposed schemes were represented as regulation or run-of-river type hydropower projects rather than large storage reservoirs with substantial seasonal carryover capacity.

Additionally, the situation presupposes the existence of a significant growth in the agricultural development sphere with the areas planted in the Sudd Wetland growing by about 40 % in comparison to the existing cultivated areas, as shown in Fig. 3, which shows a sample input used in the RIBASIM model to represent the irrigation area downstream of Mongala over a 12-time-step period (Ts1–Ts12), corresponding to one hydrological year.

The upper panel presents the seasonal distribution of cultivated area (ha) for the main crops, wheat, groundnut, sorghum, sugarcane, and cotton, based on the assumed planting calendar and crop rotation pattern adopted in the model.

Table 5. Operation Rules for the proposed Hydropower Potential Sites in South Sudan (Assumed)

Hydropower Potential	Flood Control Level (m)	Target Level (m)	Firm Storage Level (m)
Fulla Dam	622	622	616
Shukoli Dam	560	560	558
Lakki Dam	535	535	533
Bedden	510	510	504



Fig. 3. Seasonal irrigation area and related water demand downstream of Mongala as the RIBASIM Model input sample

The lower panel displays the related irrigation water requirement in terms of river discharge (m^3/sec), where the stepped blue line reflects the prescribed water supply associated with the cropping schedule. Together, the figure illustrates how seasonal agricultural demand is defined and incorporated as an input to the RIBASIM model to guide water allocation.

This agricultural expansion is supported by a projected 25% population growth and driven by development initiatives especially hydropower generation and economic opportunities. The overall impacts of infrastructure functioning, land-use alteration, and population growth under modified climatic conditions provide a rich framework for evaluating future water supply, system functionality, and development in relation to hydrological sustainability.

3.6.4. Development–climate change (-5%) combined scenario

This scenario follows the same framework as the previous Development (+5%) Climate Change Scenario, but with modifications to the climate conditions. The focus remains on development measures, while the climate change factor is reduced by 5%. Conditions included in this scenario:

- Operation of planned dams: All four dams listed in Table 5 are included in the simulation.
- Increase in cultivated area: Assume the agricultural area in the Sudd Wetland is increased by approximately 40% relative to the current cultivated area.
- Population growth: Assume an increase of about 25% due to ongoing development activities.
- Climate change adjustment: Climate variables, as mentioned in the first future scenario, are adjusted to reflect a 5% reduction relative to baseline conditions, resulting in less severe climate change impacts than previously assumed.

3.7. Calibration of the Results at Malakal

The RIBASIM model was calibrated under base-case conditions for the period 2003–2013. Figure 4 shows the comparison between simulated and observed monthly discharges at Malakal. As shown in the hydrograph (Fig. 4), the model generally reproduces the seasonal flow pattern, the timing of high-flow periods, and the overall hydrological behavior of the Bahr El Jebel Basin. To quantitatively assess model performance, three statistical indicators were used: Root Mean Square Error (RMSE), Nash–Sutcliffe Efficiency (NSE), and the coefficient of determination (R^2). These indicators were used to evaluate the agreement between simulated and observed discharge records.

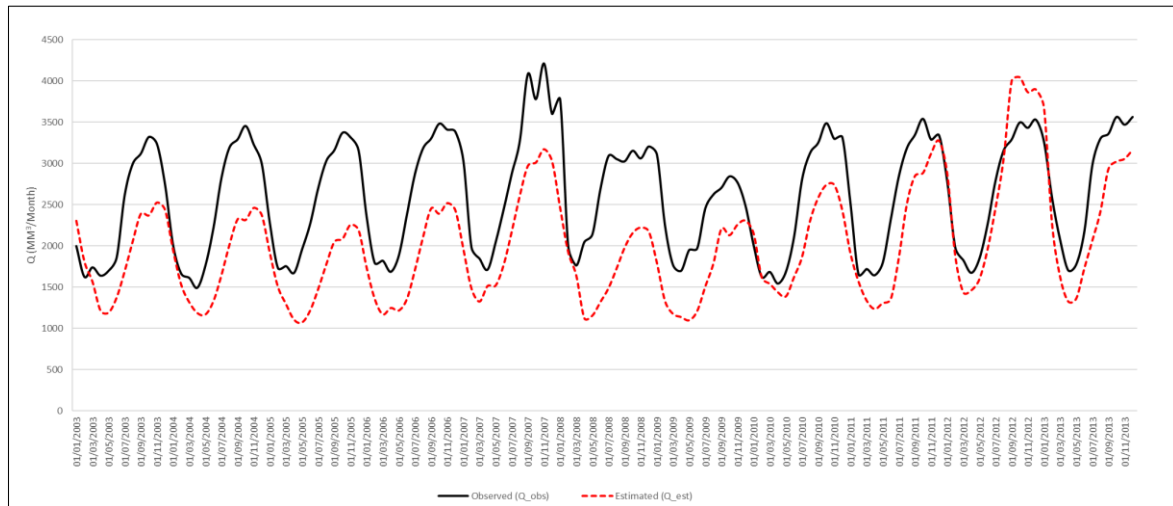


Fig. 4. Calibration of the model's results at Malakal (2003-2013)

Although the overall calibration performance shows reasonable agreement between observed and simulated discharges, noticeable deviations occur during parts of the calibration period, particularly between 2003 and 2010. These deviations are attributed to the complexity of the Bahr El Jebel Basin hydrological system with large spatial scale, wetland storage, flow attenuation, routing processes, evaporation loss, and transmission loss. The model also requires a number of input data sets and assumptions, such as wetland losses, water use conditions, upstream inflow, routing behaviour and rainfall, which can also lead to uncertainty in the model simulation. Further, the wetland is difficult to monitor continuously in the field because of the extent and accessibility of the wetland as well as the limitations with data availability in the wetland (NBI, 2020; Di Vittorio and Georgakakos, 2021). This type of uncertainty is typical of hydrological modelling and can be due to input data uncertainty, calibration data uncertainty, model structure or model parameterization (Moges et al., 2021). In this case, calibration was conducted to achieve balanced overall performance with physically reasonable parameter values, rather than over-adjusting the model to reproduce each monthly peak. Over-adjustment for a specific sub-period may increase the risk of overfitting and reduce model robustness during validation and scenario analysis (Huang et al., 2020; Shen et al., 2022).

The calibration results show that the model RIBASIM of Malakal is able to simulate the observed monthly discharge patterns with a reasonable accuracy. The RMSE value was 28.32 and the average deviation between the simulated and observed values over the calibration period was acceptable. This value indicates that the model maintains a reasonable agreement with the measured data while some deviations remain during specific high-flow periods.

Furthermore, the model recorded an NSE value of 0.92, which present a very good model performance based on common hydrological modelling criteria. The coefficient of determination was also high with $R^2 = 0.96$, representing a very high linear correlation between observed and simulated discharges. In general, these statistics verify the calibrated RIBASIM model is an acceptable representation of the hydrological regime at Malakal and is fit for use in basin-scale scenario analysis.

3.8. Validation of the Results at Malakal

The simulated and measured discharges had a high agreement during the calibration period 2003-2013 and the validation period 2014-2023 as demonstrated by the hydrological model developed in the RIBASIM. The Nash Sutcliffe Efficiency (NSE), percent Root Mean Square Error (RMSE), and the coefficient of determination (R^2) were used to evaluate model performance. The model has an NSE of 0.90, which is very good, and a RMSE of 29.8, which is an acceptable relative error. The high R^2 value of 0.92 further demonstrates that the model accounts for 0.92 of the observed discharge

variability, indicating strong performance in representing the hydrological dynamics of the study area. Overall, the model performance is good. The validation hydrograph indicates a consistent underestimation during recent extreme high-flow events at Malakal, where observed discharges exceeded simulated values (Fig. 5).

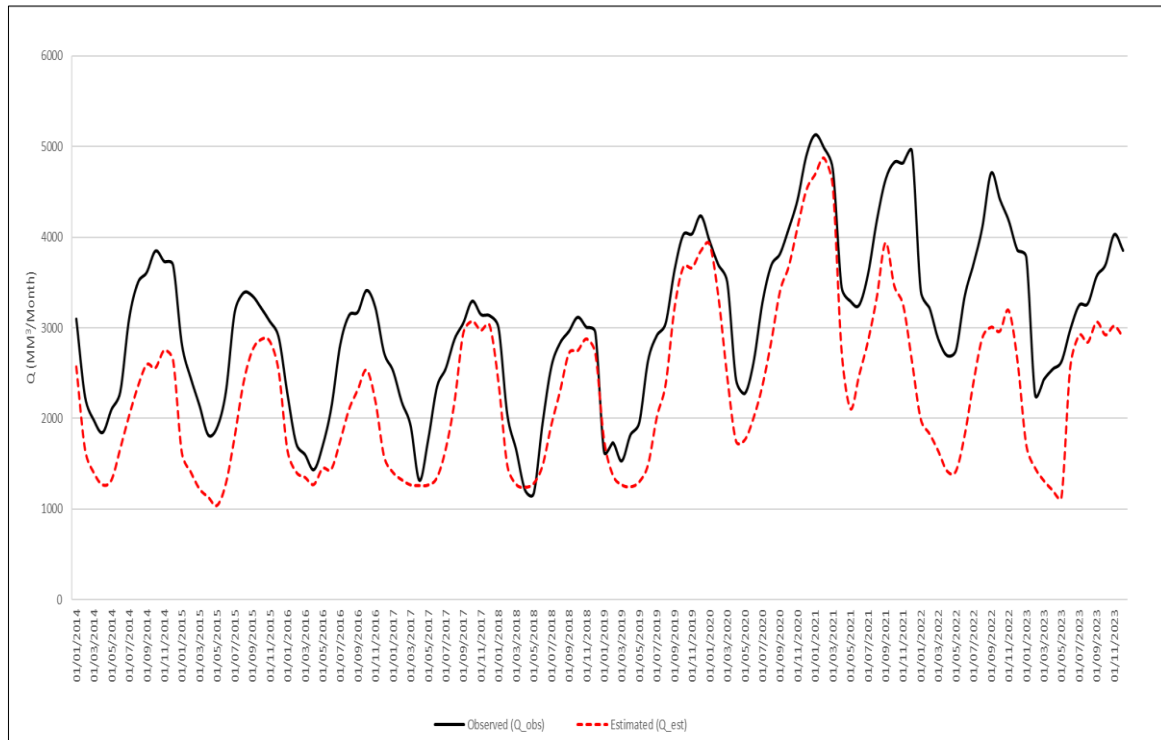


Fig. 5. Validation of the model's results at Malakal (2014-2023)

The strongest deviation occurs during 2020-2023, reflecting the effects of extreme events that lie beyond the normal calibration parameters. By this time, the Bahr El Jebel River runoff was at a record since 1903 with continuous low-flows that were higher than the peaks in drought years, which eventually caused the 2021-2023 floods (Zhang et al., 2025).

Furthermore, Fig. 6 indicates that the water levels at Malakal during 2020–2025 were markedly higher than in most of the preceding years. While water levels in the earlier period were generally within the range of about 11.0–12.5 m, the recent period shows a clear rise to approximately 12.0–14.5 m, which represents an important feature of the observed record and provides a useful basis for assessing model performance during validation.

4. Results

The results from the RIBASIM model are displayed directly on the model interface as organised time-series outputs. Figure 7 shows a representative example of these outputs, presenting the time series of downstream flow of Malakal for 103 years from 2003-2105).

The results indicate that 2067 will record a pronounced increase in downstream discharge at Malakal, representing one of the highest-flow years within the simulated period. This rise reflects stronger upstream inflows and an overall amplification of basin hydrology. Similarly, historical records show that 1964 was also a high-flow year at Malakal during the mid-1960s (Nile Basin Initiative, 2016). As shown in Figure 6, the water levels at Malakal increased noticeably during that time, particularly in 1964. The model captures a comparable pattern of increased downstream flow, suggesting that it reasonably represents both past variability and projected extreme flow conditions.

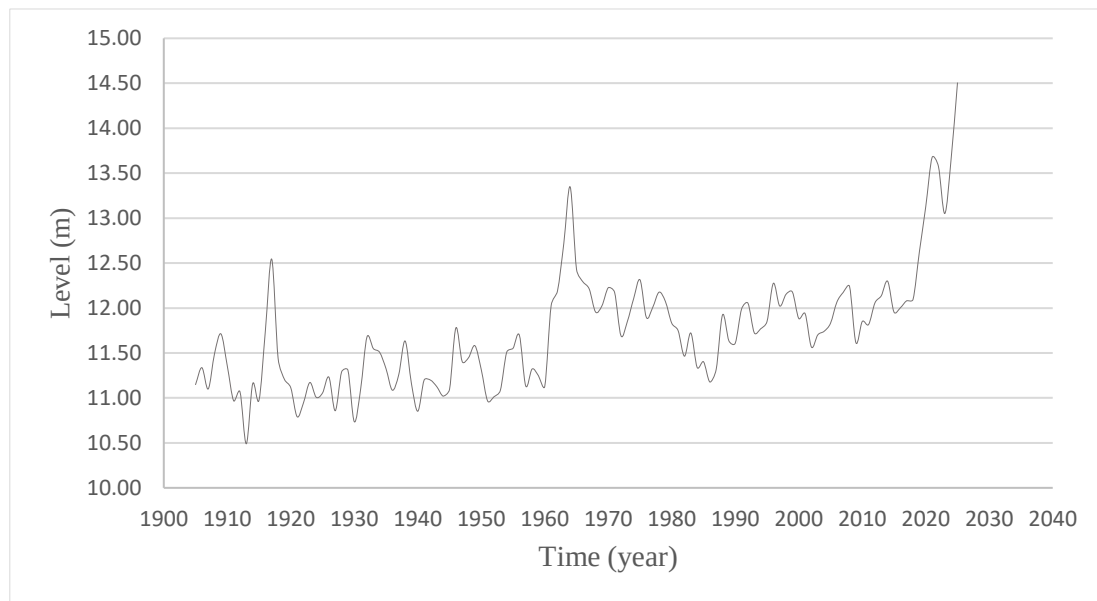


Fig. 6. Average of water levels of Malakal Station (m) from 1905-2025

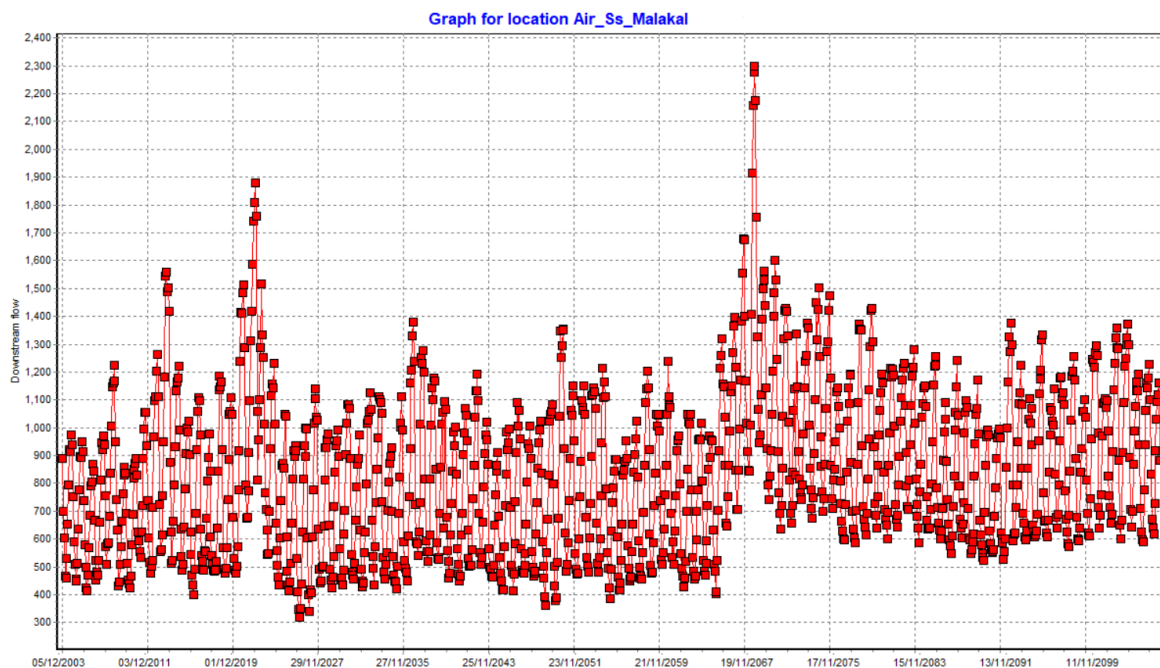


Fig. 7. Time Series of Monthly River basin Discharge (m^3/sec) under the Baseline Scenario as Displayed in the RIBASIM Model Interface

4.1. Future Scenarios Results

A 103-year RIBASIM simulation was conducted using monthly discharge (Mm^3/month) as input at the Malakal node and was extended to include the three future scenarios. Since the simulation horizon was long, the direct visual comparison of full time-series results to the Baseline scenario was not as informative as it would have been with shorter time-series, because the differences between the inter-scenarios are minimal relative to the overall variability and cannot be easily identified on long-time-period plots. To enhance interpretability, the results were summarized by calculating monthly averages over the entire simulation period (i.e., the mean of each calendar month divided by all

simulated years). The monthly-mean curves that result provide a more direct overview of seasonal trends and a measure of the disparities between Baseline and future conditions.

4.1.1. Climate change (+5%) scenario

The comparison between the Baseline and the Climate change (+5%) scenario at Malakal indicates a clear and sustained increase in Bahr El Jebel River discharge over the full simulation period (2024-2105), as shown in Figure 8. Meanwhile, there is an average monthly discharge increase of approximately 388 Mm³, from 2202 Mm³/month under baseline conditions to 2589 Mm³/month under the climate scenario. But this doesn't happen all year round. The strongest relative rise will be during the flood season with October experiencing increases of approximately 25.7% followed by September at approximately 21%. The smallest increase as a percentage will see in January (around 11.3%). These results show that the climate signal enhances high flows more than low flows.

Significantly, the magnitude of discharge rises, but there is no change in the seasonal pattern. The timing of low flows (mainly February-April) and peak flows (mainly August-October) remain unchanged, suggesting that the current flow regime is enhanced due to climate change without changing its structure. The biggest monthly difference is expected in October 2067 at around +1357 Mm³/month and the smallest in April 2041 at around +2.3 Mm³/month. The greatest overall change between the two scenarios will be seen in 2067 and the smallest annual change will be observed in 2041.

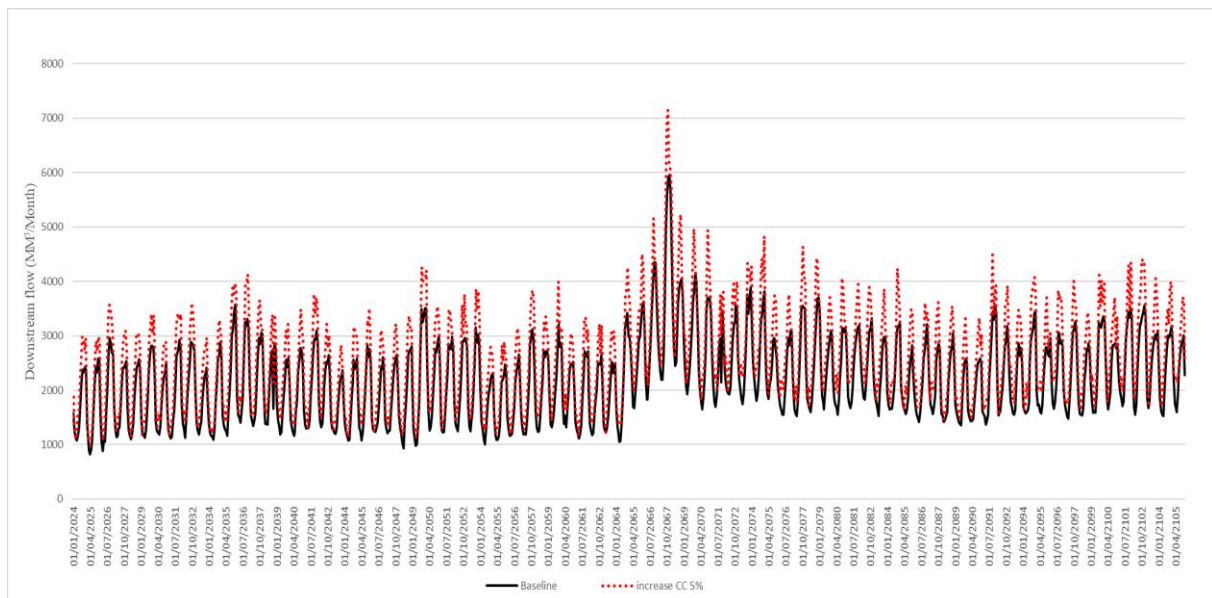


Fig. 8. Comparison of Monthly Discharge at Malakal under Baseline and Climate (+5%) Scenarios (2024–2105)

4.1.2. Development–climate change (+5%) combined scenario

The combined scenario (Development–Climate Change (+5%)) is compared with the Baseline scenario at Malakal throughout the simulation period (2024–2105) (Fig. 9) and demonstrates a steady, though moderate, rise in Bahr El Jebel River discharge under the combined scenario. Average monthly discharge will increase by approximately 77.7 Mm³/month, from approximately 2202 Mm³/month with baseline discharge to 2279 Mm³/month. Meanwhile, the increase is not equal over the year. The highest relative growth will be in September (approximately 5.10%), August (approximately 5.09%) and October (around 4.25%) during the flood season. The smallest relative increase will be seen in April (around 1.58%). This pattern suggests that the impacts of climate change and development are more pronounced in high flow periods than in low flow periods.

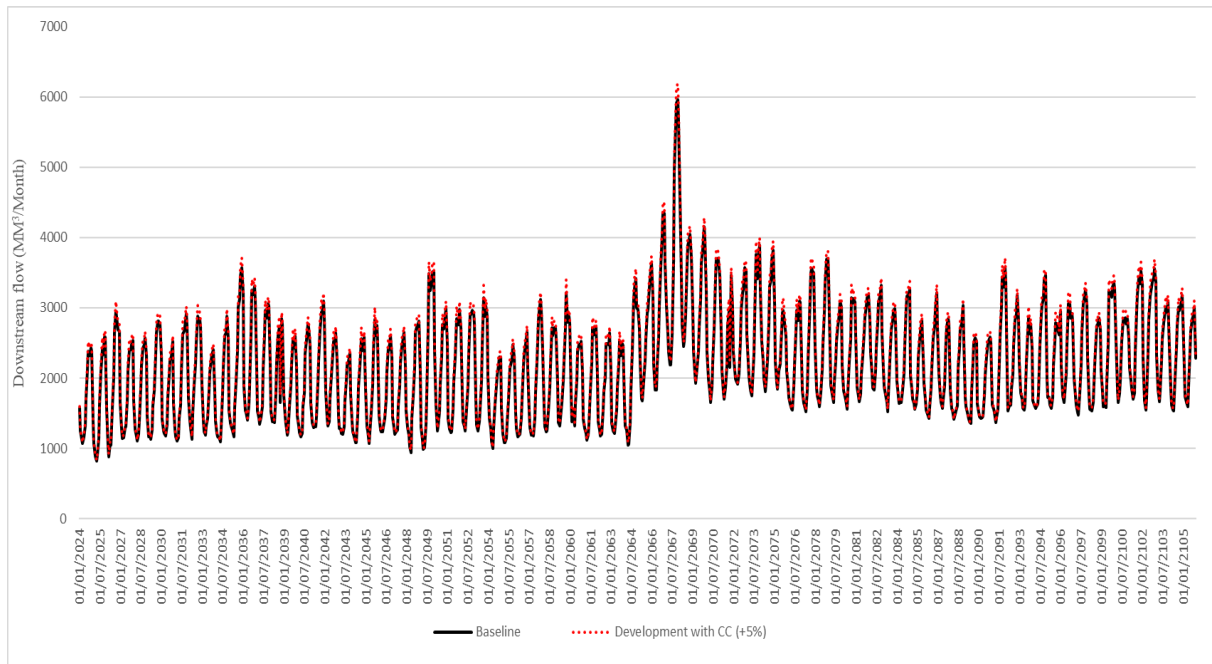


Fig. 9. Comparison of Monthly Discharge at Malakal under the Baseline and Development–Climate Change (+5%) Combined Scenario (2024–2105)

The seasonal pattern of the Bahr El Jebel River stays unchanged despite a rise in the discharge values. Low flows (mainly February–April) and peak flows (August–October) do not change, indicating that the scenario just causes the flow magnitudes to get bigger but doesn't change the flow structure of the hydrological cycle. The biggest monthly gap between the two scenarios will be in October 2067 (around +246.85 Mm³/month), and the smallest gap will be in May 2089 (around –1.26 Mm³/month; so small as to be practically negligible). The most pronounced differences among scenarios are seen in 2067, while the year with the least difference is in the late 2080s, around 2089.

4.1.3. Development–climate change (–5%) combined scenario

The comparison of the Baseline with the Development–Climate Change (–5%) Combined Scenario at Malakal over the period 2024–2105 (Fig. 10), indicates a gradual reduction in the discharge of the Bahr El Jebel River under the –5% Combined Scenario. The average monthly discharge drops from 2202 Mm³/month in the baseline to 2124 Mm³/month or a reduction of nearly 78 Mm³/month, which is approximately –3.5% overall.

This decrease is not evenly distributed throughout the year. The highest reductions will be seen in flood season, especially in August/September (–5%), then in October (–4%), while the lowest reductions will be seen in the dry season months, particularly in April (–1.5%). This pattern suggests that the 5% climate signal primarily dampens peak flows, while low flows are affected to a lesser extent.

The discharge magnitudes decrease, but the seasonal cycle of the Bahr El Jebel River stay the same. The low-flow period (February–April) and the high-flow period (August–October) are retained, which presents that the scenario is not associated with a change in the hydrological cycle, but rather a reduction in the flow intensity. The biggest monthly decrease will be seen during a peak flood month in the late 2060s, at more than –240 Mm³/month and the smallest difference will be seen during a low-flow month, at much less than –6 Mm³/month. The largest differences between the scenarios are seen in the late 2060s, and the smallest in the late 2080s.

The hydrological impacts of each assumption were examined with the Monthly Average Method that compares the three scenarios with the baseline condition, as shown in Fig. 11. This approach uses

mean discharge for each month for the whole simulation, which gives a common basis for looking at absolute and relative changes. The monthly and annual discharge of Bahr El Jebel River at Malakal is summarized under different climate and development scenarios in Table 6.

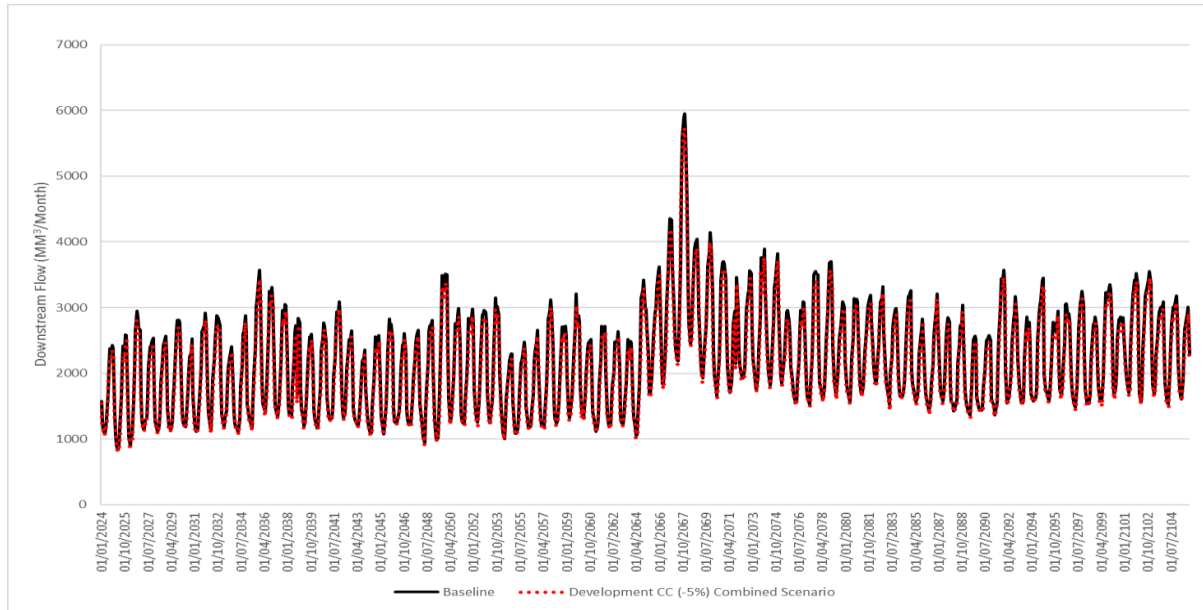


Fig. 10. Comparison of Monthly Discharge at Malakal under the Baseline and Development–Climate Change (-5%) Combined Scenario (2024–2105)

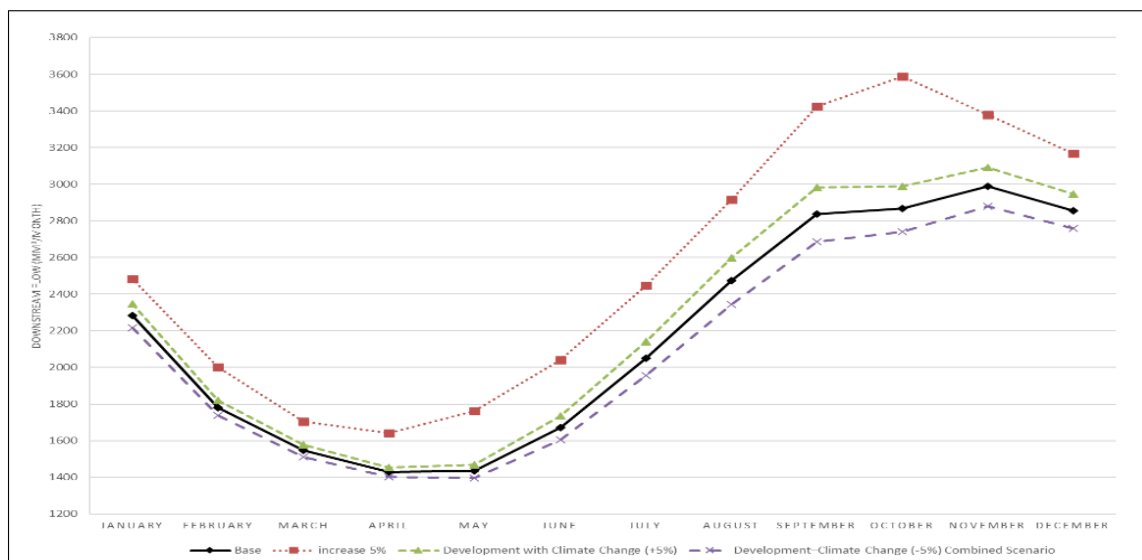


Fig. 11. Projected Monthly Bahr El Jebel River Discharge at Malakal under Baseline, Climate Change, and Development Scenarios

The simulation results show that the Bahr El Jebel Basin–Sudd Wetland is highly responsive even to relatively modest climatic perturbations, especially during the wet seasons. The clear increase in discharge at Malakal under the Climate Change (+5%) Scenario, particularly between July and October, indicates that high-flow conditions are more sensitive to climate forcing than low-flow conditions. This pattern is hydrologically reasonable because the downstream outflow from the Sudd Wetland is influenced not only by upstream inflows but also by local hydroclimatic conditions within the wetland itself, including evaporation, storage, and flow attenuation (Mohamed et al., 2006; Mohamed and Savenije, 2014). In addition, previous work has shown that wetland storage and river–wetland interactions play a major role in regulating the downstream hydrograph, which supports the

interpretation that even moderate increases in climatic inputs can produce uneven seasonal amplification of discharge at Malakal (Sutcliffe and Brown, 2018).

Table 6. Comparison of monthly and annual Bahr El Jebel River discharge at Malakal under different climate and development scenarios

Feature / Indicator	Climate Change (+5%)	Development–Climate Change (+5%)	Development–Climate Change (-5%)
Trend in monthly discharge	Continuous increase in all months	Continuous increase in all months despite additional withdrawals	Continuous decrease in all months due to the combined effects of increased withdrawals and reduced climate inputs
Absolute monthly Change (Mm ³ /month)	+199 (Jan) → +722 (Oct)	+22 (Apr) → +143 (Sep)	-27 (Apr) → -152 (Sep)
Relative monthly Change (%)	8.7% (Jan) → 25.2% (Oct)	1.54% (Apr) → 5.04% (Sep)	1.89% (Apr) → 5.37% (Aug)
Seasonal pattern	Largest increase during wet season (Jul–Oct)	Largest increase during peak-flow months 8–10	Largest decrease during peak-flow months 8–10; smallest during low-flow months

A comparison between the Climate Change (+5%) Scenario and the combined Development–Climate Change (+5%) Scenario indicates that development interventions substantially reduce the positive effect of climate forcing on downstream discharge. Although the annual mean flow increased substantially in the absence of climate change, the inclusion of dams, irrigation expansion and population-related water demand reduced this increase to a relatively small net gain, indicating that the basin's response to climate change cannot be fully explained by climate drivers alone, because additional water uses and hydraulic regulation modify the flow regime of downstream. This is in line with the integrated Nile River Basin evaluations that focus on the need to consider climate change and upstream development together and not in isolation (Booij et al., 2011). It is also consistent with more recent basin scale studies that have demonstrated that land-use and socioeconomic changes can affect seasonal downstream flows in the White Nile River system and affect discharge conditions at larger Nile River scales (Omer et al., 2023).

The Development–Climate Change (-5%) Scenario also shows that the Bahr El Jebel Basin–Sudd Wetland is vulnerable with simulated discharge reduction throughout the year with the highest reduction simulated during the peak-flow season. The outcome demonstrates that when the development-related abstraction is high, a negative climatic forcing leads to higher vulnerability of the Bahr El Jebel Basin for decreasing water availability in the downstream area. This is particularly important from a management perspective as the wet season accounts for the majority of the flow volume and highly influences wetland storage and downstream supply conditions. The planning in the Bahr El Jebel Basin going forward should take into account not only the yearly average changes, but also the changes that happen only once in a year. It should also include seasonal variations in flow and the possibility for development pressures to reduce or reverse positive climate signals. The interpretation has particular relevance in a system that has a large storage and loss zone like Sudd Wetland which shows a strong control on downstream flow transmission (Sutcliffe and Brown, 2018).

The adopted scenario framework from a methodological point of view is still relevant for identifying basin sensitivity and relative contribution of climate and development drivers although it

does not simulate event-based extremes, like severe droughts or flood waves. The value of the present results, therefore, lies in their ability to reveal the direction and magnitude of system response under controlled perturbation scenarios. This is important because recent hydrological modelling studies of the Sudd Wetland have also highlighted the difficulty of representing wetland storage, attenuation, and connectivity under conditions of severe data scarcity, particularly where uncertainties affect inflow estimates, flooded area, and internal wetland dynamics (Di Vittorio and Georgakakos, 2021). In this respect, the present study provides a structured scenario-based assessment of hydrological behaviour along the Bahr El Jebel Basin, while also pointing to the need for future investigations that incorporate more extreme climate conditions.

5. Conclusions and Recommendations

The scenario simulations show that the Bahr El Jebel Basin–Sudd Wetland are highly responsive to variations in both climatic forcing and development-related pressures. The increasing climate scenario generated the largest increase in discharge at Malakal, particularly during the wet season, indicating a greater likelihood of enhanced downstream flows and elevated flood risk under increased climatic input. When this increasing climate condition was combined with development interventions the increase in discharge was reduced, showing that water abstractions and flow regulation related to infrastructure and development can partially counterbalance the positive climate signal.

The overall results from the combined development and drier-climate scenario were a decrease in discharge, particularly in the peak-flow months, implying a higher vulnerability of the basin to reduced climate input combined with increased development pressure.

However, the results also indicate that there is potential for enhancing water resources management in the Bahr El Jebel Basin, especially in the Sudd Wetland, through integrated basin scale development if future interventions are planned to address the flood dynamics, wetland storage capacity and ecological flow needs.

These results show that in the future the water management in Bahr El Jebel Basin should not be restricted to the volume of flow per year but seasonal flow variations should also be considered. Special emphasis should be placed on enhancing preparedness for floods during the wet season particularly from July to October and that future development projects are planned in an integrated framework taking into account the ecological flow needs, the sustainability of the wetland, and the need to manage recurrent flooding in the Sudd Wetland. In this matter, coordinated basin-scale planning can help to enhance water management under present and future flood-prone conditions, as long as development actions are taken within a hydrologically and environmentally sound and sustainable framework.

The scenarios adopted were not intended as probabilistic projection but rather sensitivity based future conditions so should be thought of as a way of understanding how the basin behaves under uncertainty. Improved hydrological and climatic monitoring, in addition to further studies on more extreme drought and flood scenarios, would better support adaptive and sustainable water resources management.

Author contributions

Ahmed Y. Abed: investigation, conceptualization, formal analysis, methodology, writing-original draft, review, and editing. Aly N. El-Bahrawy: conceptualization, methodology, review and editing, and supervision. Eman Soliman: investigation, methodology, and review and editing, and formal analysis. Amr Fawzy: methodology, software, formal analysis, review and editing, and validation. and HodaSoussa: investigation, methodology, formal analysis, review and editing.

Declaration of competing interests

The authors declare no competing interests.

Data Availability

The data that support the findings of this study are not publicly available due to confidentiality.

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