Updating and improving of existing hydrologic and hydraulic models and configuring a Flood Early Warnings System (FEWS) in Sudan

Model calibration and validation report

Draft Report

21/02/2024

Prepared for General Administration of Nile Water Affairs, Ministry of Irrigation and Water Resources, Sudan

The expert in **WATER ENVIRONMENTS**

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1 Introduction

This report is a deliverable of the CTCN Technical Assistance “Updating and improving of existing hydrologic and hydraulic models and configuring a Flood Early Warnings System (FEWS) in Sudan”.

The objective of the technical assistance is to update and improve the existing hydrologic and hydraulic models and configure for Sudan the Flood Early Warning System (FEWS) setup by the Nile River basin regional entity the Eastern Nile Technical Regional Office (ENTRO) as well as to strengthen the capacity of the staff of the General Administration of Nile Water Affairs, Ministry of Irrigation and Water Resources, and link the systems with concerned stakeholders.

The objective will be achieved by:

- Expanding and enhancing the components of the existing FEWS in Sudan for increased coverage, efficiency, and lead time in the Blue Nile, Setit-Atbara, Dinder, Rahad and Main Nile (between Khartoum and Dongola) national sub-basins.
- Assessing potential and opportunities of the Eastern Nile Flood Forecast and Early Warning System EN-FFEWS of ENTRO available to Sudan - as well as its current protocols/procedures and institutional framework - to supplement the FEWS in Sudan.
- Training system operators and enhancing the capacities of key stakeholders of the FEWS to improve and benefit the country’s disaster management framework.

The scope of work under this technical assistance comprises three outputs to be achieved through three activities.

- Output 1: Assessment of the existing FEWS system protocols and identifying existing data gaps and needs.
    - Activity 1: Stakeholder consultation, assessment of available data and existing FEWS
- Output 2. Enhanced FEWS
    - Activity 2 – Enhancement of the FEWS
- Output 3. Strengthened capacity and sustainability for uptake and effective use of the upgraded FEWS.
    - Activity 3 – Capacity building for use of the enhanced FEWS

This report “Model calibration and validation report” (Deliverable associated with Activity 2.1 – Expansion and improvement of the FEWS components) is a concise documentation of the enhanced and improved hydrological and hydrodynamic models that are core components of the forecast model.

The present version is a draft version of the report with calibration and validation completed for the Tekeze-Setit-Atbara basin and the Blue Nile basin. Work on the models for the Main Nile (between Khartoum and Dongola) and the Dinder and Rahad basin are ongoing. The report will be updated with the calibration and validation of the two remaining basins.

The structure of this report is as follows:

- **Chapter 1** explains the context of the report (this chapter).
- **Chapter 2** shows the geographic scope of the models.
- **Chapter 3** describes the hydrological models of the EN-FFEWS.
- **Chapter 4** describes the hydrodynamic models of the EN-FFEWS.
- **Chapter 5** summarizes the enhancements with reflections on the way forward.

2 Geographic scope of the FEWS expansion for Sudan

Figure 2.1 below gives an overview of the entire Nile basin and Figure 2.2 shows the eastern Nile basin.

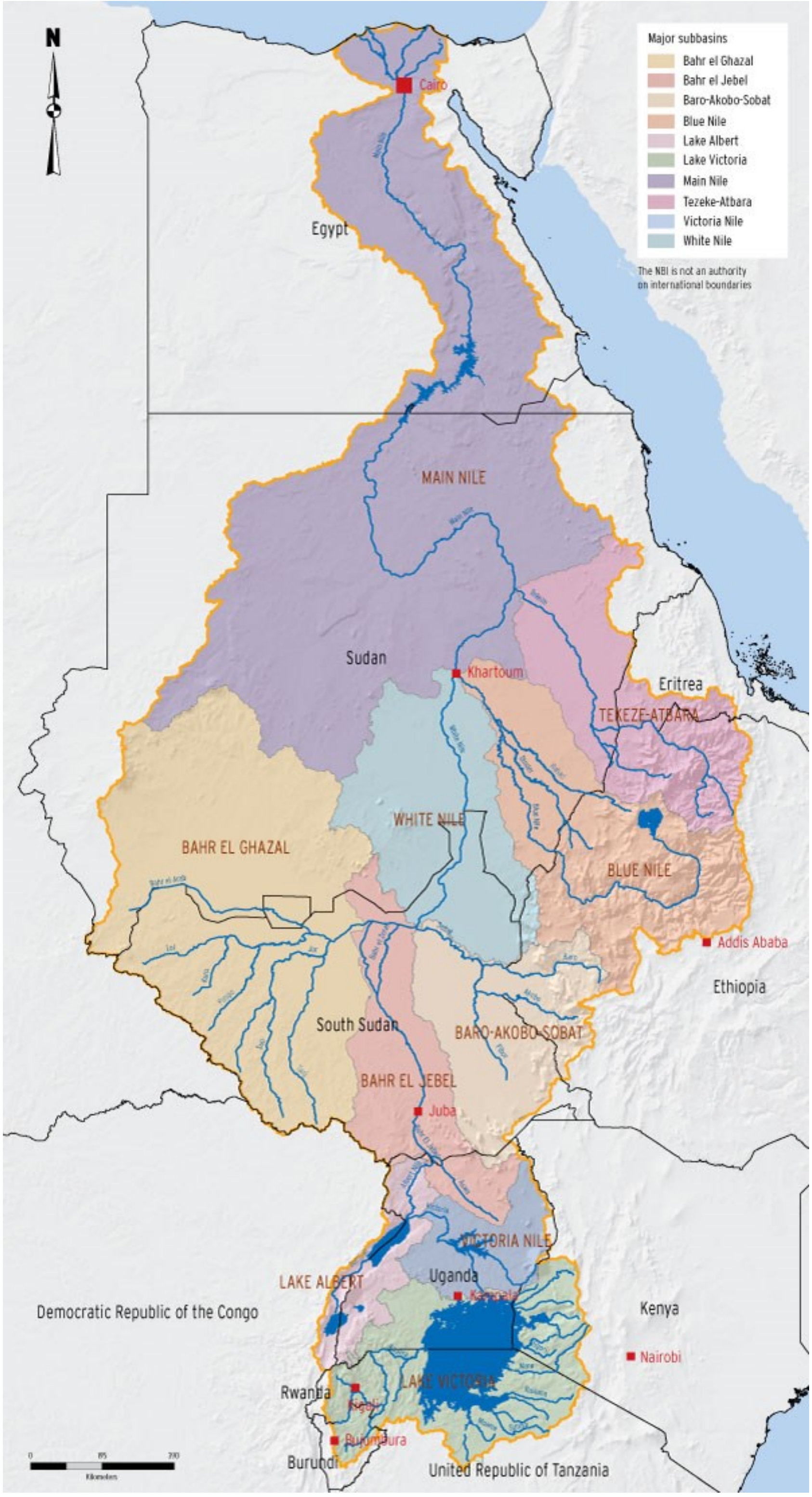


Figure 2.1 The Nile Basin - overview

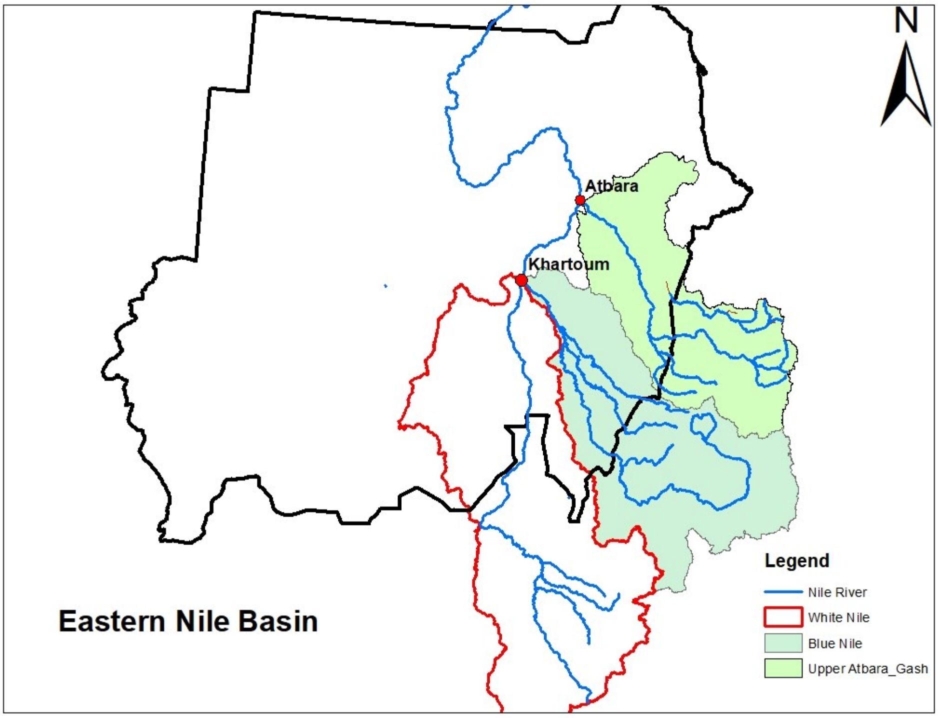


Figure 2.2 The Eastern Nile sub-basin – Tekeze-Setit-Atbara, Blue Nile and White Nile (including Baro-Akobo-Sobat) sub-basins

The enhanced FEWS for Sudan will cover the following extents (see Figure 2.3, Figure 2.4 and Figure 2.5):

- The Main Nile River between Khartoum and Dongola

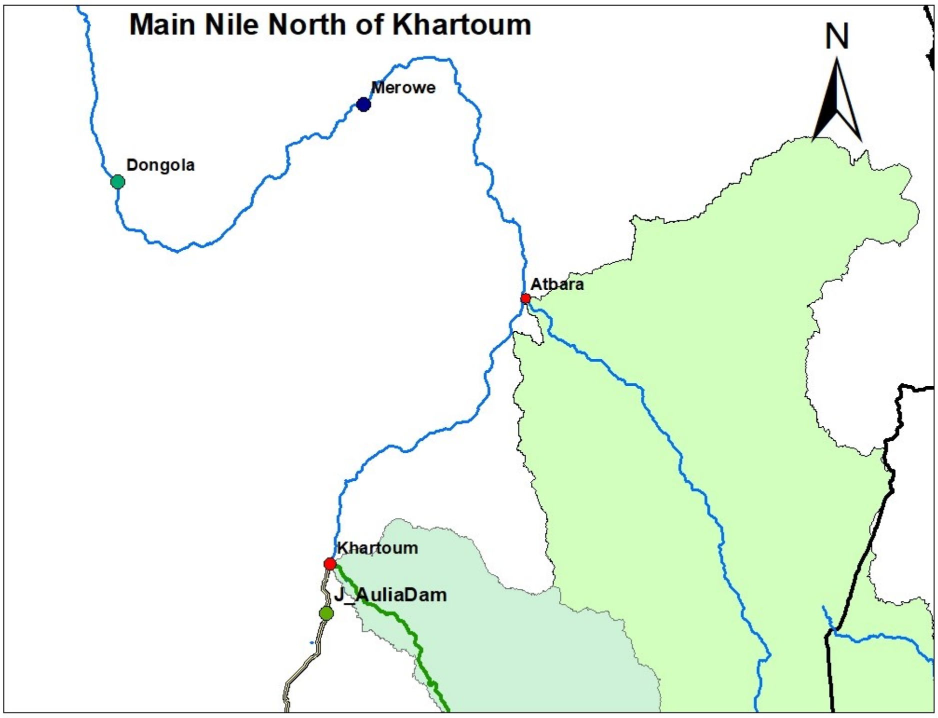


Figure 2.3 The Main Nile between Khartoum and Dongola

- The Tekeze-Setit-Atbara basin covers the catchment heading in the northern highlands of Ethiopia up to the confluence of the Atbara River. The river of interest for the EN-FEWS are Atbara downstream of the Setit inflow, parts of Setit and Tekeze downstream of the Tekeze dam.

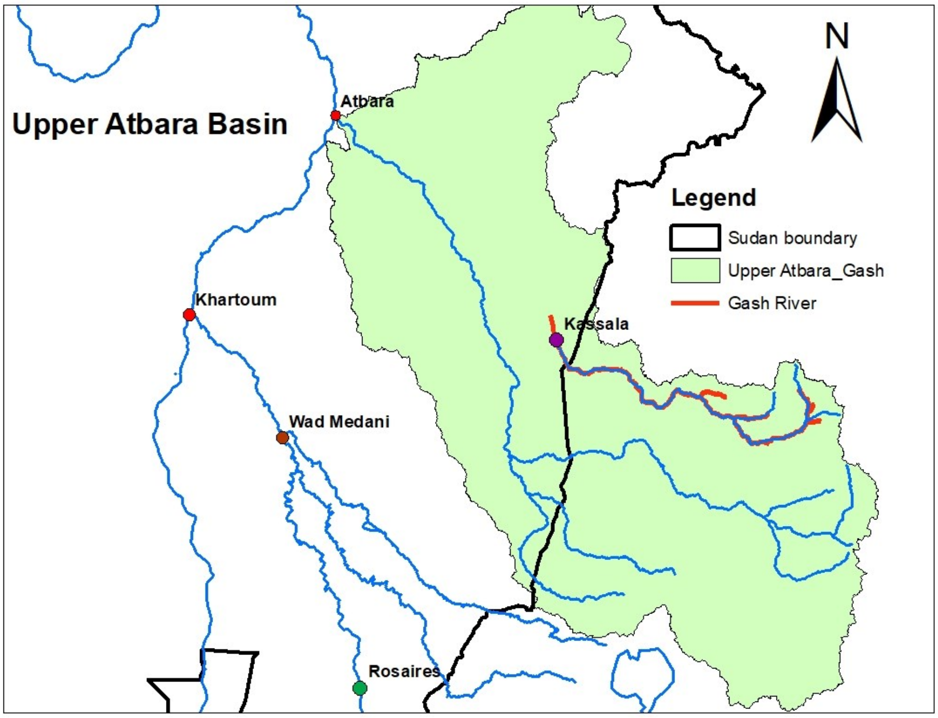


Figure 2.4 The Tekeze-Setit-Atbara sub-basin

- The Blue Nile basin encompasses the catchments that drain into the Blue Nile River between Lake Tana and Khartoum including those of the rivers Dinder and Rahad. The lower boundary condition may be influenced by conditions of the White Nile at the confluence. The river of interest for the EN-FFEWS is the Blue Nile downstream of the Grand Ethiopian Renaissance Dam (GERD).
- The Dinder River
- The Rahad River

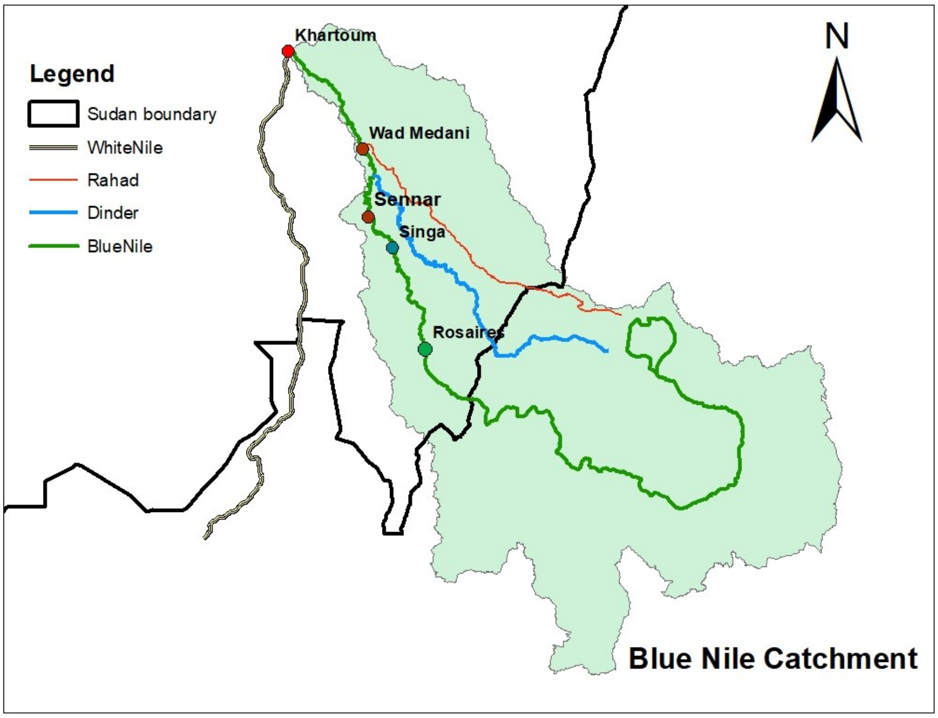


Figure 2.5 The Blue Nile, Dinder and Rahad rivers and the Blue Nile sub-basin

3 Enhancements and Improvements of the Hydrological models of the EN-FFEWS

Upscaling and improving the two relevant hydrological models of the existing EN-FFEWS (Blue Nile and Tekeze-Setit-Atbara) required, apart from migrating the models to the latest version of NAM, carrying out the following:

1. Revisit the delineation of the catchments, and re-delineate where necessary, taking into consideration relevant river reaches and flood forecast locations.
2. Investigate and adjust where necessary (e.g. with regionalization approach) the catchment model parameters in terms of plausibility and consistency.
3. Simulate the rainfall-runoff-process taking rainfall from historical GPM-data and compare the resulting discharges with the available historical records.
4. Evaluate the comparison between simulated discharges and historical observations and make plausible adjustments iteratively where possible and necessary (calibration).

The rationale for this approach is the following:

A. Using GPM as rainfall input for model configuration: The main purpose of the models is flood forecasting, and FFEWS is envisaged to be operational with the numerical weather prediction model WRF. Relationships between WRF forecasts and GPM observations can be established adequately for data assimilation purposes. This is a sound basis for data assimilation and for evaluations of flood forecasts in quasi-real-time.

B. Simple calibration of the models without rigorous validation: The available historical records of discharges are scarce and partly not plausible. Therefore, instead of quantifying the model quality with established performance indicators (such as RMSE, R2, Nash-Sutcliffe-Efficiency), visual inspection of the hydrographs – with emphasis on flow peaks and volumes of floods – was preferred.

The system will be updated with the other two models (Main Nile between Khartoum and Dongola and the Dinder and Rahad model) as soon as they are completed, and the present report will be updated accordingly.

The following sections discuss the initial results obtained in the development of hydrological models for flood forecasting and flood mapping purposes.

3.1 Main Nile between Khartoum and Dongola

The current EN-FFEWS does not include the river stretch of the Main Nile between Khartoum and Dongola (creation of hydrological model for this stretch is ongoing).

3.2 Blue Nile Basin

A preliminary calibration of NAM models has been made for the 28 sub-catchments shown below.

Figure 3.1 Blue Nile catchment. Selected data of the highlighted sub-catchments are illustrated in Figure 3.2 and Figure 3.3

GPM rainfall data has been downloaded for the sub-catchments, as this data is available in near-real-time and can be applied for the flood forecasting. The previous version of the model used rainfall data from NOAA, which is considerably lower in most years, see Figure 3.2. ERA5 potential evaporation data has also been downloaded and compared with the data applied in the original model, see Figure 3.3. ERA5 has higher values, mainly in the early years.

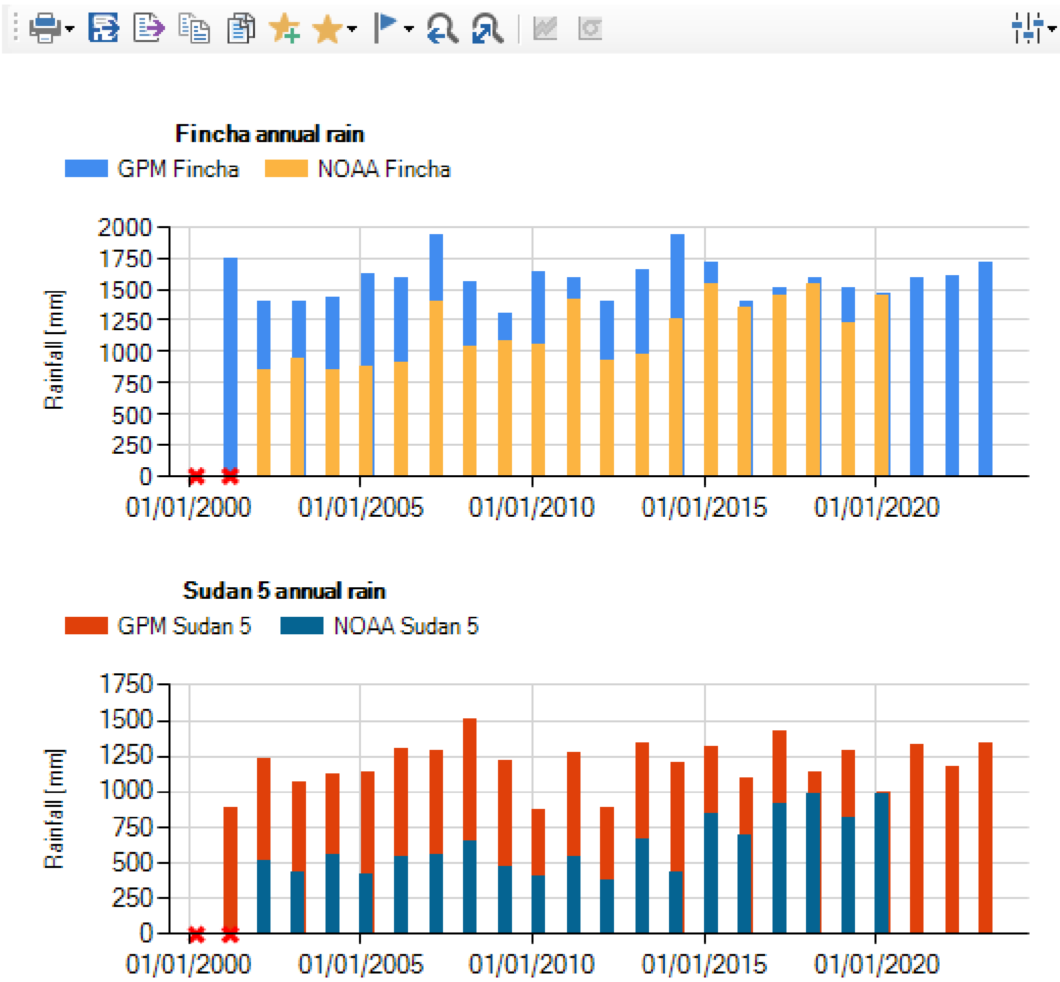


Figure 3.2 **The NOAA Rainfall applied in the previous model is considerably lower than the GPM as shown in these examples.**

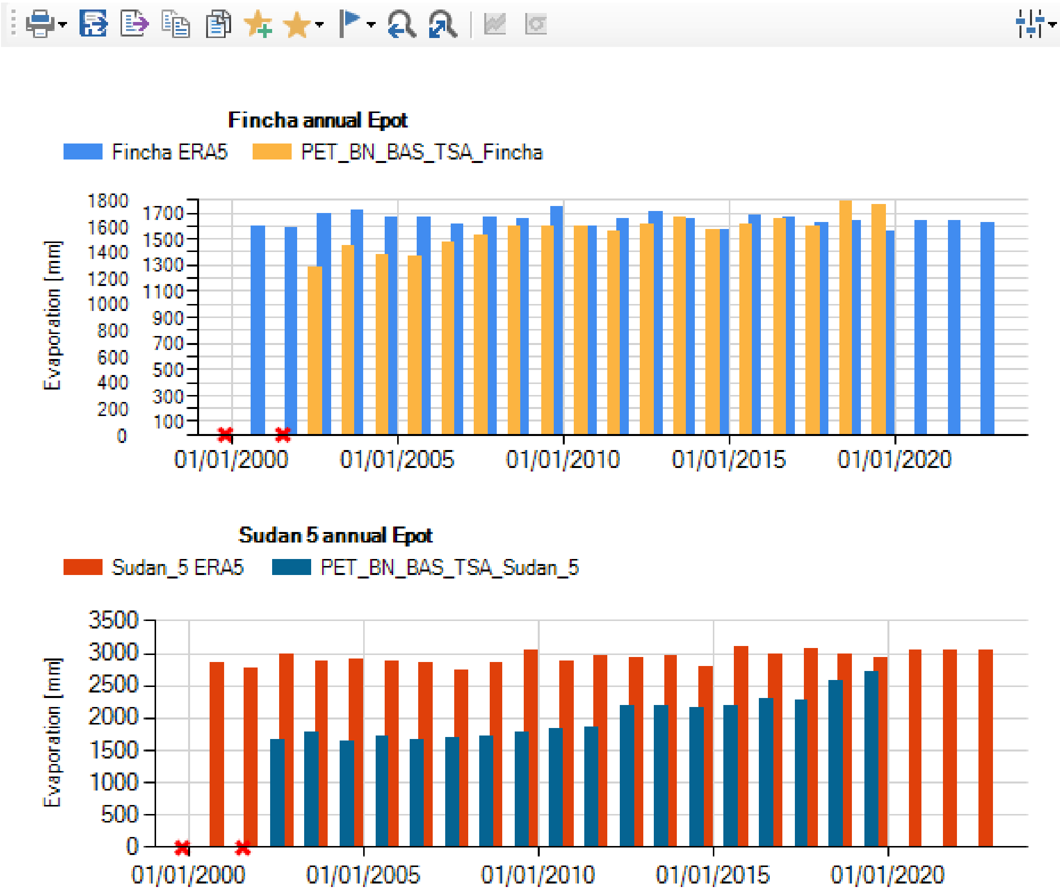


Figure 3.3 The potential evaporation (ERA5) is somewhat higher than the previously applied data, which shows an increasing trend over the simulation period.

Discharge data time series are only available at Abbay Kessie currently. Screenshots of measured flow for a few years.

It was not possible to obtain a satisfactory calibration with the GPM and ERA5 data directly. Therefore, to minimize the systematic deviations of rainfall a factor of 0.7 has been applied to the GPM rainfall data. The analysis was carried out through comparison of the datasets. The applied factor enables a reasonable calibration as can be seen from Figure 3.4, Figure 3.5, and Figure 3.6. Further adjustments will be made if/when additional hydro-meteorological data is obtained.

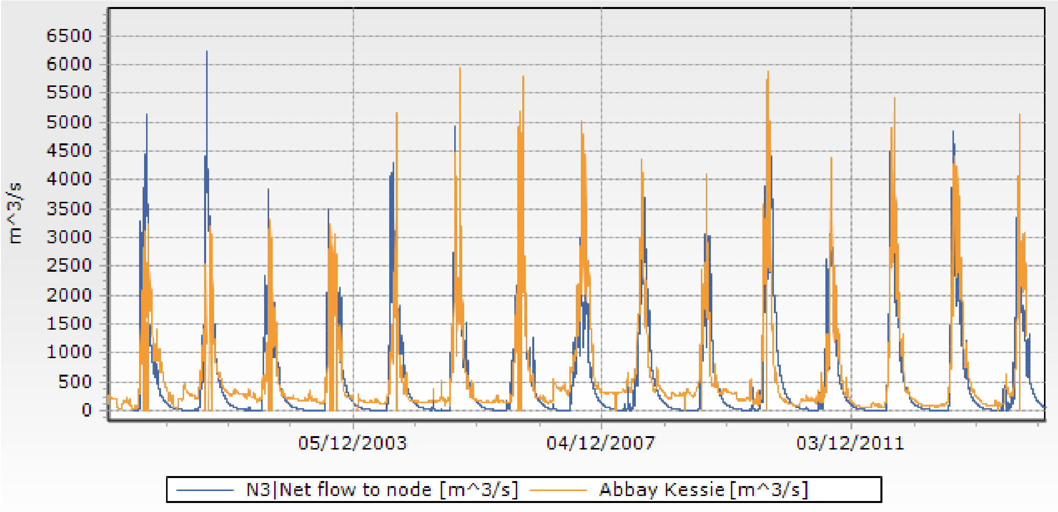


Figure 3.4 **Simulated (blue) and observed (orange) flow at Abbay Kessie. Looking at the longer record of observed flow (not shown here) it seems that discharge values above 3000 m3/s could not be measured prior to 2003.**

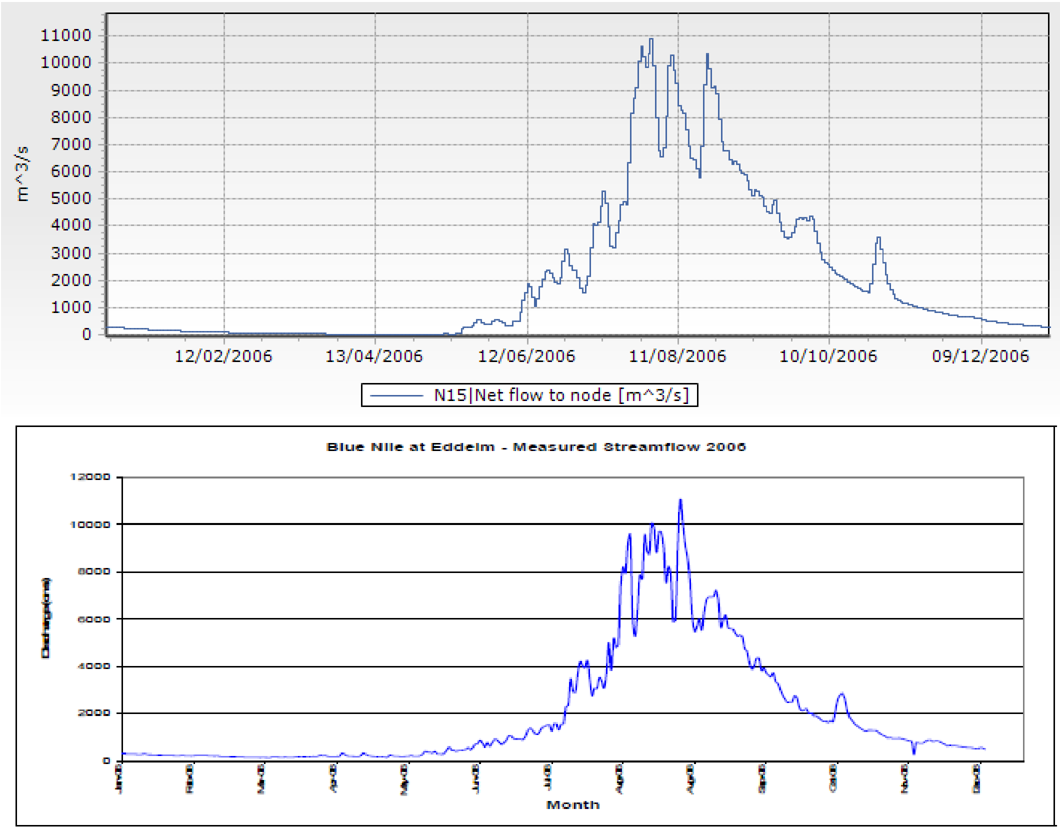
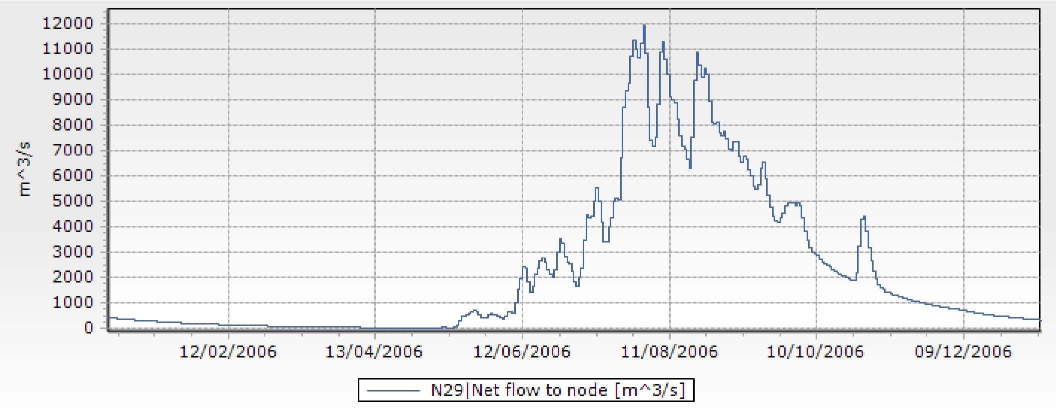


Figure 3.5 **Simulated (upper) and observed (lower) hydrograph in 2006 at Eddeim**



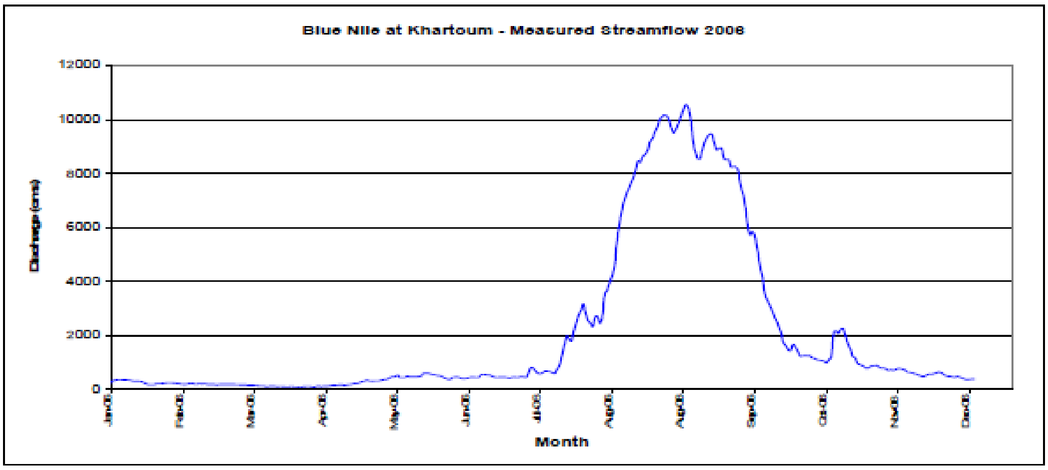


Figure 3.6 Simulated (upper) and observed (lower) discharge at Khartoum. Note that the simulation is without routing and reservoirs.

It is proposed to adjust/validate the models if/when additional discharge data is obtained.

3.3 Tekeze-Setit-Atbara Basin

The hydrological model for the Tekeze-Setit-Atbara Basin consists of 13 sub-catchments but only the upper sub-catchments of Tekezé at Embamadre have been calibrated. The flow data, which is currently available at other stations in this basin, is not applicable for model calibration for flood simulation as it represents only low flow conditions.

Figure 3.7 Screenshot of the map of the TSA basin and gauging stations

GPM rainfall and ERA5 potential evaporation data have been applied. It was necessary for this catchment to apply a factor of 0.7 to the GPM rainfall data to obtain a suitable water balance. Note that observed discharge data is often missing during year 2001 at times, when the simulated flow exceeds 3000 m^3/s.

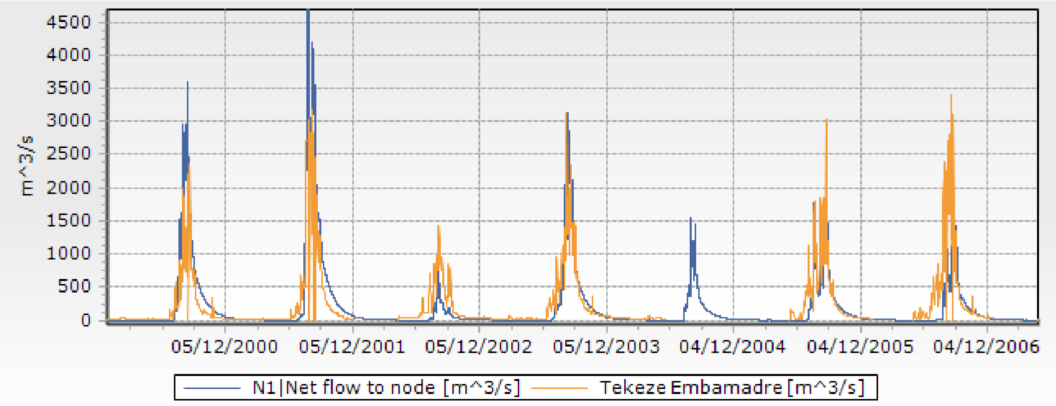


Figure 3.8 Comparison of simulated (blue) and observed (orange) flow at Embamadre station on Tekezé.

3.4 Dinder and Rahad

The current EN-FEWS does not forecast floods of the rivers Dinder and Rahad. In the current system the two rivers are rather modelled hydrologically as contributors of lateral inflows to the Blue Nile. The hydrological model of the two rivers is currently being discretized in more detail.

4 Enhancements and Improvements of the Hydrodynamic models of the EN-FFEWS

The enhancements and improvements of the hydrodynamic models have the purpose of updating and improving the already existing models for flood forecasting purposes.

The hydrodynamic modelling activity consisted mainly of analysing the existing models and assessing the initial quality of the models, as well as determining the main areas where the models can be improved to provide reliable and accurate results.

The main activities carried out until the time of delivering this report are outlined in the following sections.

4.1 Main Nile between Khartoum and Dongola

The current EN-FEWS does not include the river stretch of the Main Nile between Khartoum and Dongola (creation of this model is ongoing). The flood forecasts for this river reach will have to be developed with global earth observations products (e.g. digital elevation models). Calibration and validation of the hydrodynamic model for this sub-system will be carried out with historical hydro-meteorological datasets of the client, where available.

4.2 Blue Nile Basin

The Blue Nile modelling activity followed the same outline as the one for Tekeze-Setit-Atbara with multiple iterations of model analysis and simulation runs to improve the overall model quality and reduce instabilities.

The model quality assessment was done by running the model using the existing parameters. During this process, it was observed that the cross-sections were correctly defined, and the markers were set to convey the entire discharge along the river. The cases where the water level exceeded the markers elevation were corrected by either changing the marker location or by extending or replacing the cross-section (if possible).

During the model analysis, an evaluation of the cross-section quality vs. the DEM quality was done to assess if the DEMs quality is sufficient to be used as a source for extracting new cross-sections. In this analysis it was observed that the existing cross-sections had a higher quality than the DEM could have provided, thus they were kept in their original location and shape. Figure 4.1 shows a comparison between the existing cross-sections and those extracted from the DEM.

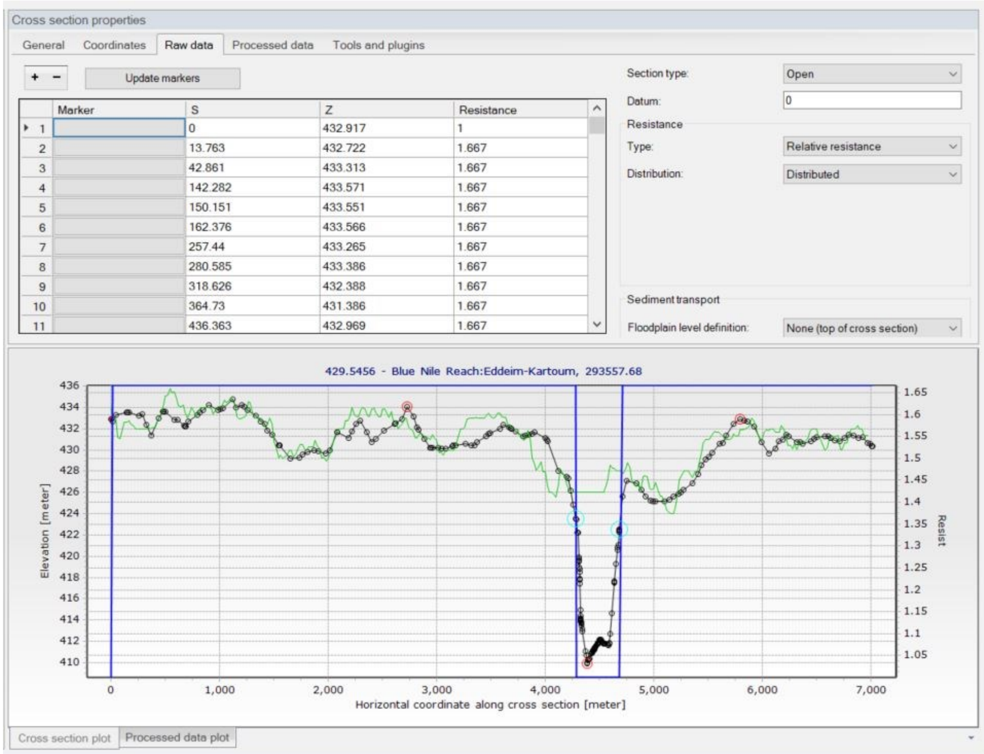


Figure 4.1 Comparison between the original cross-section (black) and the DEM (green)

The figure above shows that the main differences between the cross-section are visible in the river channel where there is a difference of up to 18m, while the overall shape and elevation range in the floodplain is quite similar. This implies that the DEM can be used to extend the cross-sections if needed, but not for new cross-section generation because of the significant difference in the river channel.

Like the Tekeze-Setit-Atbara analysis, multiple iterations were done to correctly define the markers so the historical flows, as well as the 100-year event can be fully conveyed without exceeding the marker elevations. Also, multiple iterations were done to stabilize the model, as some locations (such as the most downstream point to the confluence with the White Nile) were highly unstable providing unrealistic water levels. Figure 4.2 shows a longitudinal profile with the banks, thalweg and water level.

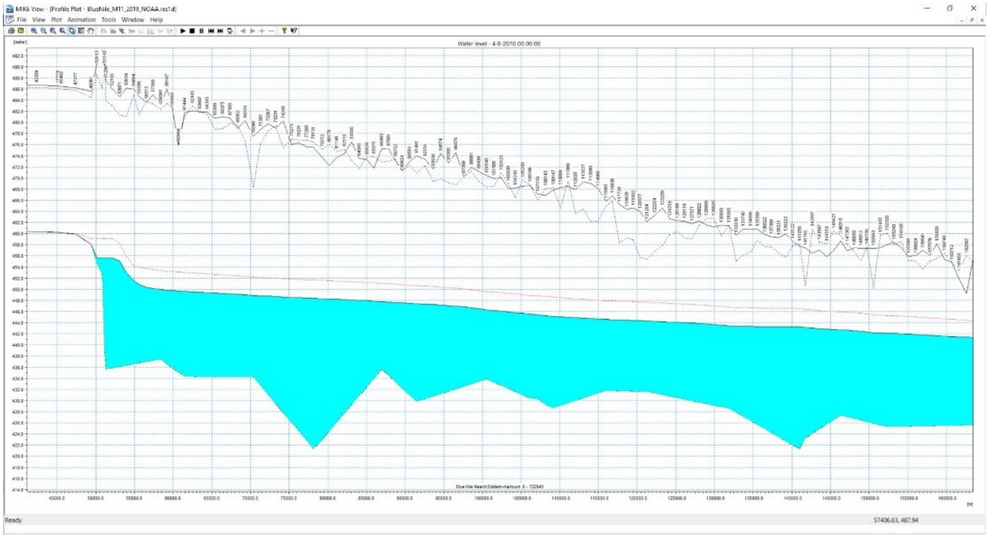


Figure 4.2 Longitudinal profile along the Blue Nile downstream of the Sennar dam.

4.3 Tekeze-Setit-Atbara Basin

The Tekeze-Setit-Atbara (TSA) model has been analysed from a hydrodynamic perspective and subjected to a series of modifications with the purpose of improving the model stability and representation of the current situation of the terrain.

Firstly, the cross-sections have been analysed one by one and multiple iterations were performed to modify the markers (points that actively define the cross-sectional area) in such a way that the flow is conveyed completely through the cross-sections and no points are registered where the water level is higher than the points defined as cross-section edges (which might lead to over-estimated water levels).

Furthermore, in the locations where a good quality DEM was available, new cross-sections have been added to improve the local quality of the model. Such cross-sections were added in the Humera and Atbara locations.

During model analysis, several model runs have been made, both using historical data and synthetic flood events. At first, the cross-section markers were adjusted based on the historical flow series, but they were determined to be too low when compared to the water levels generated by the 100-year return period event discharge. Because of this, a new iteration of the cross-sections markers was generated, as well as updating all cross-sections which were not extended enough to be able to fully convey the 100-year flood. In this regard, approximately the entire extent of the Atbara River has been updated with close to 100 cross-sections being extracted and introduced into the model. The new cross-sections were generated using a DEM from JAXA (Japan Aerospace Exploration Agency - ALOS Global Digital Surface Model "ALOS World 3D - 30m (AW3D30)"). During initial model analysis it was observed that the ALOS DEM is comparable in precision and overall shape to the cross-sections already existing in the model, thus being deemed suitable for cross-section extension and addition. In the following images a comparison between the initial cross-section layout and the updated one is made.

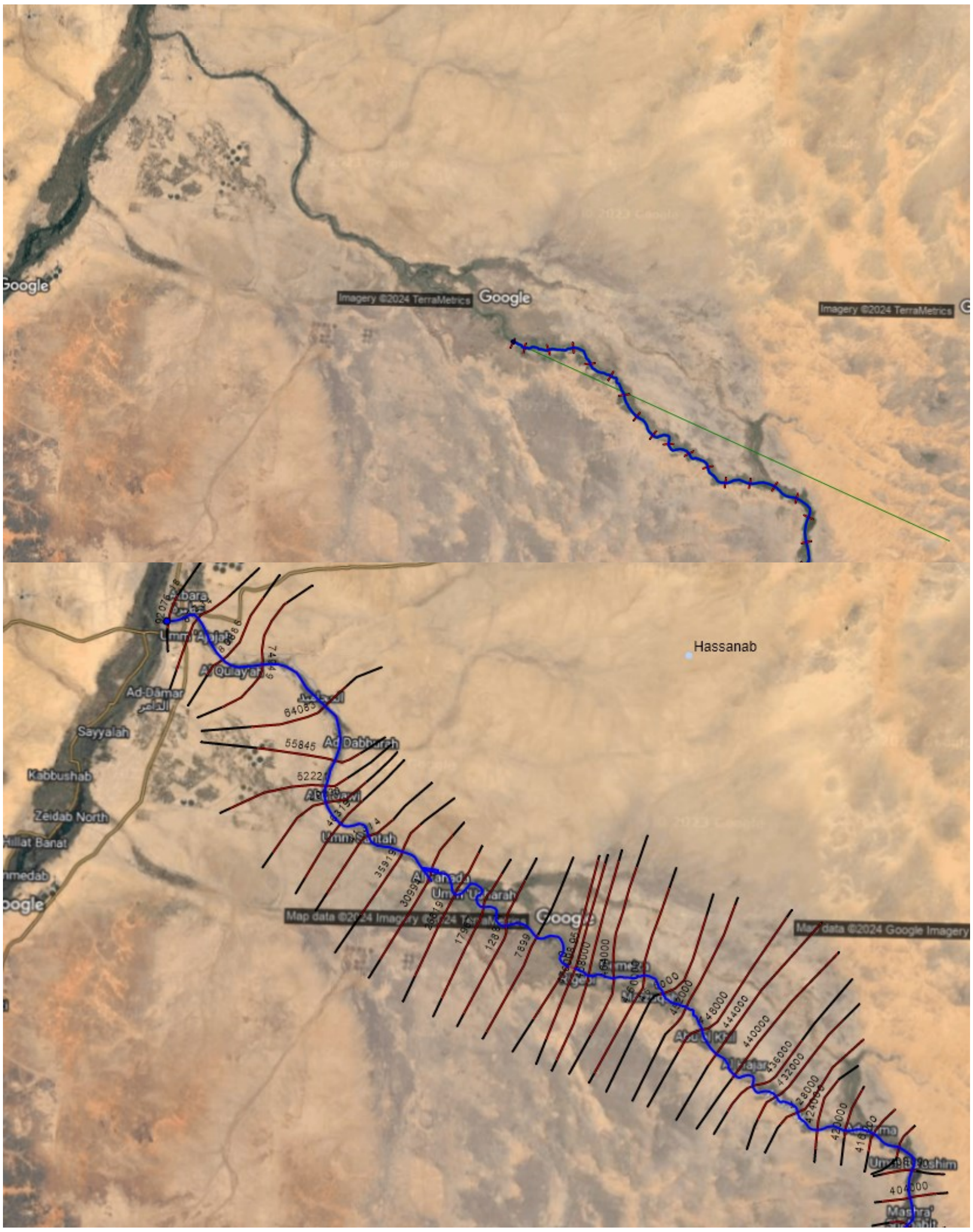


Figure 4.3 Comparison between the original model (top) and the updated model (bottom)

It can be seen from Figure 4.3 that the downstream part of the Atbara River has also been extended with approximately 92km of river and cross-sections. The cross-sections were created based on the same ALOS DEM and improved locally where the Atbara DEM was available.

The river delineation was also improved locally by adding secondary branches where they were missing from the model, as well as adding the Angereb river which flows into the Tekeze Atbara node into the reservoir, for a better representation of the flow and attenuation through the reservoir (see Figure 4.4).

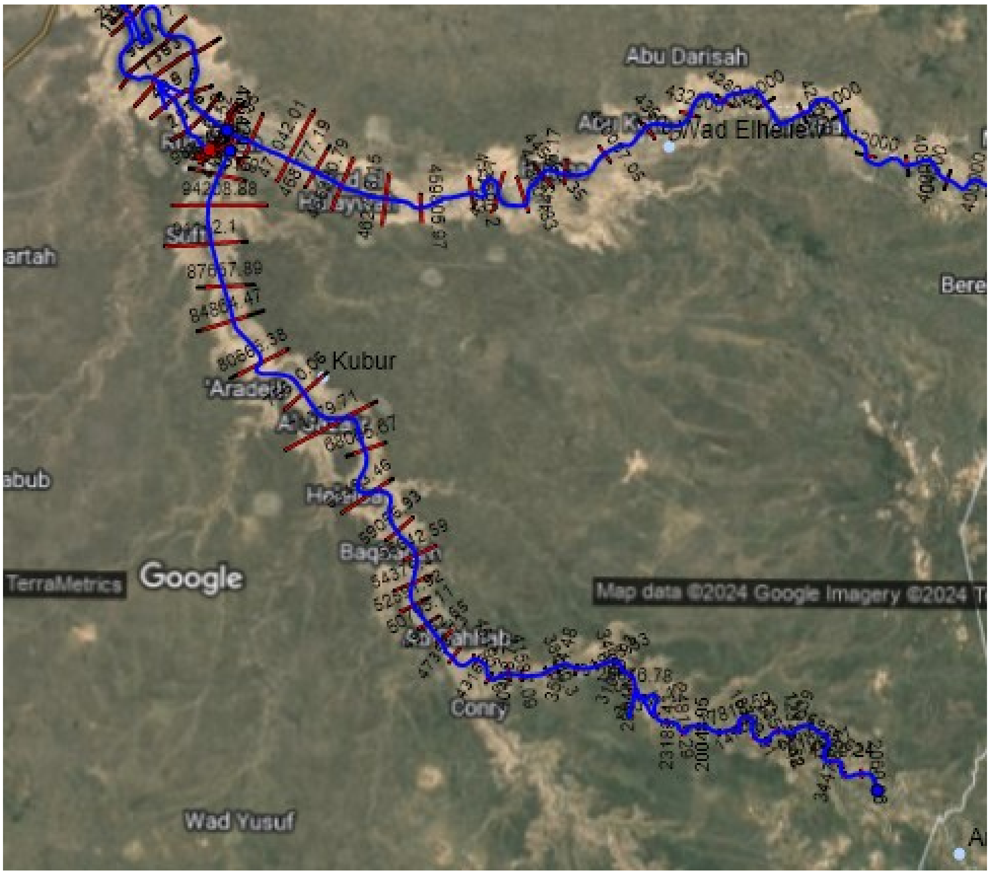


Figure 4.4 **Angereb branch added to the model and secondary branch just downstream of the dam on the left side of Atbara.**

In terms of reservoirs, the TK-5 dam was schematized into the model and a calibration attempt was made to match the operation of the reservoir, based on the data provided and available. Because of the lack of bathymetry information, the dam was schematized using a storage structure which simulates the available storage of the dam (elevation-volume curve), a weir which represents the crest level of the dam and a series of control rules simulating the outflow based on the reservoir' water level. Figure 4.5 shows the calibration attempt, compared to the real operation graph.

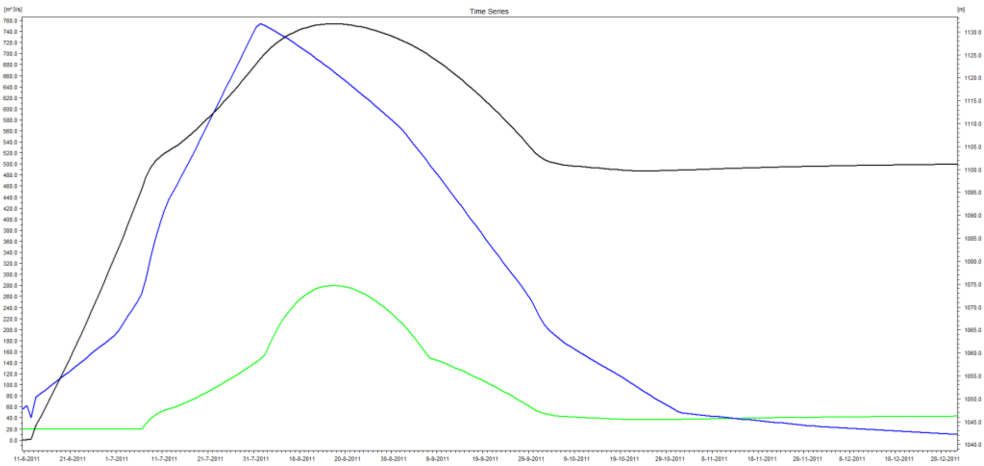


Figure 4.5 **Reservoir operation simulation – inflow discharge (blue), outflow discharge (green) and reservoir water level (black).**

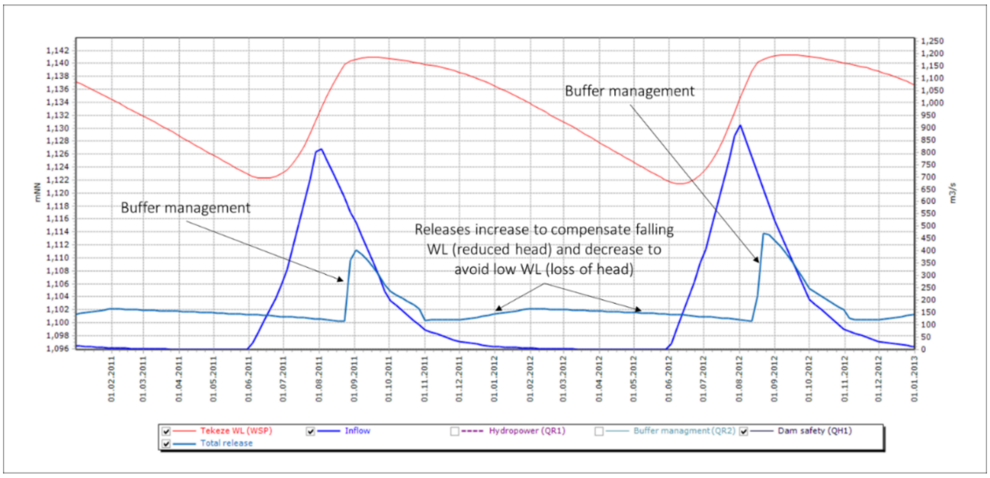


Figure 4.6 Real reservoir operation graph

4.4 Dinder and Rahad

The current EN-FEWS does not forecast floods of the rivers Dinder and Rahad. In the current system the two rivers are rather modelled hydrologically as contributors of lateral inflows to the Blue Nile. The hydrodynamic models will be developed with datasets from global earth observations products (e.g. digital elevation models). Calibration and validation of the hydrodynamic model for this sub-system will be carried out with historical hydro-meteorological datasets of the client, where available.

5 Summary and Conclusions

The **hydrological models** have been revised based on GPM as rainfall input and ERA5 as potential evaporation.

The calibration of the models showed that rainfall input must be adjusted with correction factors. Despite this, the advantage of using GPM as input to calibrate the model is that data dissemination and performance evaluation of forecasts will become consistent. This is important because the purpose of the models is flood forecasting. While reasonable results with the hydrological models have been obtained at the calibration stations it would be advantageous if additional data can be obtained on the river flow, either at gauging stations or at reservoirs, where the inflow may be derived from other observations. This would enable refinement of the models and thereby reduce uncertainties in the flood assessments.

The **hydrodynamic models'** parametrization has been scrutinized and revised as far as possible:

1. Tekeze-Setit-Atbara Basin
    a. Cross-section geometries have been adjusted and harmonized with terrain information from DEMs.
    b. Parametrization of the model including setting of markers in the cross-sections is complete.
    c. The hydrodynamic model produces plausible results and is ready to be embedded in the EN-FFEWS.
2. Blue Nile Basin
    a. Cross-section geometries have been adjusted and harmonized with terrain information from DEMs.
    b. Parametrization of the model including setting of markers in the cross-sections is complete.
    c. The hydrodynamic model produces plausible results and is ready to be embedded in the EN-FFEWS.

As described in chapters 3 and 4 the **hydrological** and **hydrodynamic models** for the Main Nile (between Khartoum and Donglola), Dinder and Rahad rivers are currently being developed and should be completed by the end of March 2024. After the development of the models, the present report will then be revised accordingly.