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Consultancy service for work package 2 – Enhancement of the Eastern Nile Flood Forecasting and Early Warning (EN-FFEWS) and Flood Risk Mapping

Enhanced and Improved EN-FEWS Report
Project No 11829050

18-MAR-2024

Prepared for Eastern Nile Technical Regional Office (ENTRO)

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Project No 11829050

Prepared for:	Eastern Nile Technical Regional Office (ENTRO)
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Project No.:	11829050
Approved by:	Oluf Z. Jessen
Approval date:	18-03-2024
Revision:	Draft 2.0
Classification:	**Confidential:** This document is only accessible to the project team members and sharing it outside the project team is subject to the client's prior approval.
File name:	ENTRO_Flood_WP2_enhanced_EN_FEWS_V2.docx

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List of abbreviations

ALOS	Advanced Land Observing Satellite
BAS	Baro Akobo-Sobat
CPU	Central Processing Unit
DEM	Digital elevation model
EN	Eastern Nile
ENTRO	Eastern Nile Technical Regional Office
EOS	End Of Simulation
FFEWS	Flood Forecasting and Early Warning System
FPEW	Flood Preparedness and Early Warning Project
FRM	Flood Risk Mitigation
GFS	Global Forecast System
GIS	Geographic Information System
GPM	Global Precipitation Measurement
ICESat2	Ice, Cloud, and land Elevation Satellite 2
IT	Information Technology
JAXA	Japan Aerospace Exploration Agency
NBI	Nile Basin Initiative
NB-RFFS	Nile Basin River Flow Forecasting System
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
SMA	Software and Maintenance Agreement
SOS	Start of Simulation
SRTM	Shuttle Radar Topographic Mission
TOF	Time Of Forecast
TSA	Tekeze-Setit-Atbara
UI	User Interface
WP	Work Package
WRF	Weather Research and Forecasting

1 Introduction

This report is a deliverable of ENTRO's project "Consultancy Service for Work Package 2 - Enhancement of the Eastern Nile Flood Forecasting and Early Warning (EN-FFEWS) and Flood Risk Mapping". The consultancy is one of three work packages as part of the Eastern Nile (EN) Flood Preparedness and Early Warning Project (FPEW):

- Work Package 1: Survey and Data Collection – ongoing consultancy for ENTRO.
- Work Package 2: Enhancement of the Eastern Nile Flood Forecasting and Early Warning System (EN-FFEWS) and Flood Risk Mapping – this consultancy.
- Work Package 3: Support in Establishing Flood Community Awareness and Preparedness – consultancy that builds on Work Packages 1 and 2.

This Work Package 2 also builds on results and outcomes from Work Package 1 from its following tasks:

- Collect Terrain Datasets of Flood Prone Areas.
- Compile Historical Hydro-Meteorological Datasets.
- Determine Key Characteristics of Flood Prone Communities.

The objective of this Work Package 2 is to contribute to the improvement of the Eastern Nile Flood Risk Mitigation (EN-FRM) Project as follows:

- An enhanced EN FFEWS, so that reliable flood forecasts and early warnings for the EN region become available to member countries.
- Flood maps with flood hazards and risks for key flood prone areas in the EN region, so that flood protection measures and flood response preparedness actions can be planned adequately.
- Enhanced forecasting capacity for better management of dam operation and water resources planning.

The scope of work under this Work Package 2 comprises five tasks for the riverine flood prone areas in the Eastern Nile basin

- Task 1: Improve Performance of the EN-FFEWS.
- Task 2: Flood Hazard Assessment and Flood Extent Mapping.
- Task 3: Flood Vulnerability Assessment.
- Task 4: Flood Risk Assessment.
- Task 5: Flood Impact Assessment Capacity Building at Regional Level.

This report "Enhanced and Improved EN-FFEWS" (Deliverable 1.2) is a concise documentation of the enhancements and improvements made to the EN-FFEWS. It documents Deliverable 1.1 "Enhanced and Improved EN-FFEWS", which comprises the enhanced and improved software system, as well as the enhanced and improved hydrological and hydrodynamic models that are core components of the forecast model. These hydrodynamic models are also the core of the flood extent models under Task 2 "Flood Hazard Assessment and Flood Extent Mapping" = Deliverable 2.1 "Flood Extent Models".

The structure of this report is as follows:

- **Chapter 1** explains the context of the report (this chapter).

- **Chapter 2** documents the software enhancements and improvements of EN-FFEWS.
- **Chapter 3** explains the hydrological models of the EN-FFEWS.
- **Chapter 4** explains the hydrodynamic models of the EN-FFEWS.
- **Chapter 5** documents the flood extents derived from the hydrodynamic models.
- **Chapter 6** summarizes the enhancements with reflections on the way forward.

2 Software Enhancements and Improvements of the EN-FFEWS

2.1 EN-FEWS configuration

The EN-FFEWS has been migrated to a development server and is accessible to the public: https://entro-ffews-dev.westeurope.cloudapp.azure.com/. Once all enhancements and improvements, including the replacement of the embedded (registered) old models with the new, improved, and enhanced ones, are concluded, the final version will be deployed on a cloud server of ENTRO's choice.

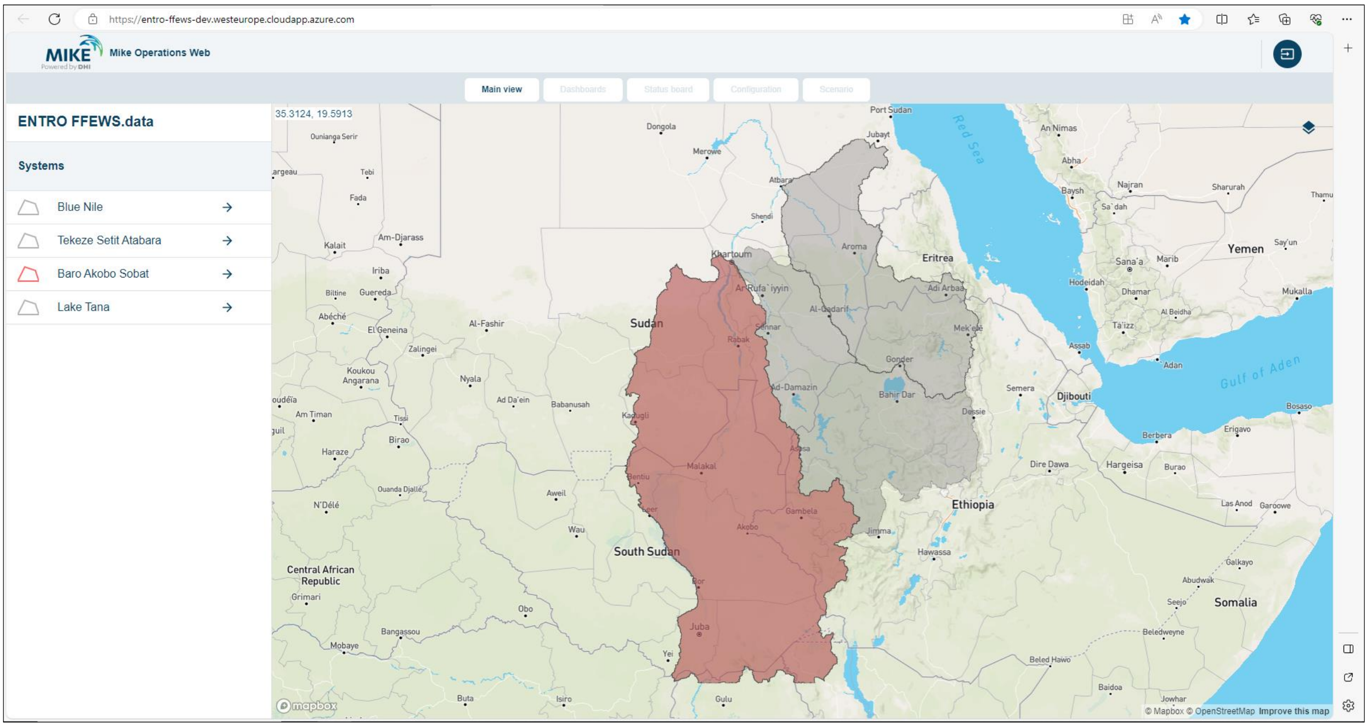


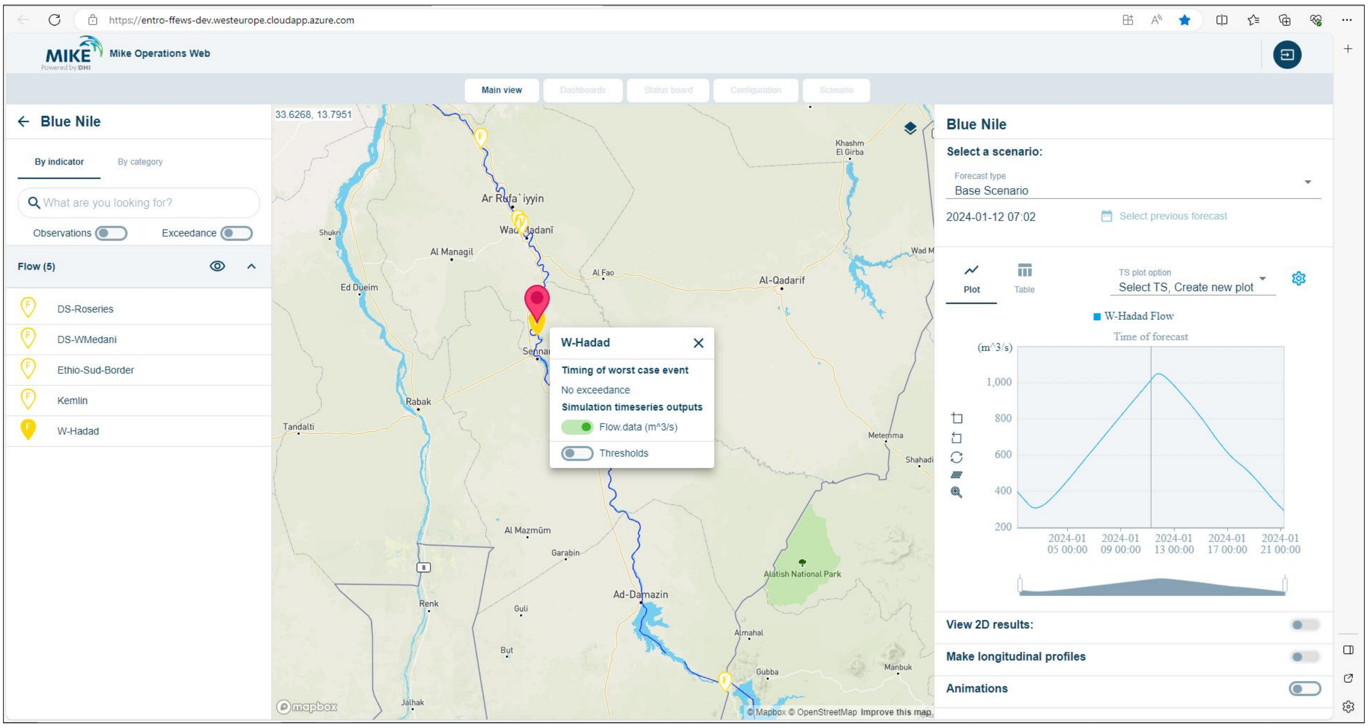
Figure 1 Screenshot of the start page of the enhanced EN-FFEWS

So far, the following recommendations of the Inception Report have been implemented:

1. **Server**
    a. Currently, the ENTRO's four flood forecasting systems run on the same server as the NBI river flow forecasting system. Presently, the C-drive has only 8.00 GB of free space. The NBI river flow forecasting system is also storage and CPU intensive. Therefore, the recommendation would be to use a different server for the four flood forecasting systems to obtain appropriate storage and CPU capacity for both the four flood forecasting systems and the NBI river flow forecasting system. An alternative could be to optimize or extend the storage and CPU capacity of the existing server. This will be done when moving to production.
3. **MIKE Software**
    a. Update the MIKE Software to the latest version.
4. **MIKE Workbench Configuration**
    a. Some python scripts were stored outside of the MIKE Workbench database. To facilitate maintenance and migration of the forecasting systems, the Python scripts have been integrated into the Script Manager of MIKE Workbench.
    b. All four models and logic now run in **one** database, to ease maintenance and reduce duplication of code.
    c. Many more output time series are included in the MIKE Workbench simulation than presented in the MIKE Operations Web or MIKE Operations Desktop. To reduce storage size and increase database performance, the number of output time series has been reduced to include only relevant forecast locations - only the time series of interest have been added to the scenarios.
    d. The script manager has been structured with folders for easier understanding and maintenance of scripts.
    e. There wasn't any database maintenance and archiving. An easily configurable database maintenance and archiving system has been implemented. It will have the following advantages:
        - Database performance.
        - Easy migration and sharing of copies of the real-time system.
        - Improved forecasting system stability in the long-term .
        - No issues in keeping the forecasting system online throughout the year.
5. **High-level user interface for flood forecasting systems**
    a. All systems are set up in MIKE Operations Web 2.0. Forecast locations and threshold definitions have been adopted from MIKE Operations Desktop as much as possible. The operator

view is now the MIKE Operations Web 2.0 website and MIKE Operations Desktop is no longer needed.

6. **Observed real-time rainfall**
    a. Observed Rainfall data does not seem up to date. The recommendation is to run the forecasting system with observed rainfall as close as possible to the time of forecast. Real-time satellite products such as GPM Late and GPM Early could be used and implemented in the real-time flood forecasting systems. If station data are available, then the satellite rainfall observations could also be bias-corrected with respect to station observations.
    The new development database uses GPM Late rainfall as observed rainfall product up to the time of forecast.


https://entro-ffews-dev.westeurope.cloudapp.azure.com

Forecast type: Base Scenario

2024-01-12 07:02

TS plot option: Select TS, Create new plot

Timing of worst case event: No exceedance

Figure 2 **Screenshot of exploring forecasts with the enhanced EN-FFEWS**

The following recommendations of the Inception Report have not been implemented yet:

7. **Dissemination** *– this will be carried out in Activity 1.2 (Improve and Enhance Dissemination Paths of Warnings).*
    a. The review did not identify routines for disseminating automatic messaged of flood warnings and alerts to relevant stakeholders. The recommendation is to implement automatic notifications via established notification channels (e.g. email and/or WhatsApp) to relevant stakeholders.
8. **System Monitoring** *– this will be carried out in Activity 1.2 (Improve and Enhance Dissemination Paths of Warnings).*
    a. It is recommended to introduce automatic messages on the system status, i.e. the job status of the scheduled jobs in the real-time forecasting system.

9. **Data Assimilation** *– this will be looked into when all necessary data becomes available.*
    a. It is recommended to introduce data assimilation in appropriate model locations if real-time water level or flow observations are available.
10. **Visualization of Gridded Rainfall** *– will be carried out next.*
    a. The web presentation of the real-time flood forecasting systems should be improved by visualizing the input gridded rainfall products.
11. **Ensemble Forecasting** *– this is not necessary and hence will be discarded.*
    a. To capture the uncertainty of the real-time water level and flow forecasts, ensemble forecasts could be produced using other products of available rainfall forecasts, e.g. national rainfall forecast products.
12. **Forecast Performance** *– the tools for this will be configured next, so that the performance evaluation can be carried out during the next flood season with the then available hydro-meteorological datasets.*
    a. The use of the real-time flood forecasting system could be informed by collecting and reporting on the forecast performance with respect to measured water level and/or flow, if available.
13. **Bias-Correction** *– this is not necessary and hence will be discarded, but the consultant is ready to advise on this matter if/when necessary.*
    a. The performance of the real-time flood forecasting systems could be improved by applying bias-correction to the observed and forecasted rainfall.
14. **Deployment** *– Activity 1.4 (Deploy the Integrated EN-FFEWS) will be concluded with this sub-activity, which will be carried out when the forecast system is technically ready for migration.*
    a. If ENTRO prefers to keep the data and real-time systems within their IT infrastructure it is recommended to deploy everything (Water Tools Portal, MIKE Operations Web 2.0, MIKE Workbench, and the embedded modelling tools) within NBI's IT infrastructure:
        - All data including user management on-premise.
        - No dependency on DHI services after project closure.
        - Updates available with Software and Maintenance Agreement (SMA).

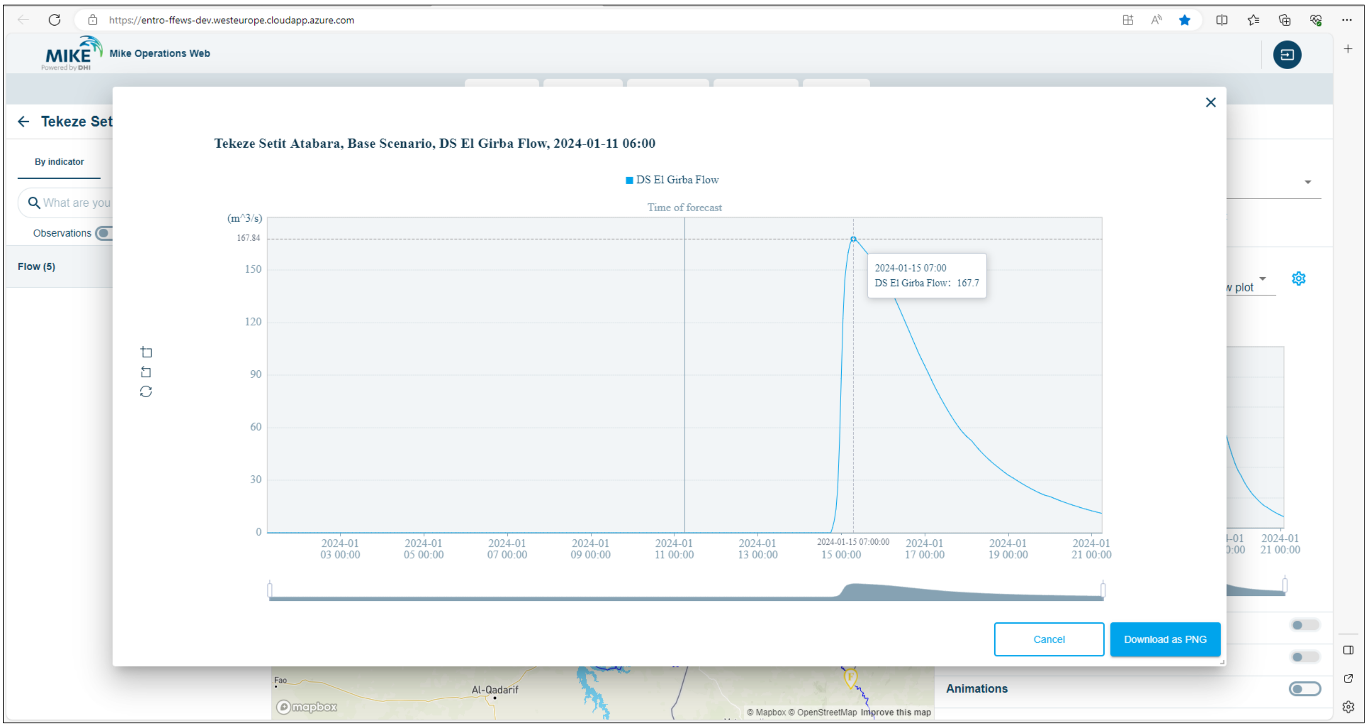


Figure 3 Screenshot of visualizing forecasts with the enhanced EN-FFEWS

The rainfall products used as input to the forecasting models are as followes:

- GPM: the Global Precipitation Measurement rainfall product is a dataset that provides information about rainfall distribution and intensity on a global scale. It is derived from data collected by the GPM satellite constellation, which includes microwave sensors capable of measuring precipitation from space.
- WRF: the Weather Research and Forecasting rainfall product is a dataset generated by the WRF model, a widely used numerical weather prediction system. It provides information about rainfall distribution and intensity over specific regions and time periods. The WRF model simulates atmospheric processes to forecast weather conditions, including precipitation.
- GFS: the Global Forecast System rainfall product is a dataset produced by the GFS model, a numerical weather prediction system operated by the National Centers for Environmental Prediction (NCEP). It provides forecasts of rainfall distribution and intensity globally and at various spatial and temporal resolutions.

The following terms are defined to aid understanding of the generation of input rainfall to the models:

- SOS: Start of Simulation, the first date of the simulation.
- TOF: Time Of Forecast, representing the specific time at which a forecast is made or is valid from. In other words, it indicates the moment where observations end, and predictions start.
- EOS: End Of Simulation, the last date of the simulation.

In the real-time operations, the concatenation of rainfall products occurs in the following order:

- GPM rainfall, with a factor of 0.7, from SOS to TOF.
- WRF rainfall, from TOF to EOS.
- If the resulting time series does not cover until EOS, GFS rainfall is used to complete the input.
- If the resulting time series still does not cover until EOS, zero rainfall values are appended to ensure the model has the correct input.
- If there is any missing data between the first GPM value and SOS, the input time series is filled with zero rainfall values to ensure the model runs correctly.

2.2 Flood forecast locations

Flood forecast locations have been defined in the 4 basins. These locations are discharge calculation points where the result from the simulation is compared to flood hazard levels. The existing locations in the EN-FEWS are reused and some additional locations were added. The Table 1 presents the list of all forecast locations. When available (provided by ENTRO) the existing thresholds were used, otherwise they were calculated based on a statistical analysis of a long simulation. The discharge with a 2-years return period is used as low hazard level, the one with 5-years as medium hazard level and the one with 10-years ad high flood hazard level.

Table 1 List of flood forecast location, discharge in m3/s associated with 2, 5, 10 and 50 years return period and existing flood hazard levels provided by ENTRO

Model	Name	Calculation point	2 years	5 years	10 years	50 years	Low hazard level	Medium hazard level	High hazard level
BN	DS-Roseries	Blue Nile Reach:Eddeim-Kartoum 56057.1	3578	4037	4341	5010	-	-	-
BN	W-Hadad	Blue Nile Reach:Eddeim-Kartoum 397539	3924	4566	4992	5927	-	-	-
BN	DS-WMedani	Blue Nile Reach:Eddeim-Kartoum 513666	3994	4882	5470	6764	-	-	-
BN	Kamlin	Blue Nile Reach:Eddeim-Kartoum 612370	3969	4849	5431	6714	5200	7500	8680
BN	Karthoum	Blue Nile Reach:Eddeim-Kartoum 713682	3955	4830	5410	6686	-	-	-
BN	Ethio-Sud-Border	BlueNile_upper_Roseires 23027	3229	4421	5211	6949	3171	9513	12684
BAS	Bonga-US-Gambela	Baro_Sobat 7016.74	862	997	1086	1283	-	-	-
BAS	Gambela	Baro_Sobat 46755.8	993	1145	1245	1466	-	-	-
BAS	Itang	Baro_Sobat 97234	614	681	726	824	334	1003	1338
BAS	DS-Junction	Baro_Sobat 277391	668	810	904	1111	-	-	-
BAS	Nasir	Baro_Sobat 318354	229	290	330	419	-	-	-
BAS	DS-Nasir	Baro_Sobat 409735	224	280	318	400	-	-	-
BAS	Adong	Baro_Sobat 559779	201	246	275	339	-	-	-
BAS	Pibor	Pibor 101872	31	82	115	189	-	-	-

BAS	US-Akobo-junction	Pibor 299040	79	169	229	360	-	-	-
BAS	DS-Akobo	Pibor 319835	118	237	316	489	-	-	-
BAS	DS-Bul-Akobo	Pibor 373958	149	299	399	618	-	-	-
BAS	Malakal	WhiteNile 32767.3	1453	1734	1921	2331	-	-	-
BAS	Kodok	WhiteNile 100637	1598	1926	2142	2619	-	-	-
BAS	US-Melut-Tributary	WhiteNile 159194	1457	1796	2020	2514	-	-	-
BAS	Al jabalyn	WhiteNile 465640	1317	1667	1899	2409	-	-	-
BAS	Ad Douiem	WhiteNile 647781	1248	1593	1821	2324	-	-	-
BAS	Gilo	Gilo 12133.3	36	80	108	172	-	-	-
BAS	Pochalla	Akobo 16770.7	42	91	123	194	-	-	-
BAS	UP-Akobo	Akobo 71772	43	94	127	200	-	-	-
BAS	Maban	WN_MacharMarshes-KhawrYabus	123	238	313	480	-	-	-
TSA	Tekeze-Dima	Tekeze 217936	1053	1725	2170	3150	-	-	-
TSA	Tekeze-Humara	Tekeze 376882	1466	2362	2955	4260	234	850	1200
TSA	Showak	Atabara 26000	2155	3517	4420	6406	-	-	-
TSA	DS El Girba	Atabara 226000	2082	3409	4288	6221	-	-	-
TSA	Kubur	Angereb 48255.7	710	1016	1218	1663	-	-	-
TSA	Al fahada	DS_Atbara 28406.5	1956	3186	4000	5793	-	-	-
TSA	Atbara	DS_Atbara 83960	1946	3168	3976	5756	-	-	-
LT	Upper-Ribb	Ribb_dam 3399.56	24	36	43	59	-	-	-
LT	Lower-Gumara	GUMARA RIVER REACH 34806.9	299	352	387	464	-	-	-
LT	Ribb Addis Zemen	Ribb River Reach:New 5492.92	26	30	33	40	55	164	219
LT	Lower-Old_Ribb	Ribb River Reach:New 26752.5	52	67	77	98	-	-	-
LT	Lower-Ribb	Old Ribb Reach:Old 17416.2	34	51	63	87	-	-	-
LT	Aba Libanos	Megech River Reach:Megech 1044.65	108	137	156	197	-	-	-
LT	Middle-Megech	Megech River Reach:Megech 2013.48	109	137	156	197	-	-	-
LT	Lower-Megech	Megech River Reach:Megech 12807.2	113	141	160	202	-	-	-
LT	Dirma at Kola Diba	Dirma River Reach:Dirma 2706.55	27	35	40	51	32	95	126
LT	DS-Dirma	Dirma River Reach:Dirma 18121.6	48	61	70	88	-	-	-
LT	Lower-Dirma	Dirma River Reach:Dirma 29706.8	68	85	96	120	-	-	-
LT	Gumara Woreta	GUMARA RIVER REACH 11964.3,,	211	251	278	337	77	231	308
LT	Upper-Gumara	LakeTana_Gumara_US	162	197	220	270	-	-	-
LT	Megech Azezo	LakeTana_Megech_US	107	135	154	195	89	266	355

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

Upscaling and improving the four hydrological models of the EN-FFEWS (Blue Nile, Tekeze-Setit-Atbara, Baro-Akobo-Sobat and Tana), apart from migrating the models to the latest version of NAM, was done by carrying out the following:

1. Revisiting the delineation of the catchments, and re-delineating where necessary, taking into consideration relevant river reaches and flood forecast locations for the EN-FFEWS.
2. Investigating and adjusting where necessary (e.g. with regionalization approach) the catchment model parameters in terms of plausibility and consistency.
3. Simulating the rainfall-runoff-process taking rainfall from historical GPM-data, and comparing the resulting discharges with the available historical records.
4. Evaluating the comparison between simulated discharges and historical observations, and making 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 the EN-FFEWS will be operational using 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 following sections discuss the initial results obtained in the development of hydrological models for flood forecasting and flood mapping purposes.

3.1 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 currently available at other stations in this basin, is not applicable for the calibration of a flood model as it is only capturing low flow conditions.

Figure 4 **Image of the TSA basin (green polygons) and gauging stations (red points).**

GPM rainfall and ERA5 potential evaporation data have been applied. In the case of this basin, it was necessary to apply a factor of 0.7 to the GPM rainfall data to obtain a suitable water balance, see Figure 15. Note that observed discharge data is often missing during year 2001 at times, when the simulated flow exceeds 3000 m^3/s, see Figure 6.

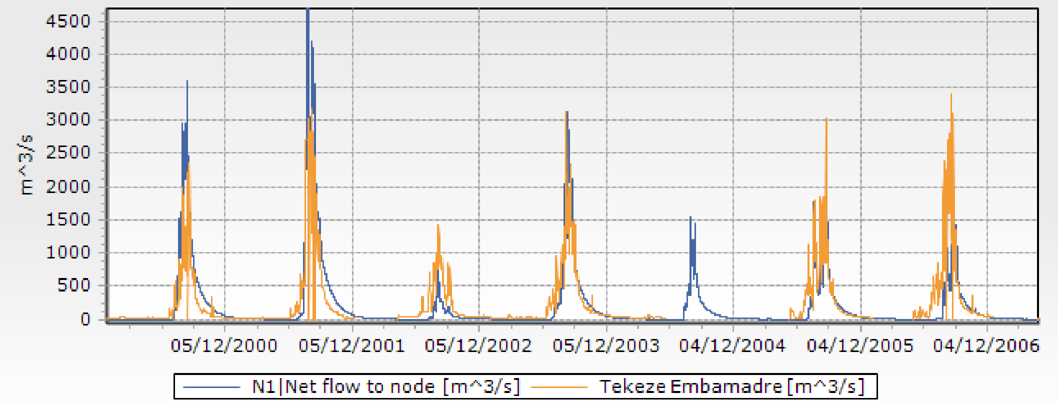


Figure 5 Comparison of simulated (blue) and observed (orange) flow at Embamadre station on Tekezé.

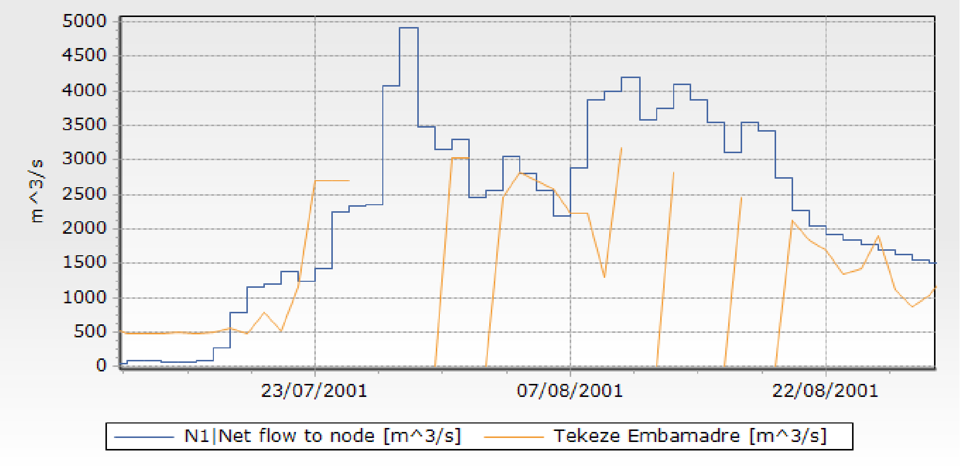


Figure 6 Comparison of simulated (blue) and observed (orange) flow at Embamadre station on Tekezé during 2001. Note that observed flow above 3000 m^3/s is missing.

3.2 Blue Nile Basin

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

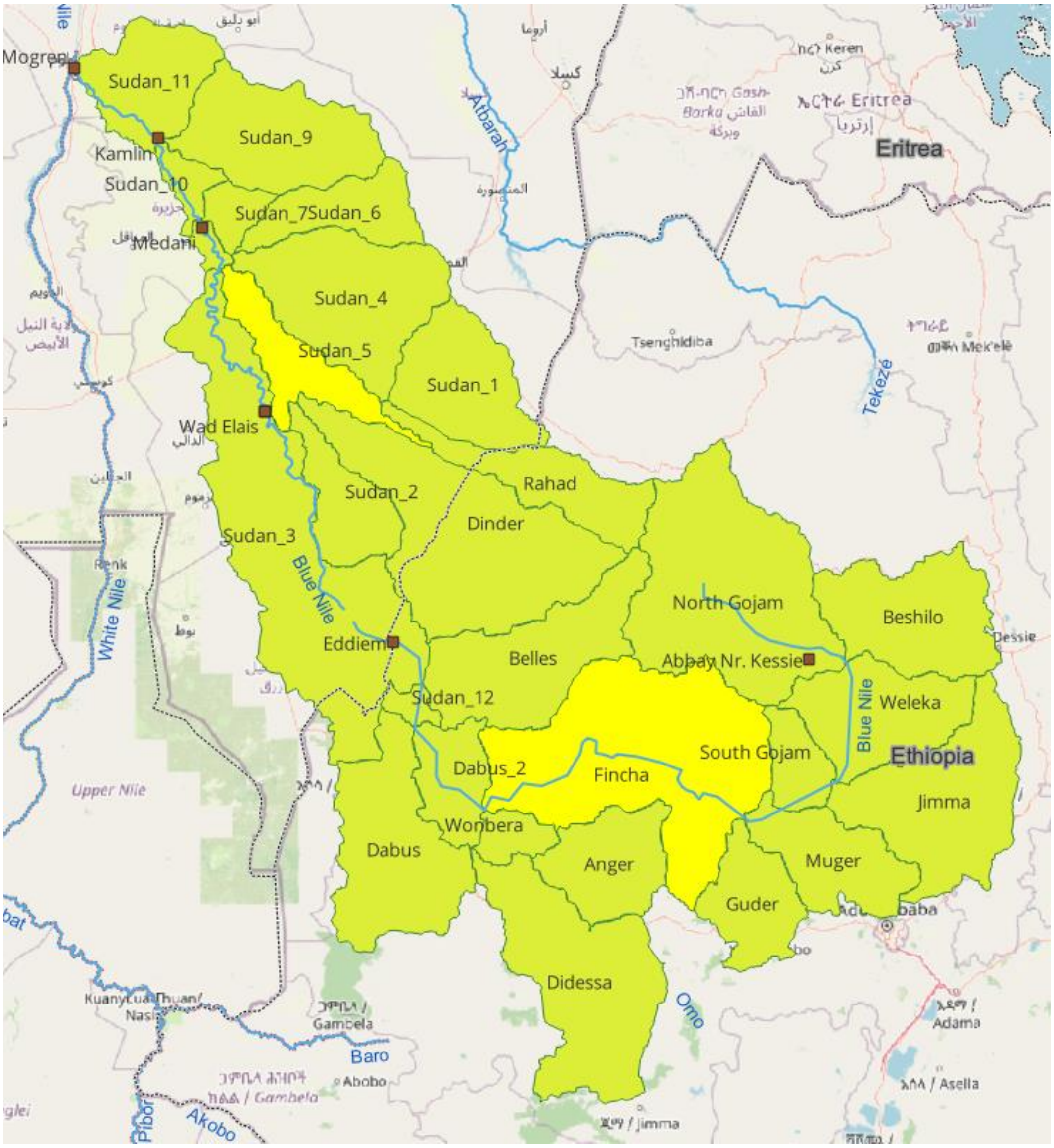
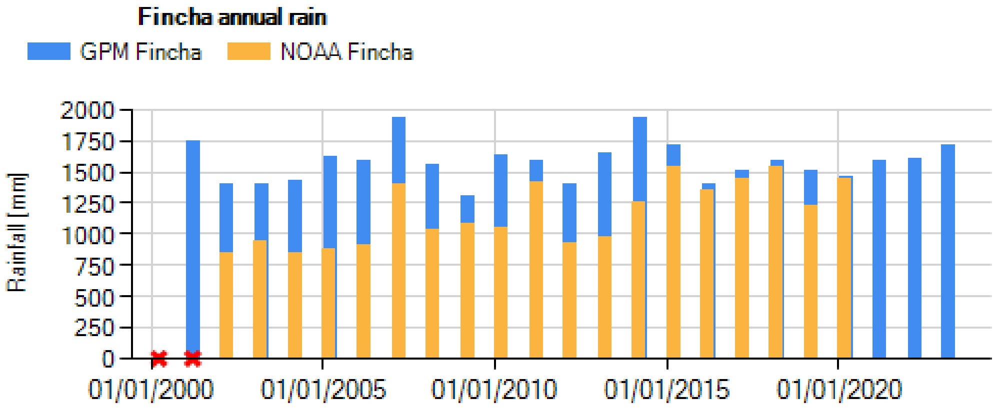


Figure 7 **Blue Nile basin. Selected data of the highlighted sub-catchments are illustrated in Figure 8 and Figure 9**

GPM rainfall data has been downloaded for the sub-catchments, as this data is available in near-real-time and can be applied for flood forecasting. The previous version of the model used rainfall data from NOAA, which is considerably lower in most years, see Figure 8. ERA5 potential evaporation data has also been downloaded and compared with the data applied in the original model, see Figure 9. ERA5 has higher values, mainly in the early years.



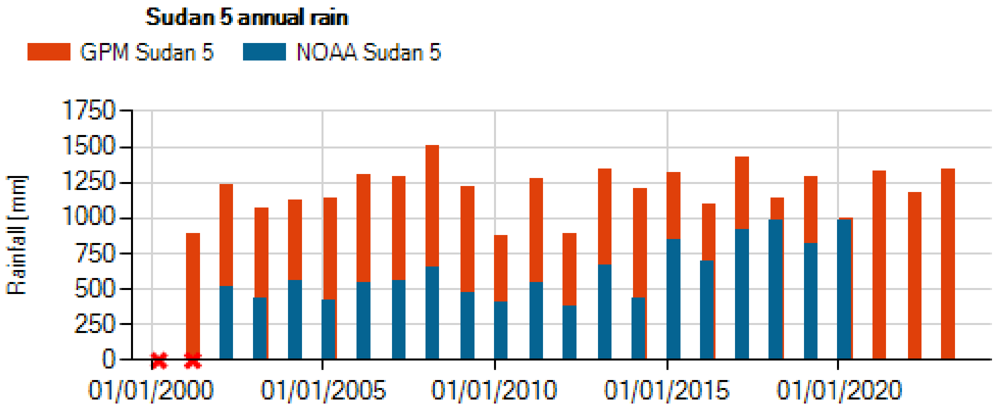


Figure 8 **The NOAA Rainfall applied in the previous model is considerably lower than the GPM as shown in these examples.**

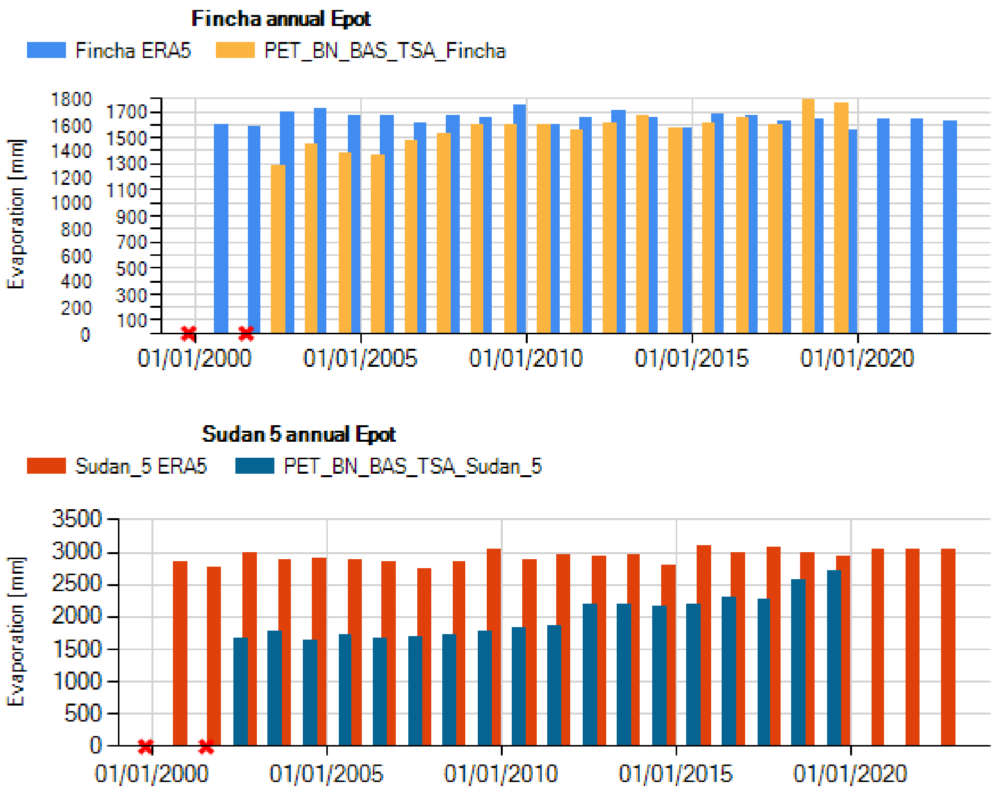


Figure 9 **The potential evaporation (ERA5) is somewhat higher than the previously applied data, which shows an increasing trend over the simulation period.**

Discharge data time series are only available at Abbay Kessie currently. Screenshots of measured flow for a few years can further be found in Riversides report on flood risk mapping of January 2010.

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 10 to Figure 13. Further adjustments will be made if/when additional hydro-meteorological data is obtained.

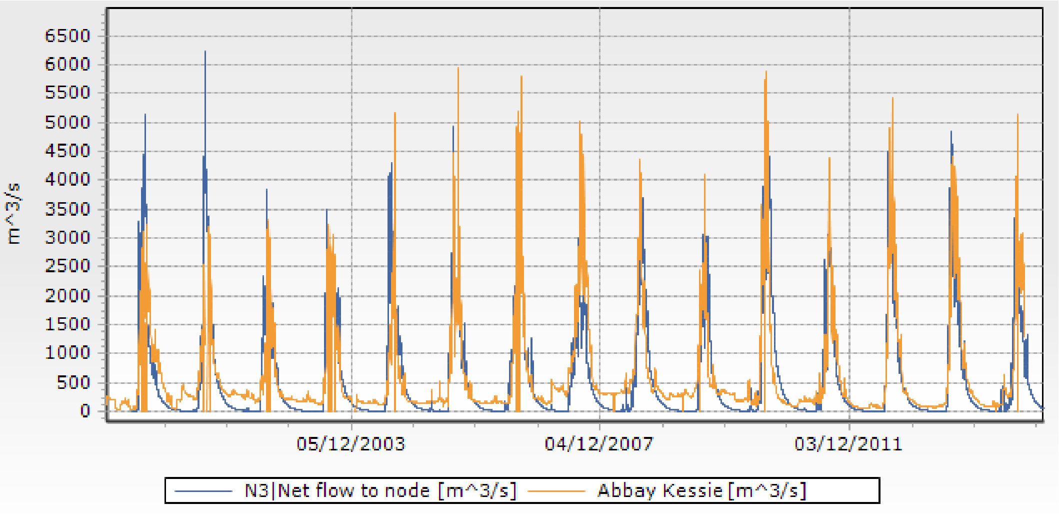


Figure 10 Simulated (blue) and observed (orange) flow at Abbay Kessie. Looking at the longer record of observed flow (not shown here) it seems that discharge values above 3000 m^3/s could not be measured prior to 2003.

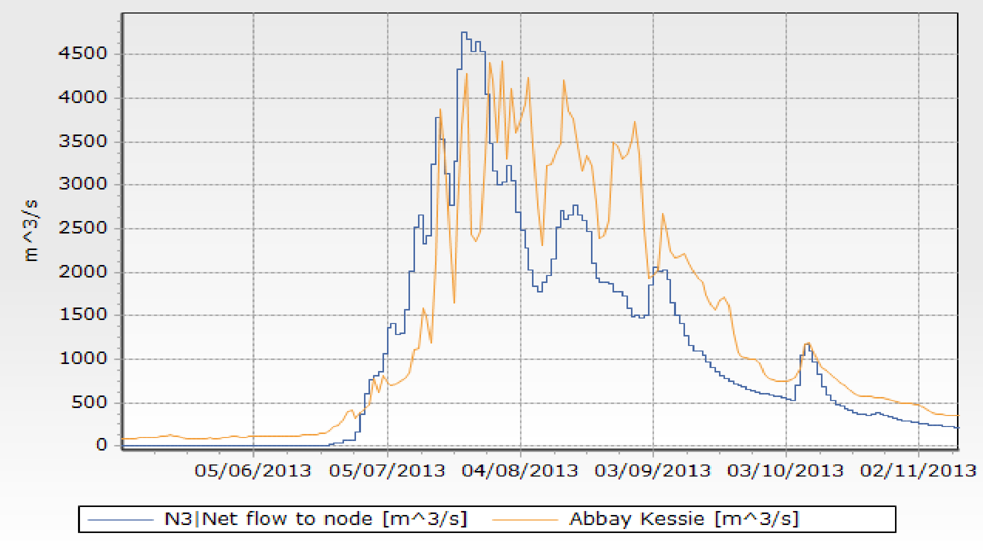


Figure 11 Simulated (blue) and observed (orange) flow at Abbay Kessie during 2013.

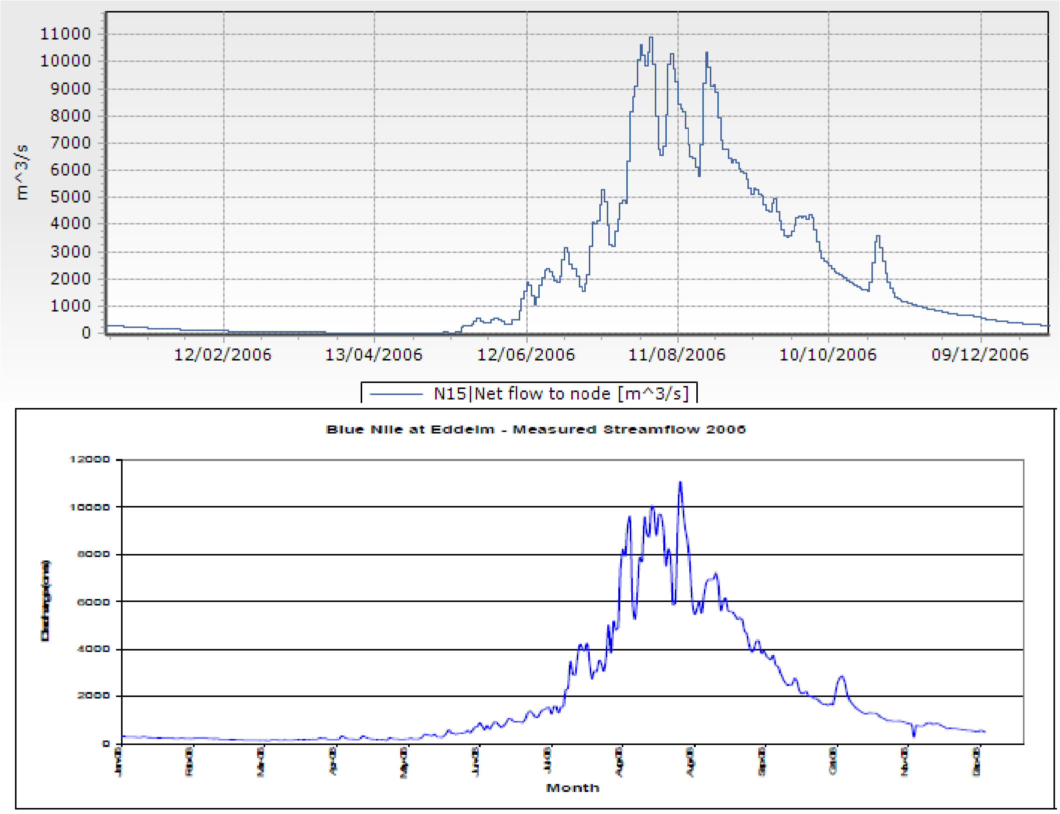


Figure 12 Simulated (upper) and observed (lower) hydrograph in 2006 at Eddeim (Riverside 2010 Flood risk mapping report).

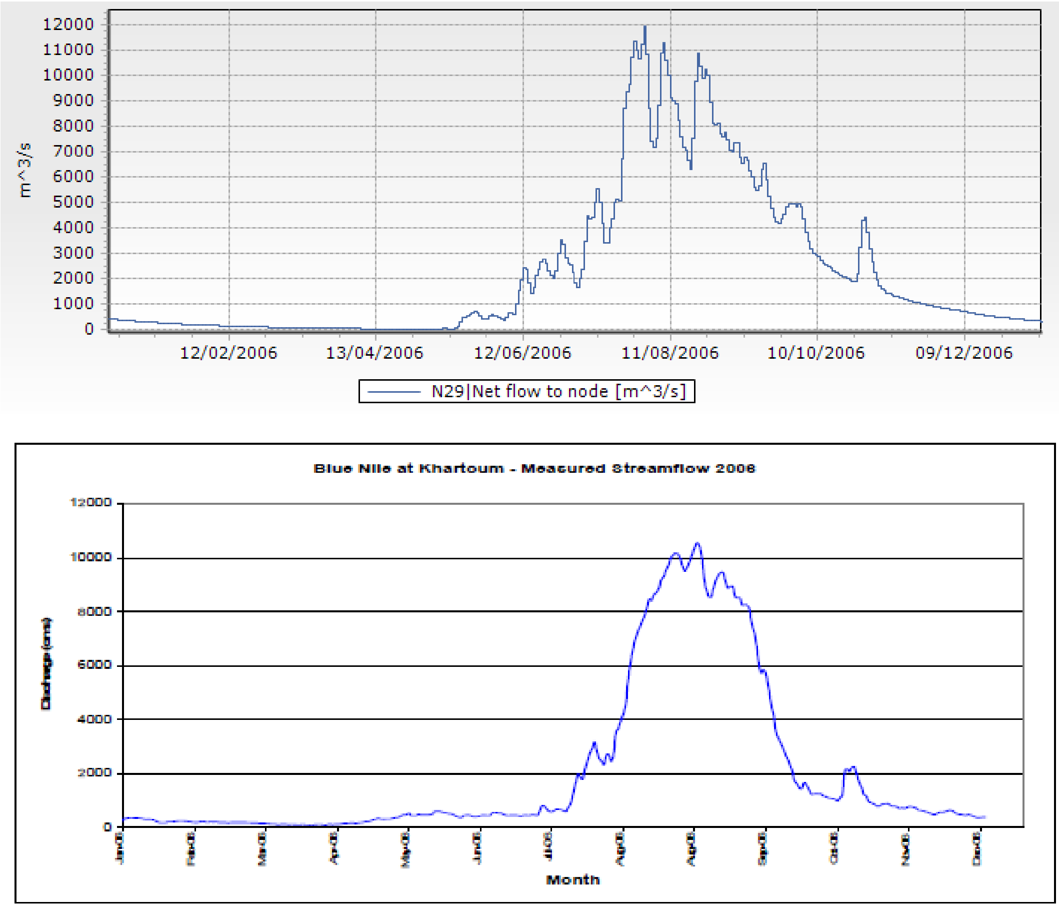


Figure 13 Simulated (upper) and observed (lower) discharge at Khartoum (Riverside 2010 Flood risk mapping report). Note that the simulation is without routing and reservoirs.

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

3.3 Tana Basin

The delineation of the modelled catchments is presented in the figure below.

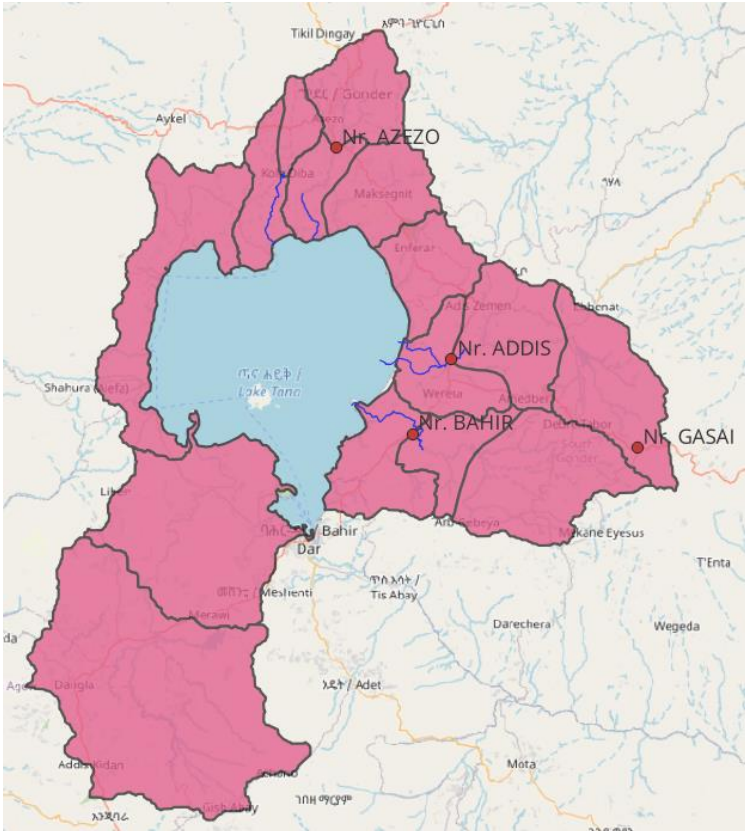


Figure 14 **Sub-catchment delineation (pink polygons) and gauging stations (red points) at Lake Tana basin.**

In the Lake Tana area, calibration is possible for the Ribb at Addis, the Gumara at Bahir, and the Megech at Azezo. Discharge data at the latter is shown in Figure 15, indicating erratic values after 2005.

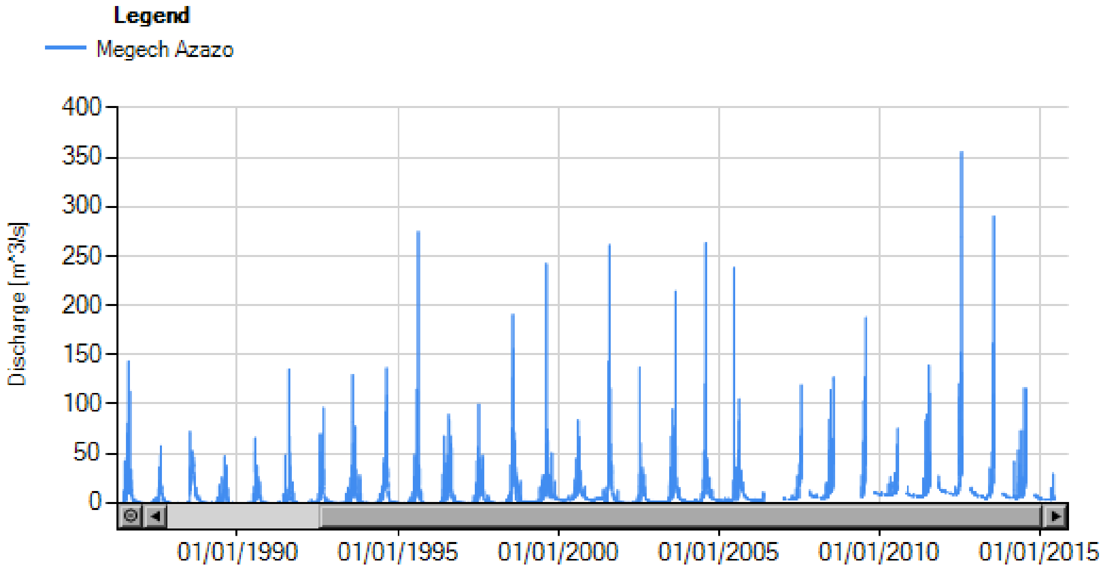


Figure 15 **Discharge data at Azezo on the Megech River seems unrealistic after 2005.**

Calibration results are shown below. A factor of 0.7 for some catchments and 0.8 for other catchments has been applied to the GPM rainfall of the sub-catchments to obtain these results. The R-squared values are given in the figure captions.

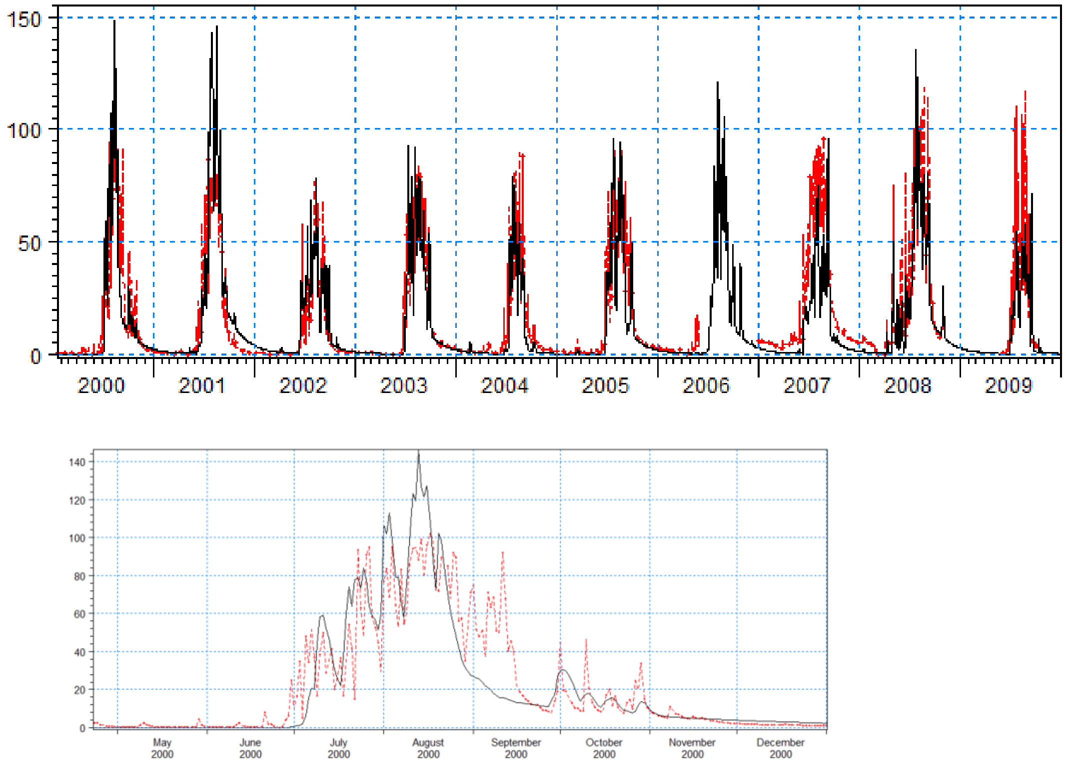


Figure 16 NAM calibration on Ribb at Addis, comparing the simulated (black) and observed (red) flow.

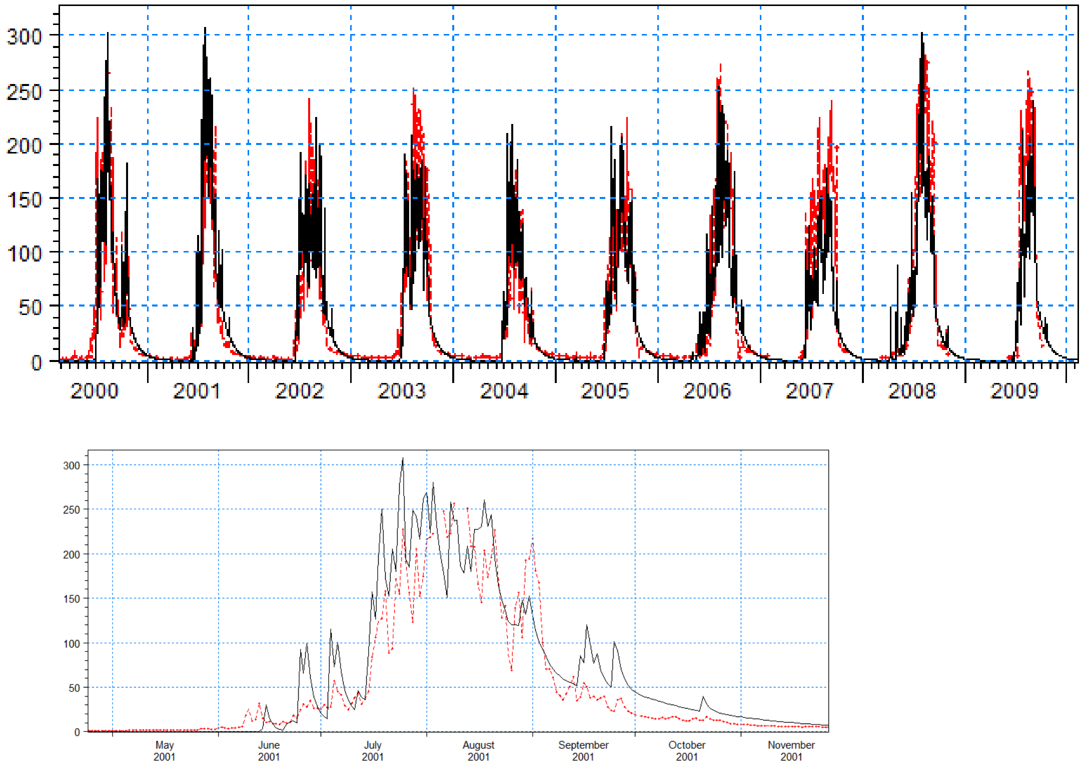


Figure 17 NAM calibration on Gumara at Bahir, comparing the simulated (black) and observed (red) flow.

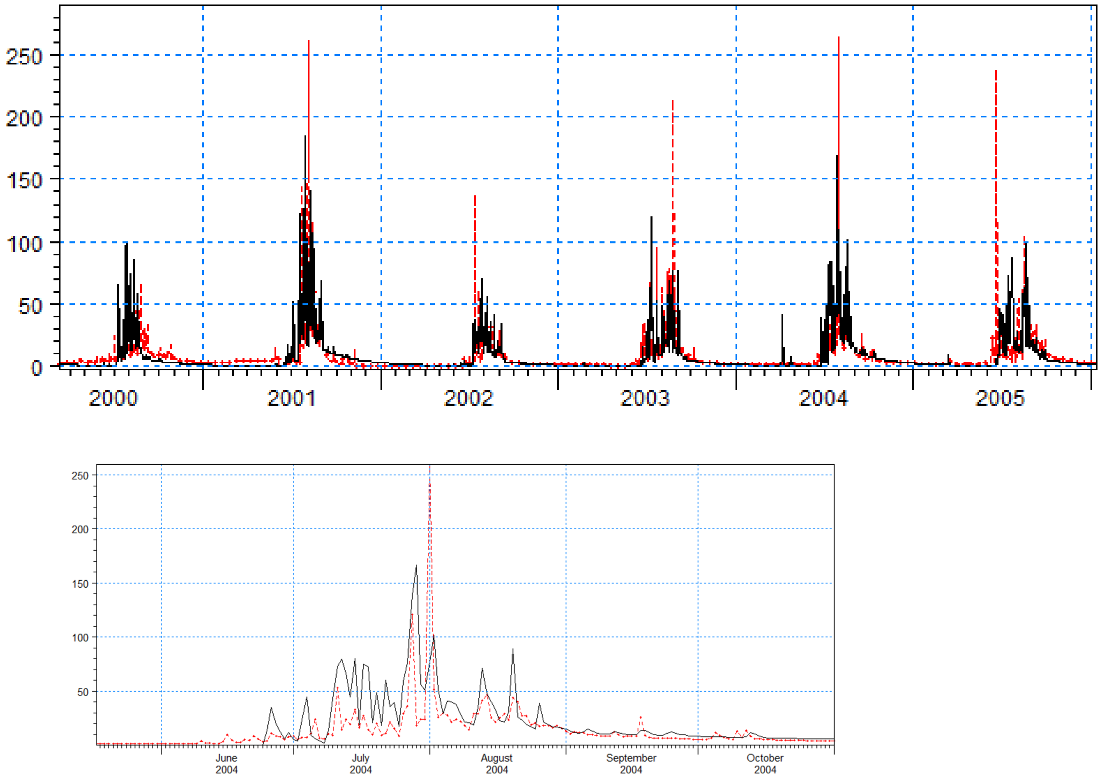


Figure 18 NAM calibration on Megech at Azezo, comparing the simulated (black) and observed (red) flow.

3.4 Baro-Akobo-Sobat Basin

The hydrological model for the Baro-Akobo-Sobat Basin consists of 20 sub-catchments. GPM rainfall and ERA5 potential evaporation data have been applied.

Figure 19 **Sub-catchments (green polygons) and gauging stations (brown points) in the BAS area**

Discharge data is available at three stations within this basin. Two of these are located close to each other on the Baro River, i.e. Gambela and Itang. The catchment area at the former is 95% of the catchment areas at downstream Itang, so one would expect quite similar flow data at the two stations. This was also the case during the 1990s, see Figure 20, whereas the data in the early 2000s indicate significant differences. Based on this comparison, the discharge data at Itang is considered unreliable after year 2000 and therefore not applied in the model calibration.

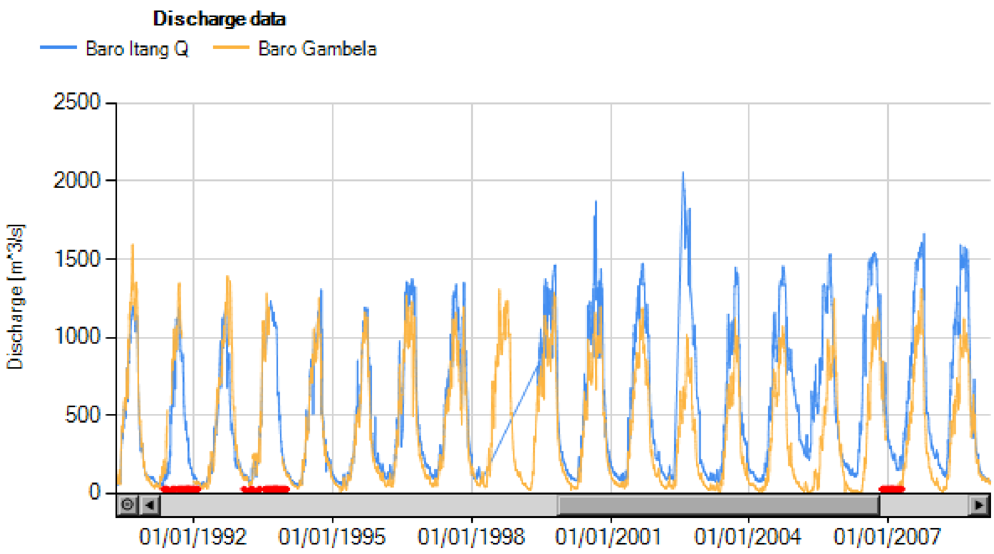


Figure 20 **Comparison of flow data at Gambela and Itang on the Baro River.**

The calibration result for Gambela on Baro River is shown in Figure 21.

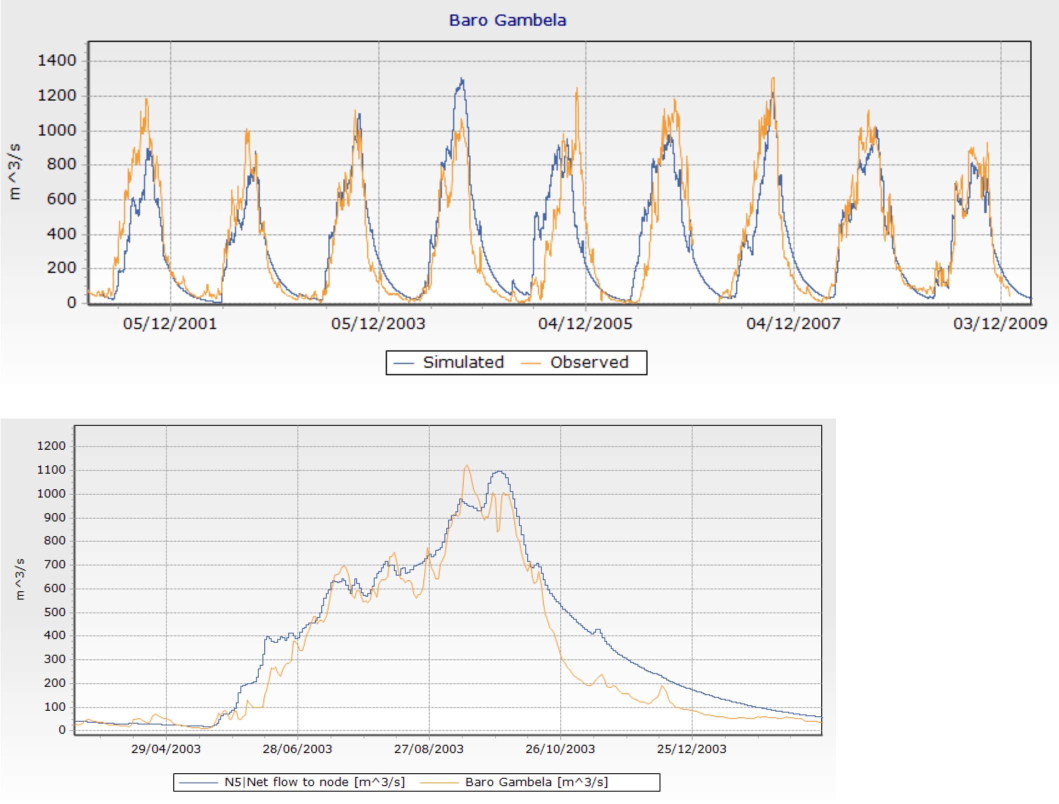


Figure 21 **Comparison of simulated (blue) and observed (orange) flow at Gambela station on Baro River.**

The Inflow coming from Bahr El Jebel upstream Malakal was calculated based on available data at Malakal (White Nile) Doleib Hill (Sobat) stations. Figure 22 shows the discharge measured from 1958 to 1962 and the difference between both stations. A shift of 2 days was added to the flow at Doleib Hill to take into account the propagation time.

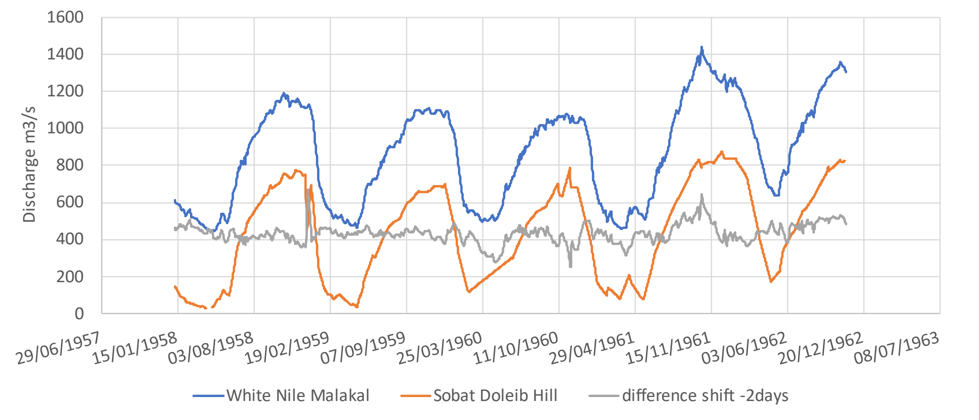


Figure 22 Measured discharge at Malakal (White Nile) Doleib Hill (Sobat) stations

The inflow from Bahr El Jebel is calculated as the monthly median difference between both stations as shown in Figure 23. The same hydrograph is used every year, because the large swamp upstream Bahr El Jebel plays an important role in flow attenuation.

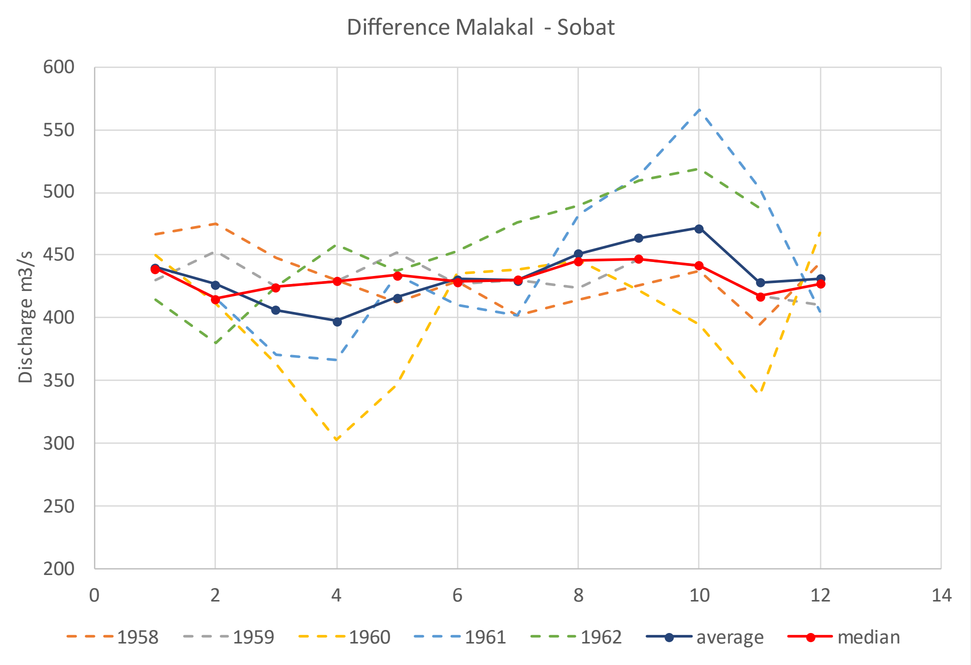


Figure 23 Monthly flow difference between Malakal and Doleib Hill

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

The enhancements and improvements of the hydrodynamic models has 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, 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 existing models were extracted from ENTO server where the existing EN-FEWS id configured.

The general rule used to define the spacing between model cross sections is to get model running in a stable manner and producing plausible results. Key criteria to determine adequate distances between cross-sections include simulation time step and longitudinal slope of the river. This may need interpolation of cross-sections between measured cross-sections.

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

4.1 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.

For the model extension in the downstream Atbara area, the cross-sections were generated having in mind several principles, such as capturing the significant changes along the river (both in terms of river width and slope), ensuring the model stability and producing plausible results. The cross-sections were delineated so that the topography is well represented, and the effective flow area is being represented accurately based on the available DEM. The cross-sections were also traced having in mind being perpendicular to the flow direction, both in the river channel, as well as for the left and right floodplains, reason why the cross-sections can be seen to “bend” around the river banks and change direction on the left and right floodplains.

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-section 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 available.

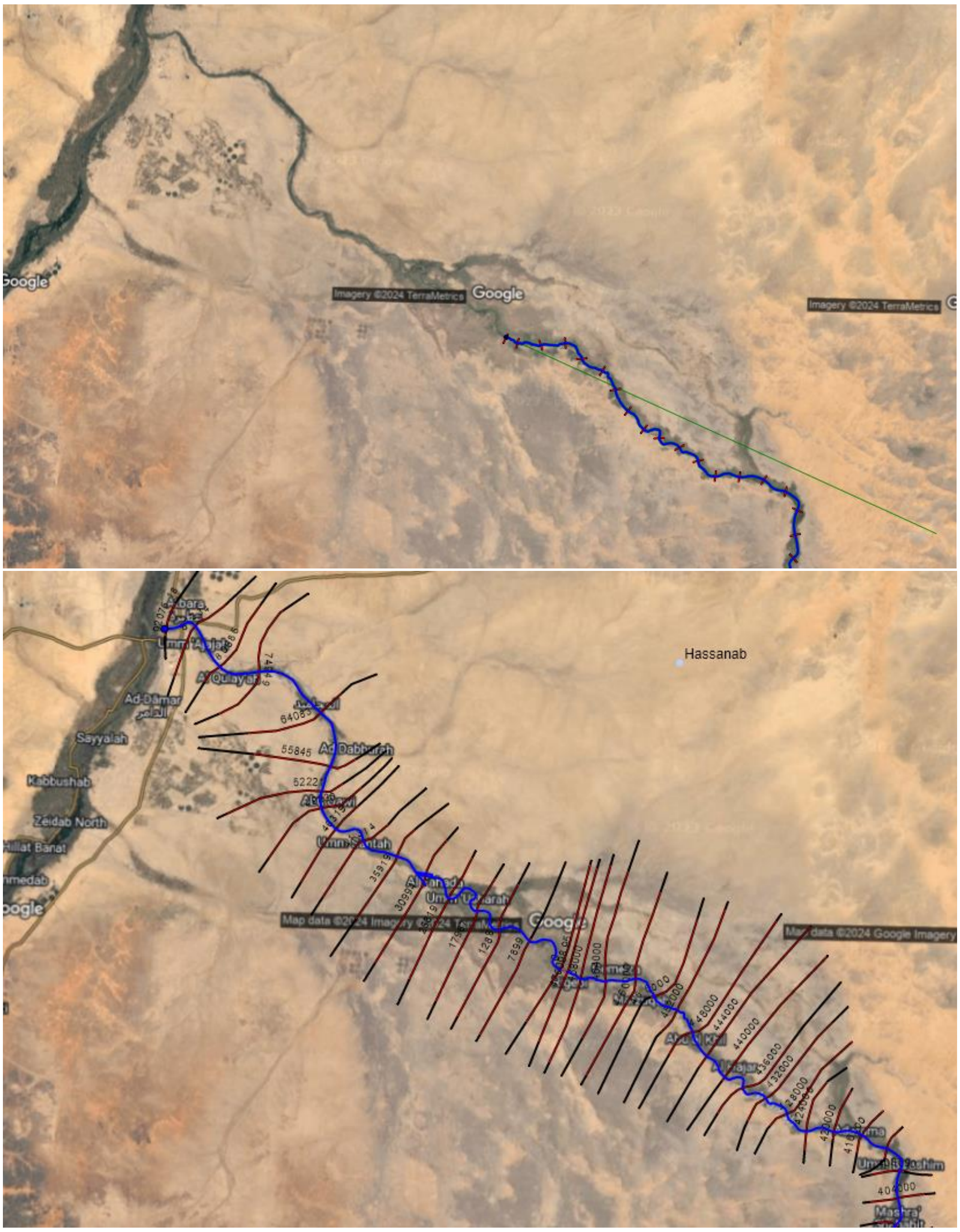


Figure 24 Comparison between the original model (top) and the updated model (bottom)

It can be seen from Figure 24 that the downstream part of the Atbara River has also been extended on approximately 92km with the corresponding 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 25).

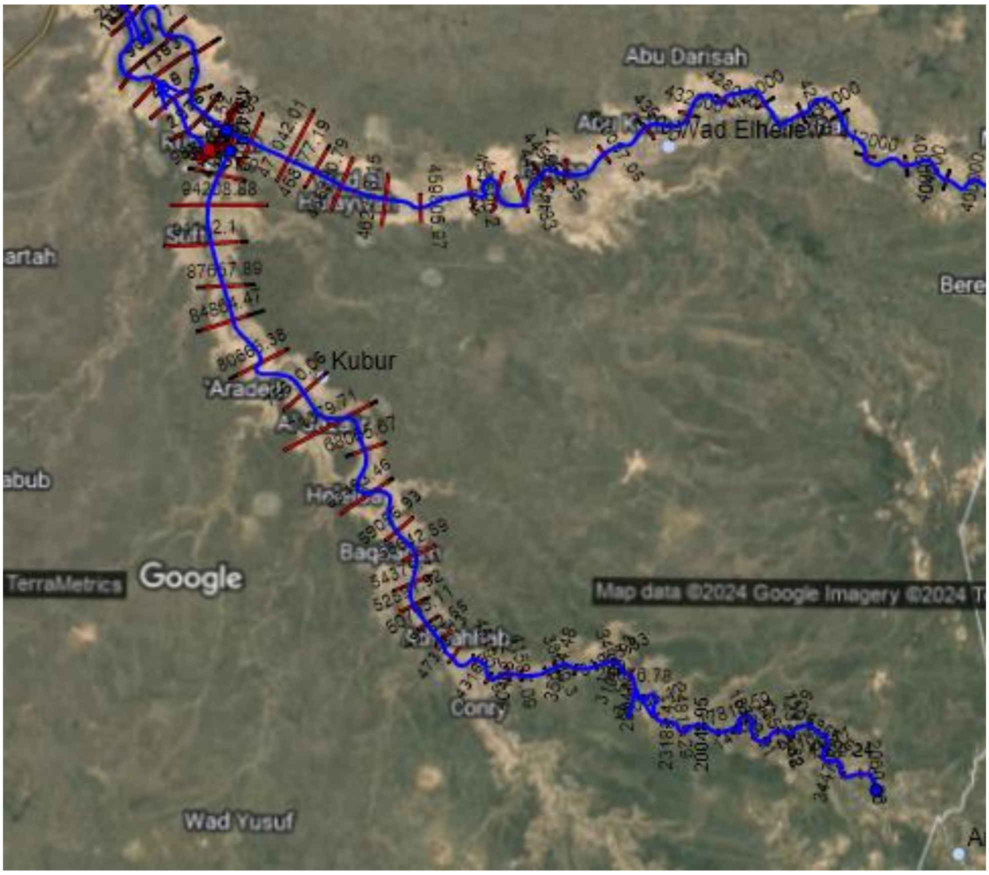


Figure 25 **Angereb branch added to the model and secondary branch just downstream of the dam on the left side of Atbara.**

In order to properly capture the dynamic between the Atbara and White Nile rivers, the White Nile has been included in the Tekeze Atbara model on a stretch of 155km. For this river sector, the ALOS DEM has been augmented using several cross-sections extracted from satellite data, respectively ICESAT2. Based on the ICESAT 2 data, a bathymetry has been estimated (in terms of water depth below the water level recorded during the satellite pass through the area) and implemented in the DEM. The augmented DEM was then used as a basis to extract the needed cross-sections for the model construction process. Also, in order to properly simulate the transfer between upper Nile and this White Nile sector, a boundary condition was extracted from the upstream model and implemented as a discharge boundary condition for the downstream model (see section 4.2). Following this workflow the flow conditions are more accurately represented in the Tekeze Atbara model due to the inclusion of the Nile sector and its respective flow conditions, allowing the model to represent potential backwater happening during high flows on the Nile. A close-up of the confluence area and model extension is presented in the figure below:

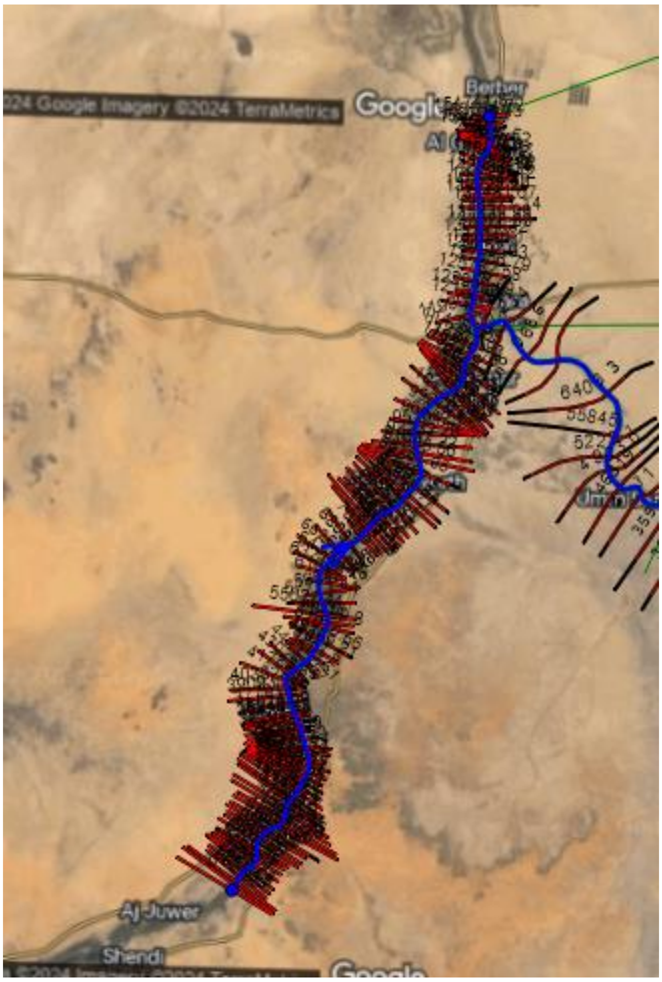


Figure 26 White Nile extension for the Tekeze Atbara model

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. The control rules were implemented having in mind the average yearly variation of the water levels in the TK5 dam and the minimum outflow requirement downstream of the dam which should be around 100m^3/s.

Figure 27 shows the calibration attempt, compared to the real operation graph.

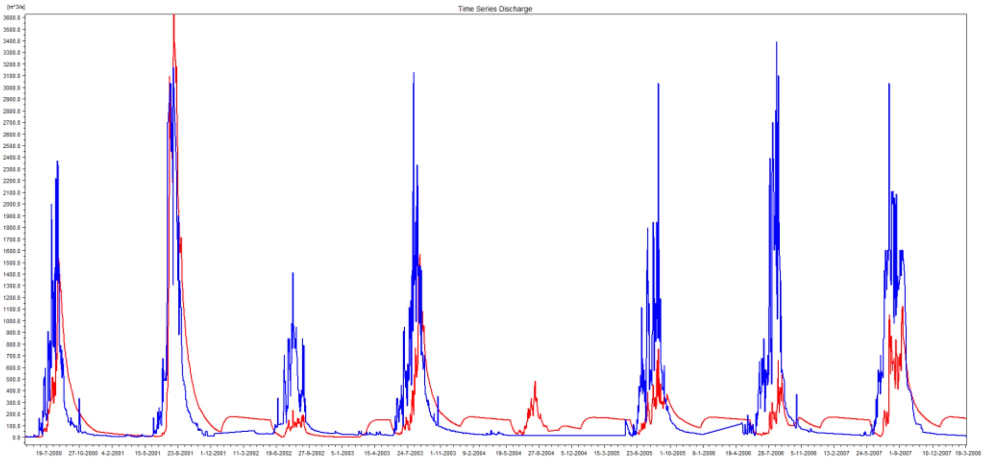


Figure 27 Reservoir operation simulation – comparison between the simulated discharges (red) and observed (blue) at Embamadre station

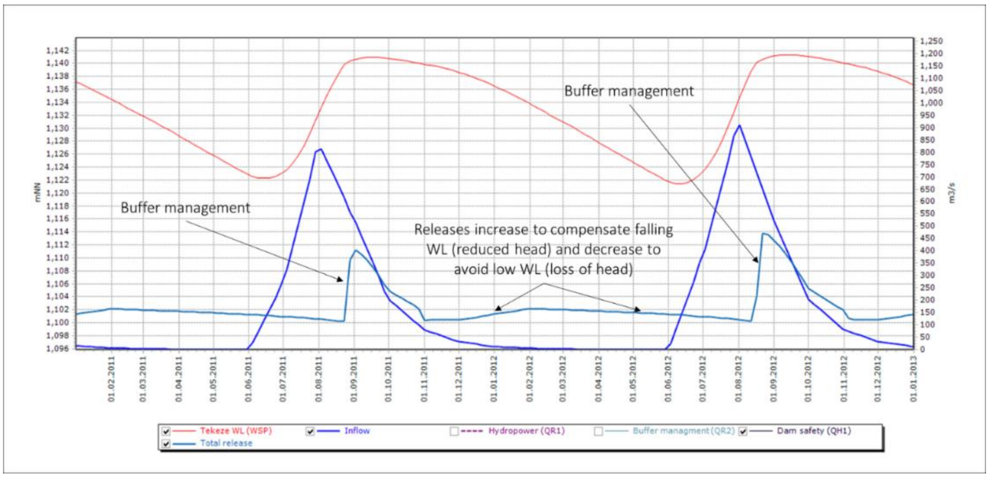


Figure 28 Real reservoir operation graph – Tekeze WL (red), Inflow (dark blue), Total release (light blue) (SWRA)

The reservoir operation for Girba and Upper Setit Atbara reservoirs has been also included in the Tekeze Atbara model. The reservoirs were implemented using cross-sections and the control rules are being enforced through a weir and gate for each of the 3 dams (Girba, Setit and Atbara). In terms of reservoir operation, the dams are regulating the flows based on the water level setpoints and the actual modelled water level in each dam. The water level setpoint represents the design water level and implicitly the water resource allocation for a specific reservoir and dictates how the dam release equipment is being operated in order to aim to maintain the setpoint for each month of the year. The water level setpoint is a design parameter and takes into account various factors such as maintaining a minimum ecological flow downstream, as well as delivering the necessary water resources to the users. An example of the water level setpoint can be seen in the image below:

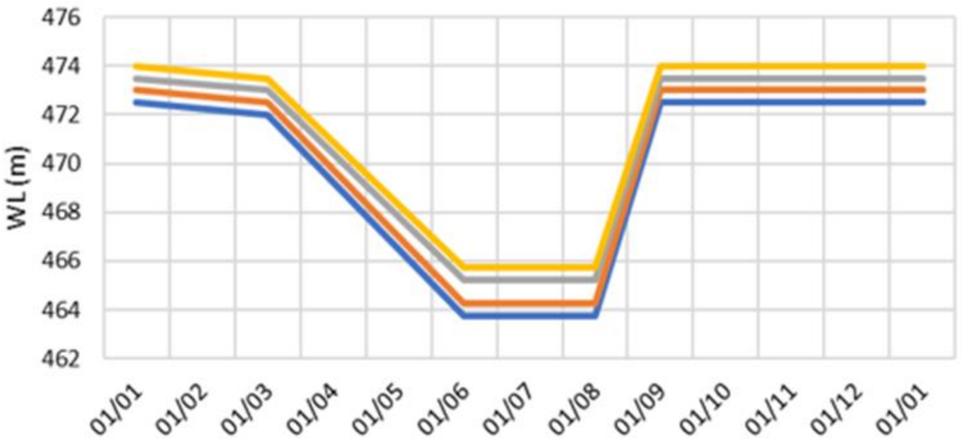


Figure 29 Example of the water level setpoints for the Kashm el Girba reservoirs (SWRA)

The results for Upper-Setit Atbara and Girba are presented below, and in the Girba results graph one can observe the comparison between the simulated and observed reservoir water levels. At Atbarah dam, no measurement station data are available, so the comparison was not possible.

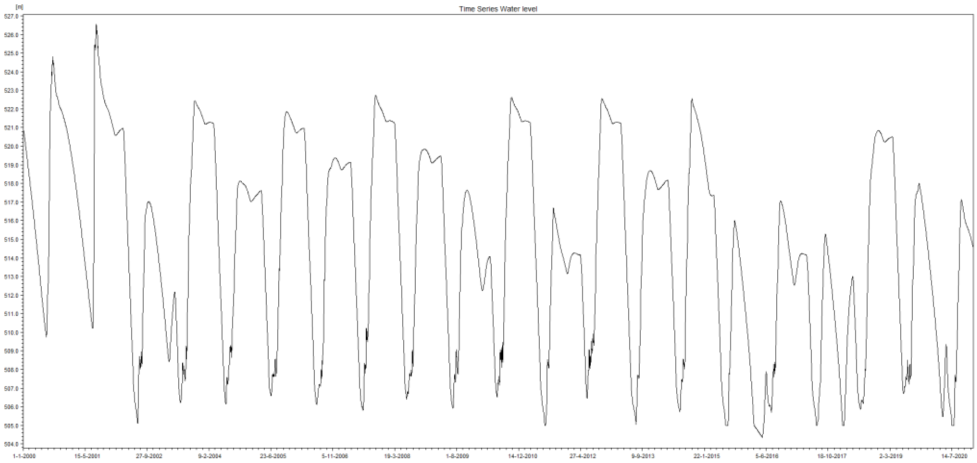


Figure 30 Simulated water level in the Upper Atbara reservoir

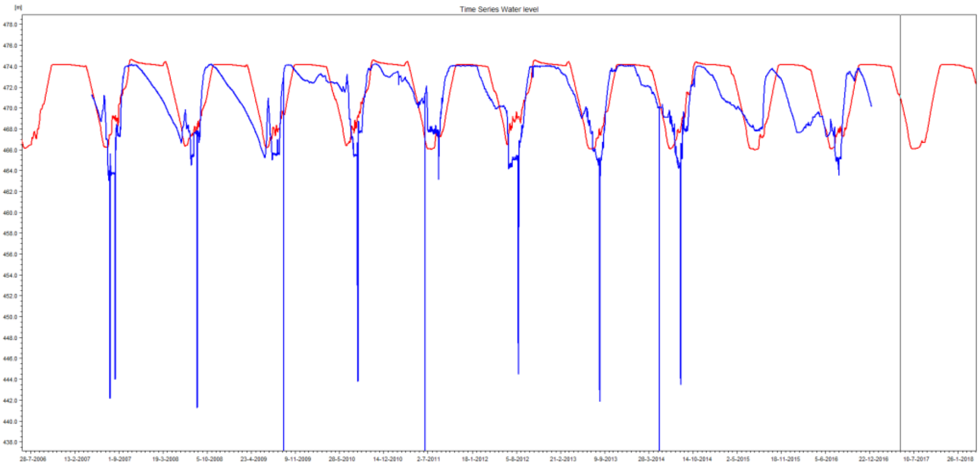


Figure 31 Comparison between the simulated (red) water levels and blue (observed) water levels for the Girba reservoir.

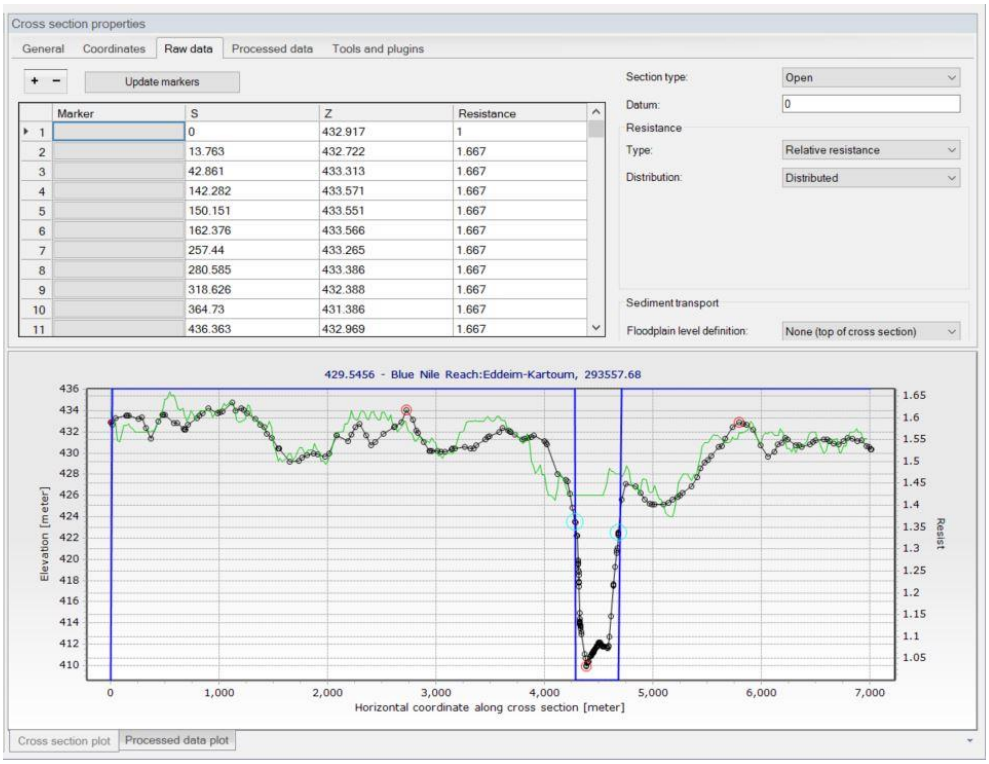
The hydrodynamic model made with the latest version of MIKE-Hydro-River is submitted together with this report – see <MIKE-HYDRO-River_TSA.ZIP>

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 ALOS DEM quality was done to assess if the ALOS DEM's 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 ALOS DEM could have provided, thus they were kept in their original location and shape. Figure 32 shows a comparison between the existing cross-sections and those extracted from the ALOS DEM.



	Marker	S	Z	Resistance
1		0	432.917	1
2		13.763	432.722	1.667
3		42.861	433.313	1.667
4		142.282	433.571	1.667
5		150.151	433.551	1.667
6		162.376	433.566	1.667
7		257.44	433.265	1.667
8		280.585	433.386	1.667
9		318.626	432.388	1.667
10		364.73	431.386	1.667
11		436.363	432.969	1.667

Section type: Open
Datum: 0
Type: Relative resistance
Distribution: Distributed
Floodplain level definition: None (top of cross section)

Figure 32 **Comparison between the original cross-section (black) and the DEM (green)**

Figure 32 shows that the main differences between the cross-sections are visible in the river channel with a difference of up to 18m, while the overall shape and elevation range in the floodplain is quite similar. This implies that the ALOS 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.

Similar to 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, because at some locations (such as the most downstream point to the confluence with the White Nile) the model was highly unstable, providing unrealistic water levels which can affect flood alerts. Figure 33 shows a longitudinal profile with the banks, thalweg and water level (current time step in blue and maximum water level in red).

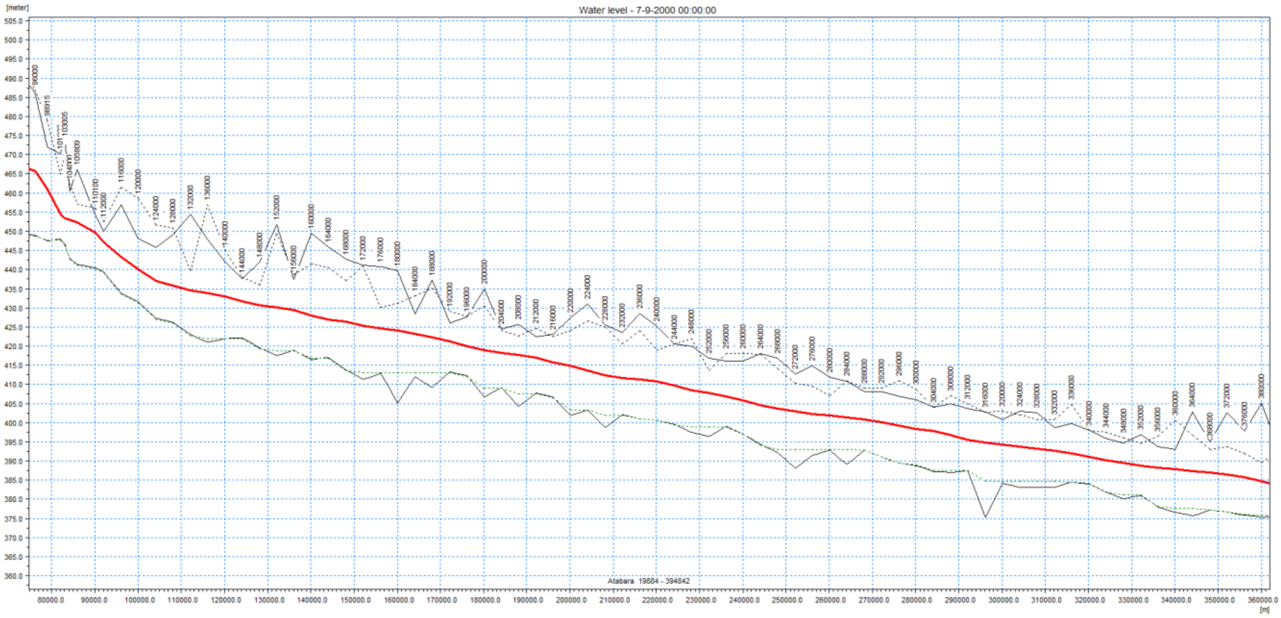


Figure 33 Longitudinal profile along the Blue Nile downstream of the Sennar dam (water level in blue, maximum water level in red and cross-section edge markers in black).

Similar to the Tekeze Atbara river, the Blue Nile model has been extended downstream to include part of the White and upstream to include part of the Main Nile in order to fully consider the complex dynamics occurring in the confluence area. The model extent was schematized as follows.

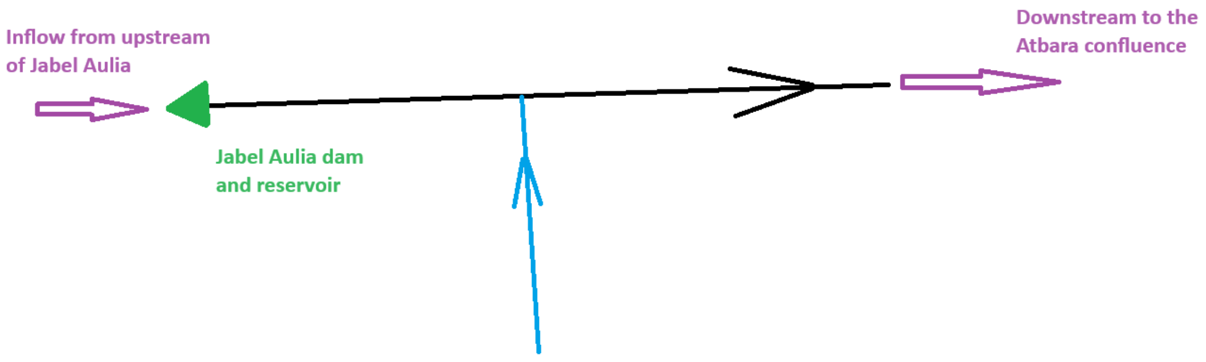


Figure 34 Schematics of the Blue Nile model extension

The Jebel Aulia dam was represented using a storage described as a level-area-volume curve, as well as a structure setup consisting of a weir and gate which are operated based on a water level setpoint.

The image below shows the full Blue Nile model, starting from Lake Tana, including the GERD dam, the Rosieres dam, as well as Sennar dam and a stretch of the Main Nile from Jebel Aulia to downstream of Khartoum. From Lake Tana to GERD dam, a simple routing pethood was used to propagate the runoff from the upstream catchments downstream.

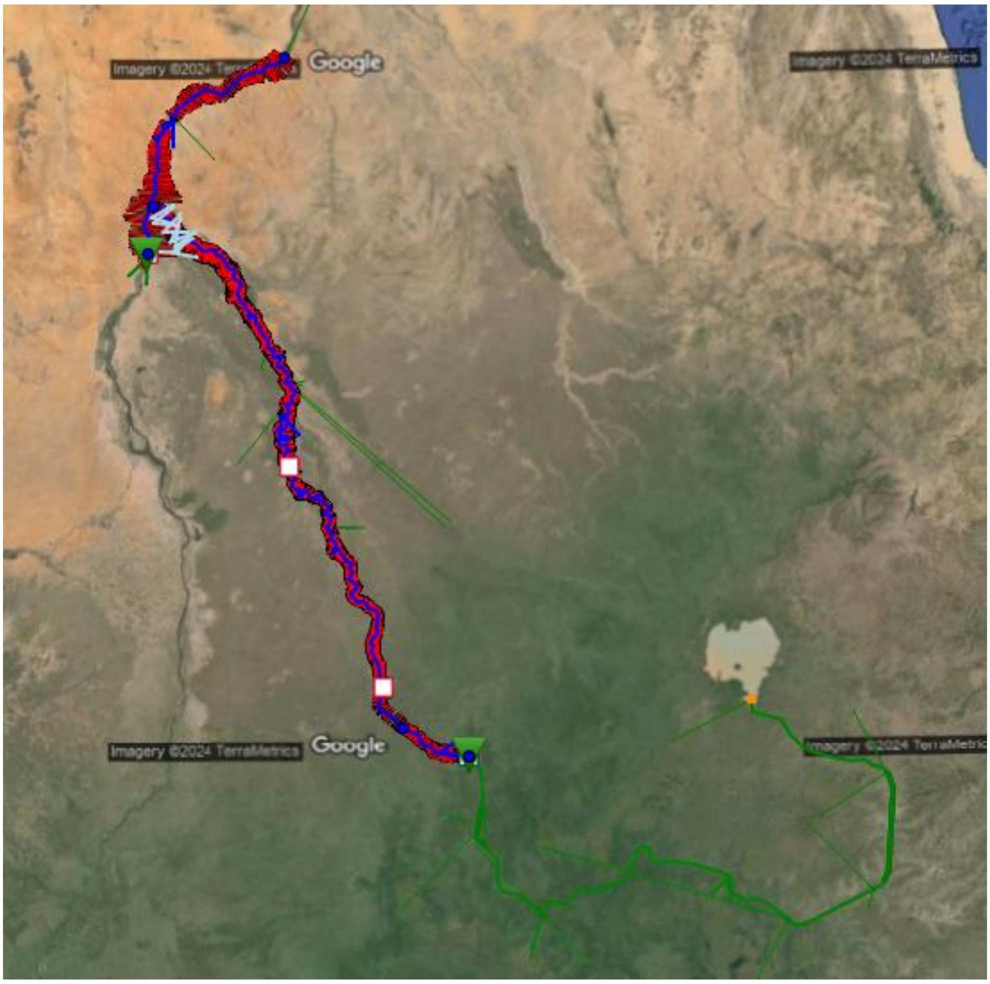


Figure 35 Model extent – Blue Nile including a river stretch of the Main Nile

The hydrodynamic model made with the latest version of MIKE Hydro River is submitted together with this report – see <MIKE-HYDRO-River_BN.ZIP>

4.3 Tana Basin

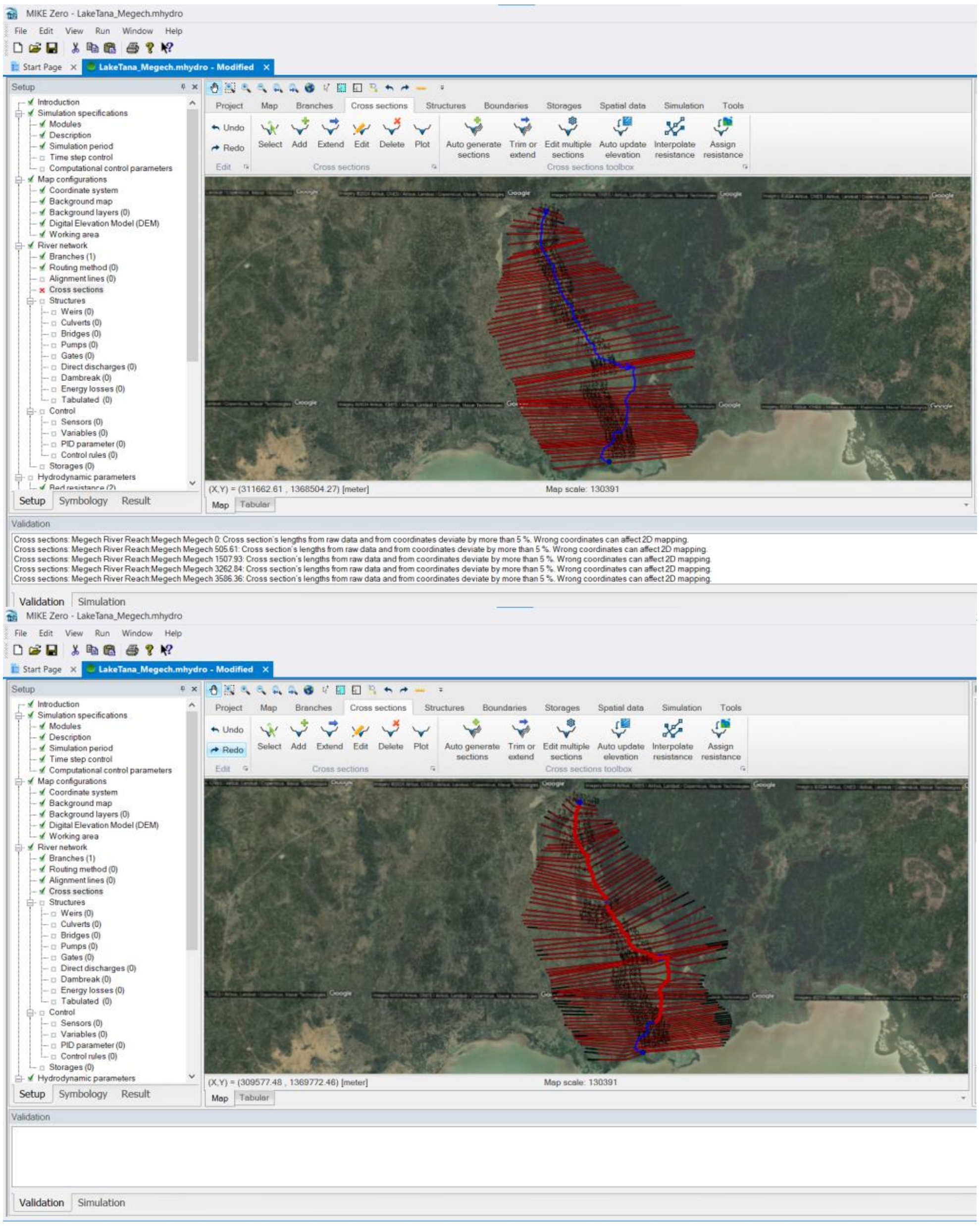
The existing model for Lake Tana was analysed. It includes the following rivers: Dirma, Megech, Ribb and Gumara.

Figure 36 The 4 rivers in the Tana Basin that were analysed.

The model analysis started by checking the imported models from the FEWS platform into MIKE Hydro River in terms of running the simulation and then in terms of overall quality. The models were not running initially due to various errors, which were corrected, to allow the models to run.

As the models were exported from the EN-FEWS platform and because they were originally created using a different software solution, the overall model setup was successfully imported, but not all the elements were fully transferred to the MIKE Hydro River setup, such as the cross-sections coordinates, as well as the discharge transfer connections between various floodplains.

Because of the above, the model quality was improved by manually adding the coordinates of the original cross-sections and creating a correct representation. Furthermore, the markers were updated, as they were incorrectly transferred from the old model to the new setup files. Figure 37 shows the improvements of the models in terms of cross-section correction.



```
(X,Y) = (311662.61 , 1368504.27) [meter]
```

```
Cross sections: Megech River Reach:Megech Megech 0: Cross section's lengths from raw data and from coordinates deviate by more than 5 %. Wrong coordinates can affect 2D mapping.
Cross sections: Megech River Reach:Megech Megech 505.61: Cross section's lengths from raw data and from coordinates deviate by more than 5 %. Wrong coordinates can affect 2D mapping.
Cross sections: Megech River Reach:Megech Megech 1507.93: Cross section's lengths from raw data and from coordinates deviate by more than 5 %. Wrong coordinates can affect 2D mapping.
Cross sections: Megech River Reach:Megech Megech 3262.84: Cross section's lengths from raw data and from coordinates deviate by more than 5 %. Wrong coordinates can affect 2D mapping.
Cross sections: Megech River Reach:Megech Megech 3586.36: Cross section's lengths from raw data and from coordinates deviate by more than 5 %. Wrong coordinates can affect 2D mapping.
```

```
(X,Y) = (309577.48 , 1369772.46) [meter]
```

Figure 37 **Visualisation of the cross-sections for Megech in the initial model import (top) and improved model (bottom).**

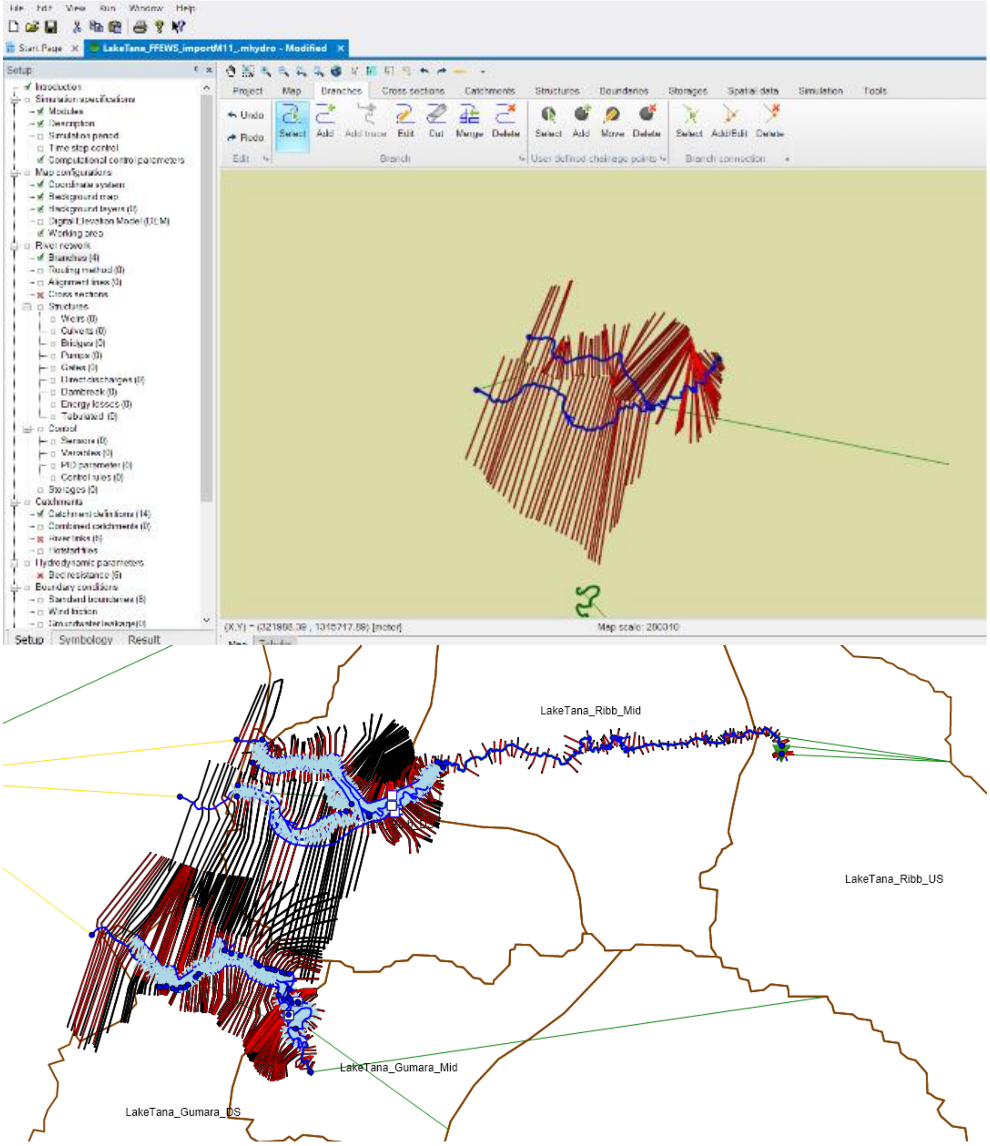


Figure 38 Visualisation of the cross-section correction for Ribb model: initial model (top) and improved model (bottom).

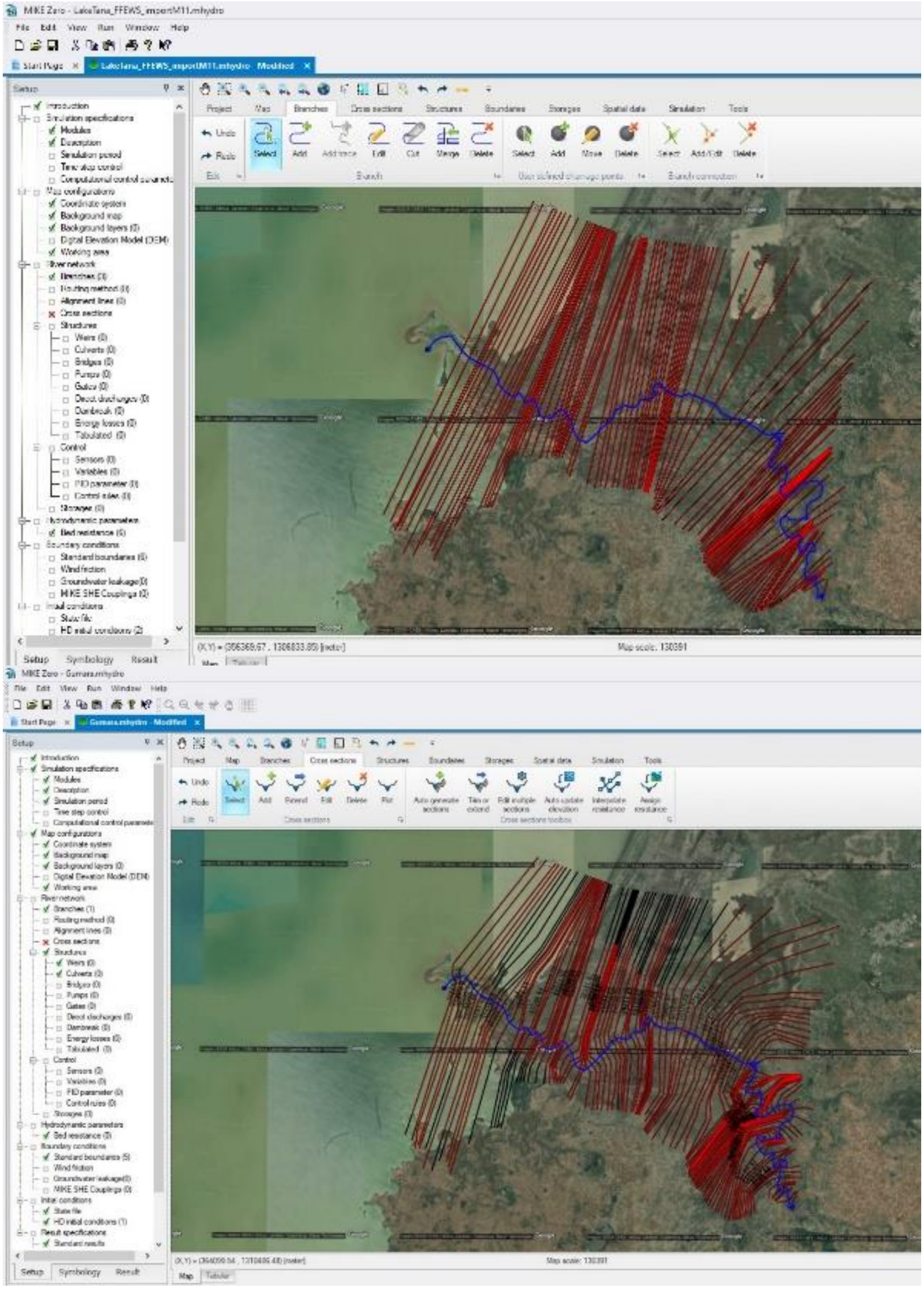
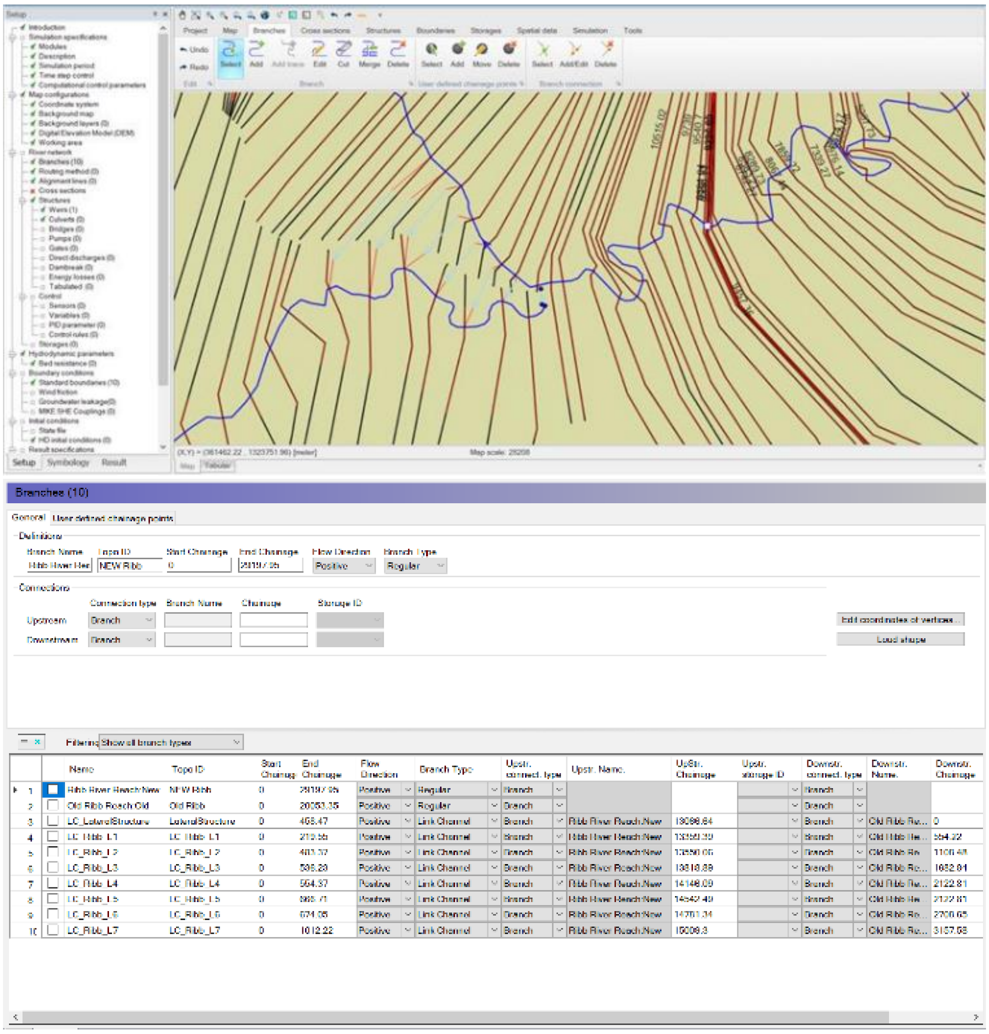


Figure 39 **Cross-section correction for Gumara: initial model import (top) and improved model (bottom).**

The Lake Tana region is characterized by a flat topography which is not well captured by the available ALOS DEM. By analysing the available cross-sections and comparing them to the available ALOS DEM it was clear that there were inconsistencies, further induced by the lack of ALOS DEM data used originally in the model creation process. Because of this, the uncertainties when generating the flood maps are significant and can only be reduced by using a more accurate DEM dataset.

The roughness coefficients were also analysed and updated. For Megech, for example, the roughness coefficients were estimated between 0.025 and 0.035 for the river channel, and between 0.05 and 0.065 for the floodplain. The estimation was done mainly based on aerial imagery and online photos that could be found for some locations along the river.

Multiple iterations were done for all 4 rivers to improve the stability and the representation of the terrain and flow conditions in the model. For example, to properly represent the flow transfer between the old and new Ribb river branches, new floodplain connections have been added to represent the flow transfer during the high discharge events. Without the flow connections, the flood extent could be wrongly interpreted, and the water levels might get underestimated. Figure 40 shows the lateral link structures for some of the cross-sections where there is no clear separation between the old Ribb and new Ribb floodplains for the 100-year flood event.



Definitions

Branch Name	Topo ID	Start Chainage	End Chainage	Flow Direction	Branch Type
Ribb River Rea	NEW Ribb	0	28197.95	Positive	Regular

Connections

	Connection type	Branch Name	Chainage	Storage ID
Upstream	Branch			
Downstream	Branch			

Filtering Show all branch types

	Name	Topo ID	Start Chainage	End Chainage	Flow Direction	Branch Type	Upstr. connect. type	Upstr. Name.	UpStr. Chainage	Upstr. storage ID	Downstr. connect. type	Downstr. Name.	Downstr. Chainage
1	Ribb River Reach New	NEW Ribb	0	28197.95	Positive	Regular	Branch				Branch		
2	Old Ribb Reach Old	Old Ribb	0	20053.35	Positive	Regular	Branch				Branch		
3	LC_LateralStructure	LateralStructure	0	468.47	Positive	Link Channel	Branch	Ribb River Reach New	13098.64		Branch	Old Ribb Re...	0
4	LC_Ribb_L1	LC_Ribb_L1	0	212.55	Positive	Link Channel	Branch	Ribb River Reach New	13350.39		Branch	Old Ribb Re...	554.22
5	LC_Ribb_L2	LC_Ribb_L2	0	403.37	Positive	Link Channel	Branch	Ribb River Reach New	13550.06		Branch	Old Ribb Re	1100.48
6	LC_Ribb_L3	LC_Ribb_L3	0	536.28	Positive	Link Channel	Branch	Ribb River Reach New	13818.89		Branch	Old Ribb Re...	1652.81
7	LC_Ribb_L4	LC_Ribb_L4	0	564.37	Positive	Link Channel	Branch	Ribb River Reach New	14148.09		Branch	Old Ribb Re...	2122.81
8	LC_Ribb_L5	LC_Ribb_L5	0	698.71	Positive	Link Channel	Branch	Ribb River Reach New	14542.49		Branch	Old Ribb Re...	2122.81
9	LC_Ribb_L6	LC_Ribb_L6	0	674.05	Positive	Link Channel	Branch	Ribb River Reach New	14701.34		Branch	Old Ribb Re...	2700.65
10	LC_Ribb_L7	LC_Ribb_L7	0	1012.22	Positive	Link Channel	Branch	Ribb River Reach New	15009.3		Branch	Old Ribb Re...	3157.58

Figure 40 River links between the old and new Ribb branches to convey the flows between flood plains.

Once the models were updated and the stability and accuracy of the results was ensured, further work was done in terms of including Lake Tana in the model as a structure, as opposed to using average time series of water level defined as downstream boundary conditions of the rivers. Using this method, the water level in the lake would actually be calculated based on the inflows from the rivers and hydrological catchments and outflows through the Chara Chara weir and through the hydropower inlet.

In order to achieve an integrated approach of the Lake Tana basin, the hydrological and hydrodynamic models built for each river were integrated into one model and the Lake was added as a combination of a storage structure (using the Level-Area-Volume curve), as well as a weir structure and an outflow discharge simulating the hydropower inlet.

The image below shows a snapshot from the integrated Lake Tana model:

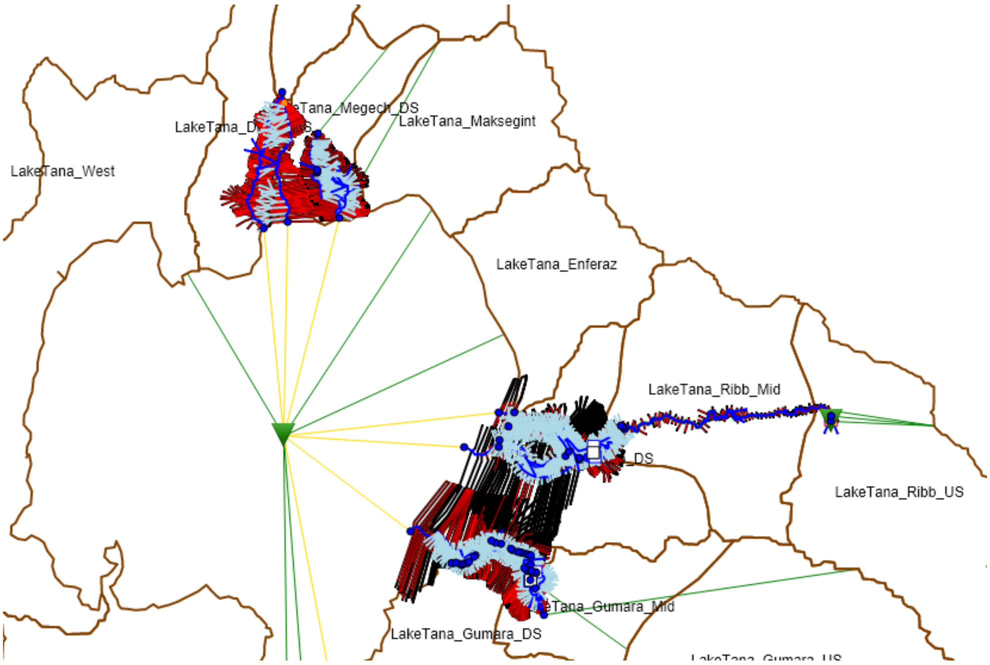


Figure 41 **Schematization of the Lake Tana hydrological and hydrodynamic model.**

The figure below shows the water level variation in the lake, with all hydrological inputs being a part of the same model.

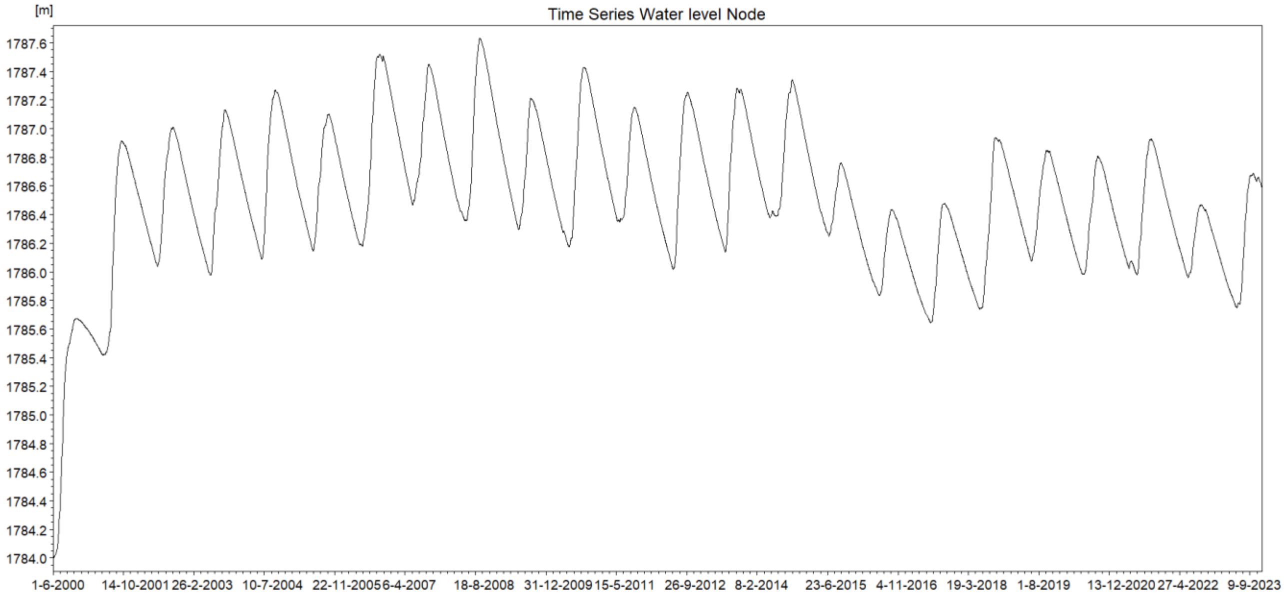


Figure 42 **Water level variation for Lake Tana.**

Aside from lake Tana, the Ribb model has been extended also to include the Ribb reservoir in the upper catchment of the Ribb river. The reservoir was implemented using a storage structure which considers the Level-Area-Volume curve according to SWRA and a composite structure consisting of a weir and gate which is being operated according to the yearly water level variation setpoint.

The image below shows the variation of the Ribb reservoir water level:

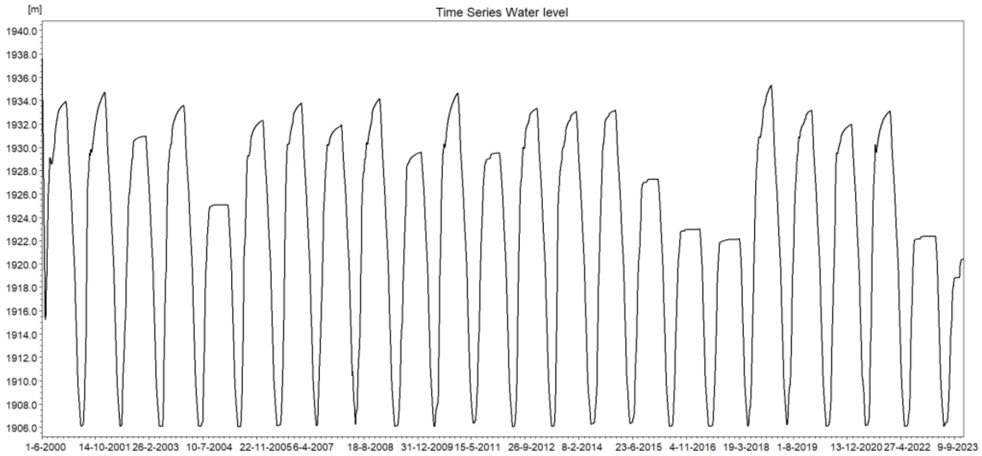


Figure 43 Water level variation for the Ribb reservoir

The hydrodynamic model made with the latest version of MIKE Hydro River is submitted together with this report – see <MIKE-HYDRO-River_Tana.ZIP>

4.4 Baro-Akobo-Sobat Basin

The Baro-Akobo-Sobat (BAS) model has followed the same workflow outlined for all rivers. The model analysis has started with the model verification and simulation, with initial changes being made to the model setup to be able to successfully run a simulation of 100-years return period flood.

The model was mainly corrected in terms of marker locations, as there were locations where the cross-sections were incorrectly limited by using markers 1 and 3 (left and right extents).

The roughness coefficients were also checked and a mistake regarding the roughness distribution along the river was corrected as it was producing exaggerated water levels (roughness coefficient was distributed linearly between 0.07 and 0.7 along the river).

After correcting the errors and updating the markers the model was successfully run for the historical flow record period. By analysing the results, it was observed that the water levels calculated by the model were much higher than the cross-section limits, implying that the cross-sections would need to be extended significantly to properly convey the entire flow. The image below shows the maximum water level computed compared to the cross-section limits.

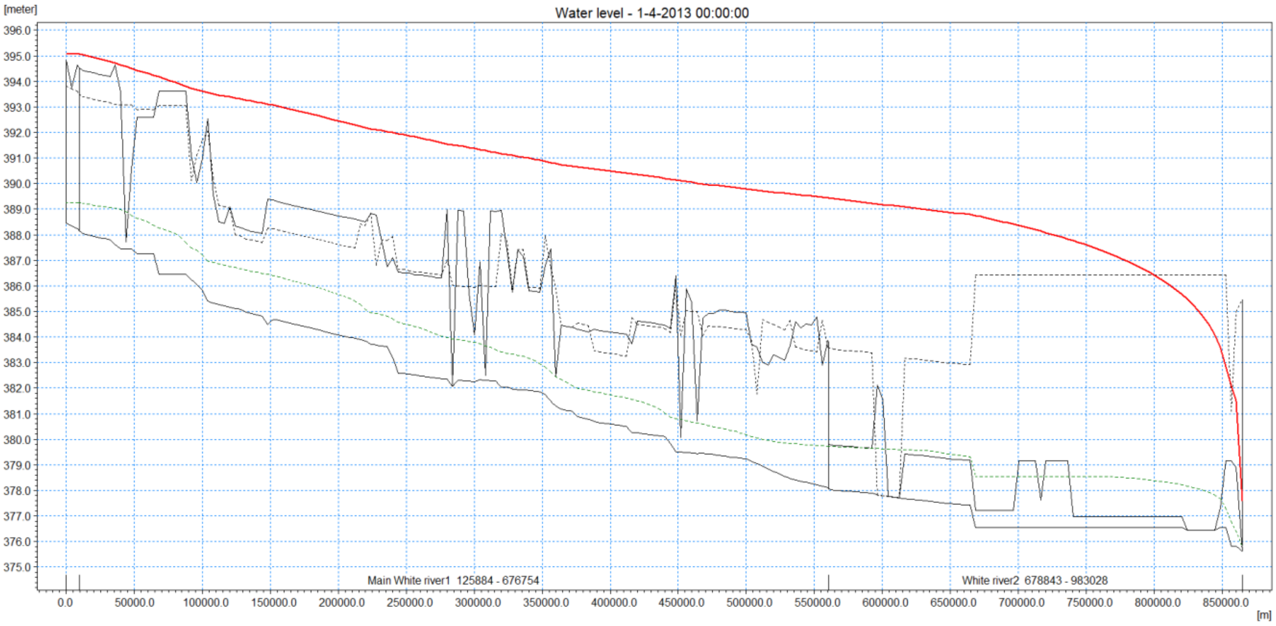


Figure 44 Water levels calculated using the model (red line).

Because of the issue presented above, the BAS model was rebuilt from scratch using input data from the ALOS DEM primarily and WP1 DEMs where available. The cross-sections were delineated based on the available DEM and the main criteria for cross-sections delineation were:

- to maintain the cross-section direction perpendicular to the main flow direction for both the river channel as well as the side branches.
- to follow and consider the main changes regarding width of the flow, meanders and changes in river slope;
- as well as ensuring a continuity between the main river channel and the secondary branches and floodplains.

Based on the criteria above, a number of roughly 650 cross-sections were created and close to 20 side branches were delineated and constructed in order to convey the flow through the river channel and floodplains. In order to ensure the connectivity between the floodplains and river channels, a number of around 400 link channels were added.

A schematization of the model can be seen in the pictures below:

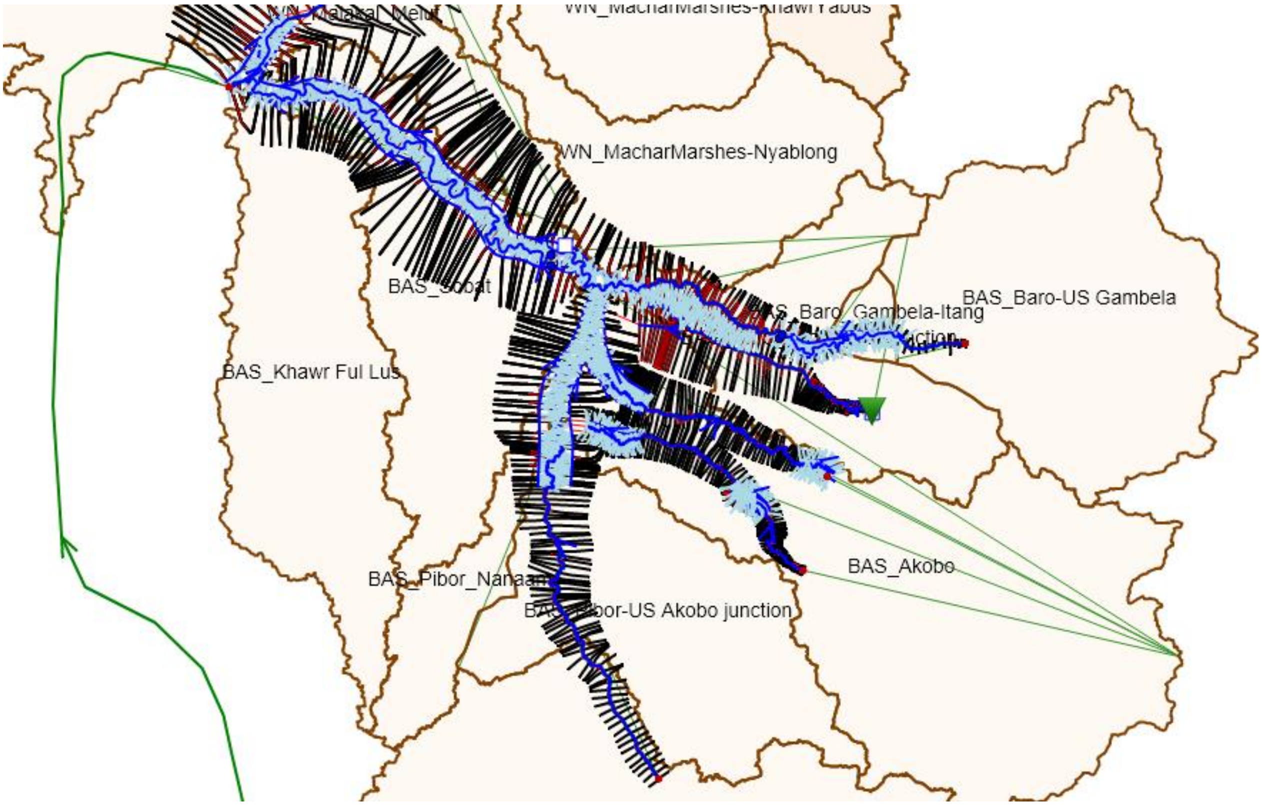


Figure 45 **Schematization of the BAS model – hydrologic and hydrodynamic components for Baro, Sobat, Abobo, Gilo and Akobo rivers.**

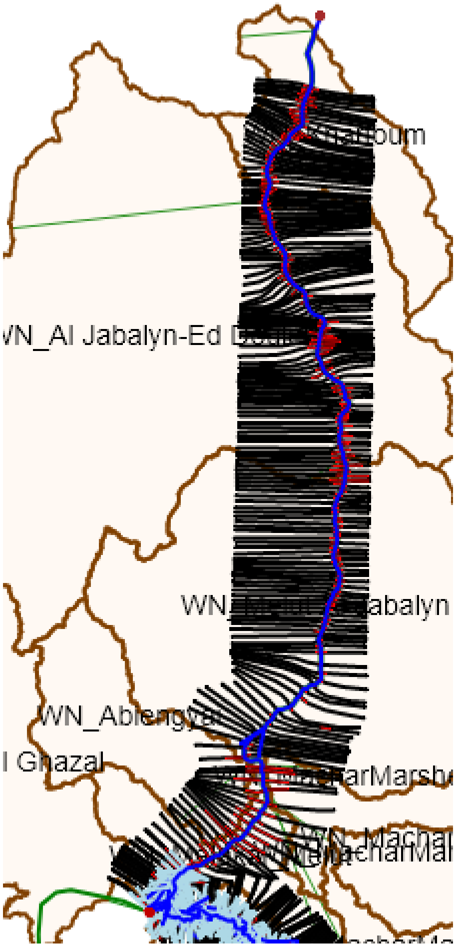


Figure 46 **Schematization of the BAS model – hydrologic and hydrodynamic components for the White Nile.**

Apart from the Baro, Akobo, Sobat, Gilo and the White Nile, the Abobo river has also been included in the model setup to represent Alwero dam. The dam was included using a storage structure (benefit of the Level-Area-Volume curve) and a weir which quantifies the outflow downstream.

The picture below shows the Alwero dam area and the connections between the main channel and the floodplains.

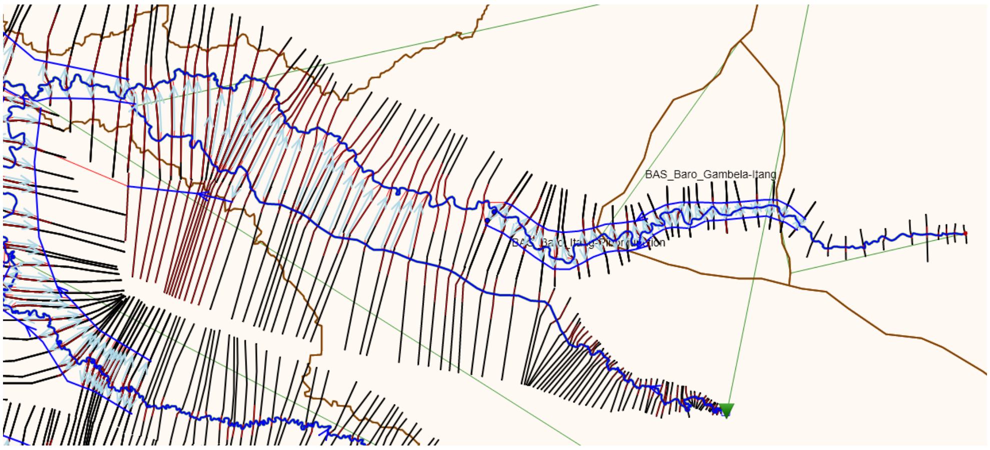


Figure 47 **Abobo and Baro rivers, together with the cross-sections and link channels connecting the main rivers and side branches.**

The Machar marshes were implemented in the model using a combination of floodplains, link channels and a weir which extracts water from the model. This weir structure is implemented to quantify the discharge which flows into the floodplain and does not return back to the river, by being trapped in the floodplain and lost due to infiltration and evaporation processes.

The model results were analysed and compared with observed discharge time series available for several stations, such as Itang, Gambela or Malakal. Also, multiple iterations were done to ensure the water volume continuity along the river so that no water is being lost due to model stability issues or schematization (link channels trapping the water).

The following section shows the calibration results in the key stations along the river basin.

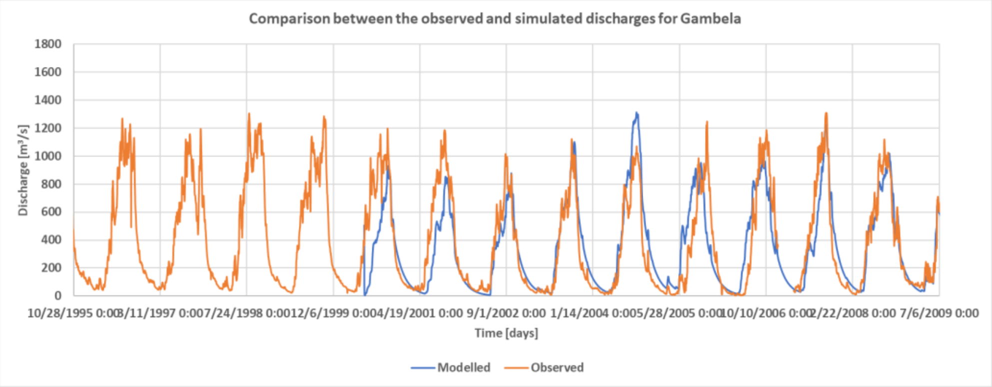


Figure 48 **Comparison between the observed (orange) and simulated (blue) discharges for Gambela station.**

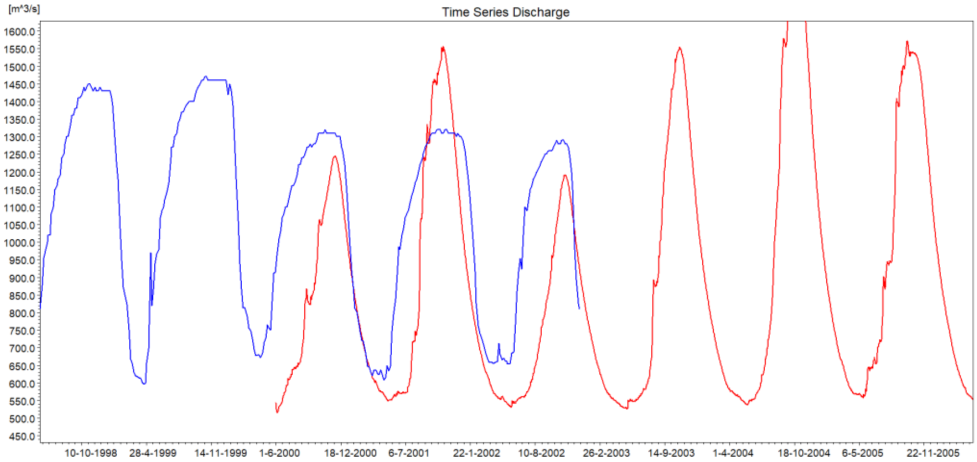


Figure 49 **Comparison between modelled (red) and observed (blue) flow discharge for Malakal station.**

The hydrodynamic model made with the latest version of MIKE Hydro River is submitted together with this report – see <MIKE-HYDRO-River_BAS.ZIP>.

5 Flood Extents

Flood extents are the main input for determining flood hazard at the selected flood locations. Flood extents are calculated for selected return periods, of 2-year, 5-year, 10-year, 50-year, 100-year, 200-year and 500-year.

Rainfall-runoff simulations were carried out with the hydrological models described in chapter 3, using GPM as input rainfall. The obtained discharge timeseries at selected nodes/locations were statistically fitted to Log-Pearson III frequency distribution functions.

Then the obtained lateral inflows for selected return periods at selected river locations were used to simulate water surface profiles with the 2D hydrodynamic models described in this chapter.

The water surface elevation and implicitly the water depth, as well as the water velocity was calculated using 2D models based on sets of finite elements meshes which allow for a very precise representation of all characteristic parameters and features of the river channel, floodplains, as well as structures present in the flood prone areas.

The 2D models were based on the DEMs available, such as the WP1 DEMs and also ALOS, the latter being used to add information where none was available from the WP1 datasets. The computational meshes were generated for each area considering the following principles:

- The 2D domain has been selected in such a way that is it extended enough to avoid any numerical instabilities induced by imposing various types of boundary conditions.
- The river geometry has been carefully defined to capture the transitions between river channel, banks and floodplains
- The river channel, as well as the area adjacent to it and the settlements' areas were described using a finer mesh which provides more computational nodes and implicitly a better resolution of the results.
- The computational meshes were optimised for numerical stability and precision of the results.

The results generated by the 2D models represent a continuous surface depicting various parameters, such as the water level, water depth, current velocity, as well as the velocity components in x and y directions.

The 2D model results were processed in a GIS environment and the final results are presented, for all return periods, as:

- Water depth raster file at a 2 m resolution
- Water velocity raster file at a 2 m resolution
- Flood extent shapefile.

In order to validate the maps, due to the lack of on-site flooding marks or other type of data showing flood water level/depth, satellite imagery was used to derive the flood extents for various events between 2018 and 2021. Those satellite imagery derived flood extents were then compared to the results obtained from the 2D hydraulic models.

The satellite imagery data were extracted from Sentinel 1 and Sentinel 2 satellite products. Sentinel 1 uses SAR (active radar) data, which allows for the radar to operate even under cloudy conditions, while Sentinel 2 data is based on optical data. The flood extents derived from both satellites provide either direct observations of the flood (in case of Sentinel 2) or the relative change of the land cover between 2 dates (in case of Sentinel 1).

Inherently, the satellite data is also prone to uncertainty as the data which is provided is largely influenced by the track of the satellite and the time period when the satellite is flying over the flooded area. Because of this, the satellite derived data is not depicting a maximum flood extent, but rather a snapshot of the flooding at the time when the satellite was positioned over the affected area. It is possible that the snapshot was being taken during the ascension of the flood extent or during the recession, once the peak has already propagated downstream. Moreover the quality of the flood extent derived from satellite imagery can be affected by the cloud coverage.

Furthermore, for a proper comparison to be made between the earth observations and the 2D model results, the flood events that were observed need to have an associated probability. If the flood event associated probability is known, then a direct comparison can be made which can provide valuable input regarding the calibration of the 2D model parameters. The comparisons presented in the following section were done for all modelled return periods and assess qualitatively the match between the observed and modelled datasets.

Because of the satellite data uncertainty, the flood extents derived from satellite imagery should be analysed with caution as they are not depicting the maximum flood extent and that differences between the modelled and observed floods are to be expected in this case. For a proper comparison with the modelled results, onsite flood extents, markers, water depths, velocities is a necessity.

The section below shows a comparison between the satellite imagery derived flood extents and the extents derived using the 2D hydraulic models. For the comparison the return period of the flood caught by the satellite was assessed based on the statistical analysis and the flood extent from the closest return period was used.

5.1 Tekeze-Setit-Atbara Basin

The statistical analyses and the fitting of frequency distribution functions have been carried out for the following locations:

1. Dirma
2. Humera
3. Showak
4. Girba
5. Al Fahada
6. Atbara

The results – flow timeseries for selected return periods at the above locations – are submitted in the Excel-workbook <Return period floods TSA.XLSX>.

As an example, the following chart shows the hydrographs for Atbara (near the river's mouth):

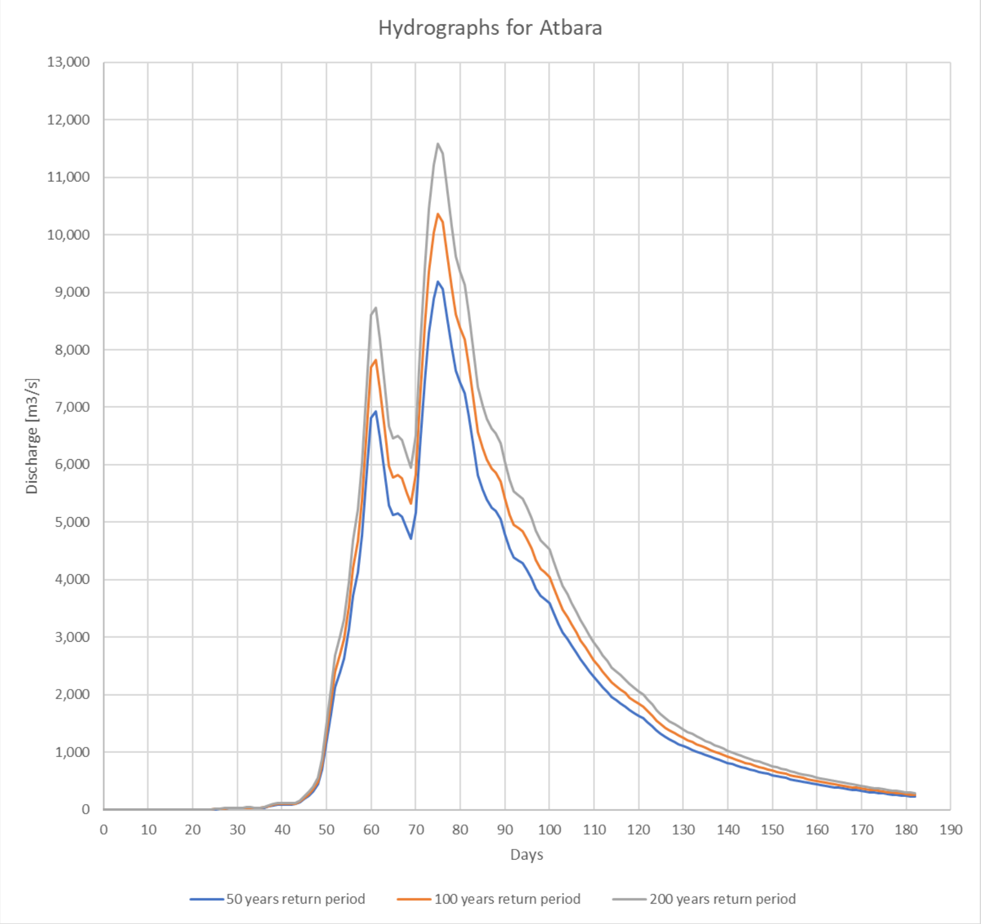


Figure 50 Discharge hydrographs for Atbara for return periods 50-year, 100-year, and 200-year.

GIS result layers for all return periods simulated have been generated for the selected flood locations in this basin – see the respective files in <FEXT_TSA.ZIP>. As an example, the following image shows the extents for Humera).

Figure 51 Flood extent for the 100-year flood event for at Humera.

A comparison was made between the Humera and Atbara flood extents, considering the Sentinel 1 and 2 satellite imagery data. The comparison shows that the flood extents match in some locations and in general shows a better agreement with the higher occurring probabilities, such as 2 years return period (T2) and 5-years return period (T5). Below a comparison between the T2 flood extent (obtained using the 2D model) and the Sentinel data (2020) is shown.

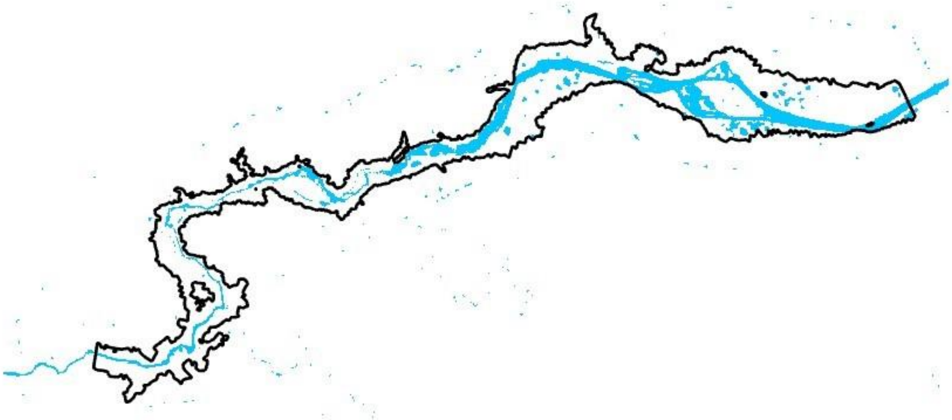


Figure 52 Comparison between the modelled results – T2 (black) and the Sentinel data (blue) for Humera.

For Atbara the observed flood extent is higher, partly due to the confluence with the White Nile and also the lower topography, leading to more places where water can accumulate in the floodplain. **Error! Reference source not found.** below shows a comparison between the 500 years return period (T500) model result and Sentinel data (2018), depicting the amount of water stored in the floodplain during or after the flood event.

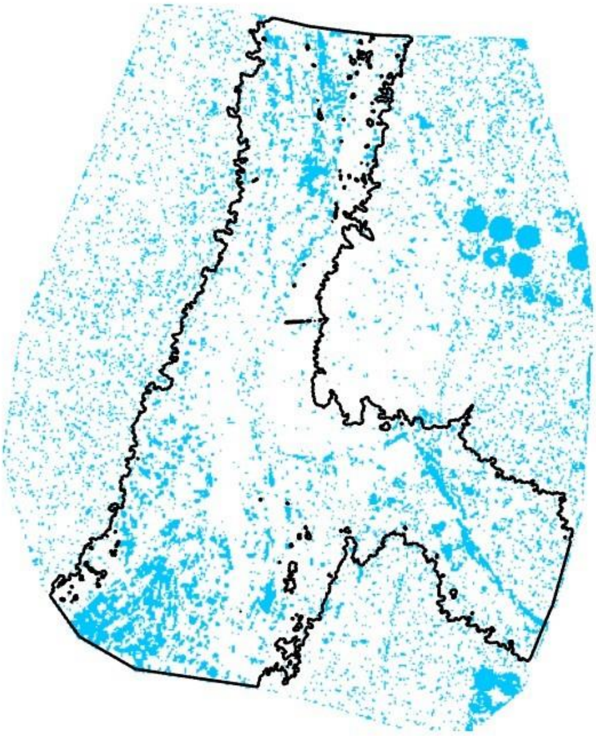


Figure 53Comparison between the T500 model results (maximum flood extent in black) and the Sentinel data (unknown time during the flood event in blue).

5.2 Blue Nile Basin

The statistical analyses and fitting of frequency distribution functions have been carried out for the following locations:

1. Eilafun
2. El masudiya
3. El Roseires
4. El Suki
5. Ethio-Sud-Border
6. Fadasi
7. Kharthoum
8. Kemlin
9. Rufa'ah
10. Singa
11. W-Hadad
12. Wad Medani

The results – flow timeseries for selected return periods at the above locations – are submitted in the Excel-workbook <Return period floods BN.XLSX>.

As an example, the following chart shows the hydrographs for Khartoum:

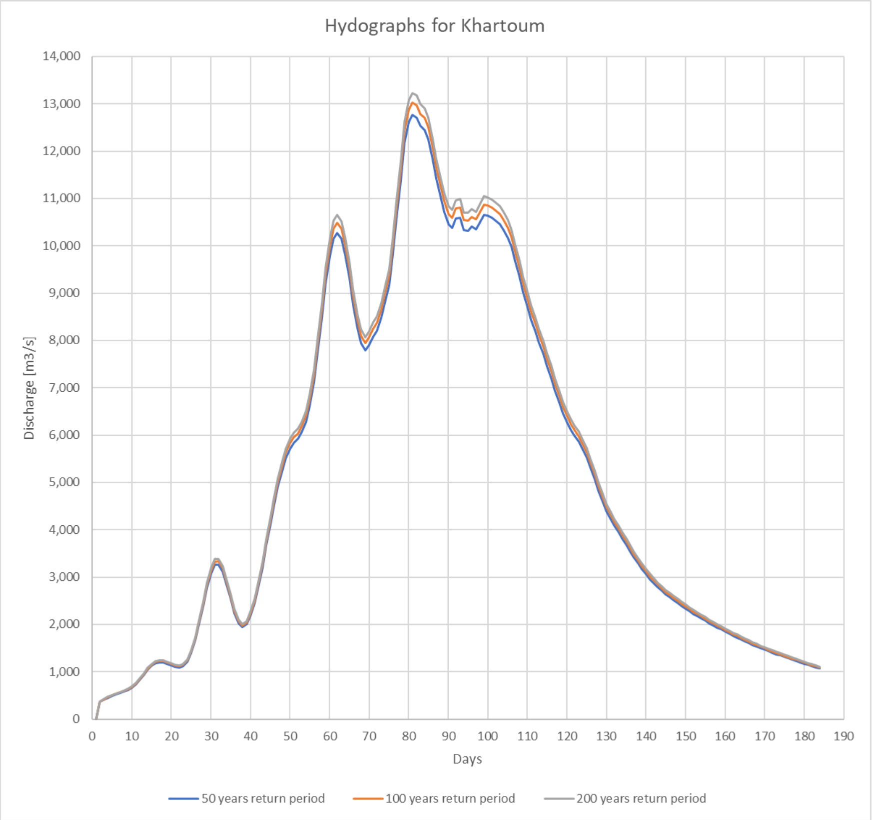


Figure 54 **Discharge hydrographs for Khartoum for return periods 50-year, 100-year, and 200-year**

GIS result layers for all return periods simulated have been generated for the selected flood locations in this basin – see the respective files in <FEXT_BN.ZIP>. As an example, Figure 55 shows the extents for Wad Medani).

Figure 55 Flood extents for the 100-year flood event at Wad Medani.

The model results were compared to the Sentinel data in terms of the flood extent. The comparison shows resemblance between the model results for the 2-years return period flood (T2) and the observed data (2020), as seen in Figure 56.

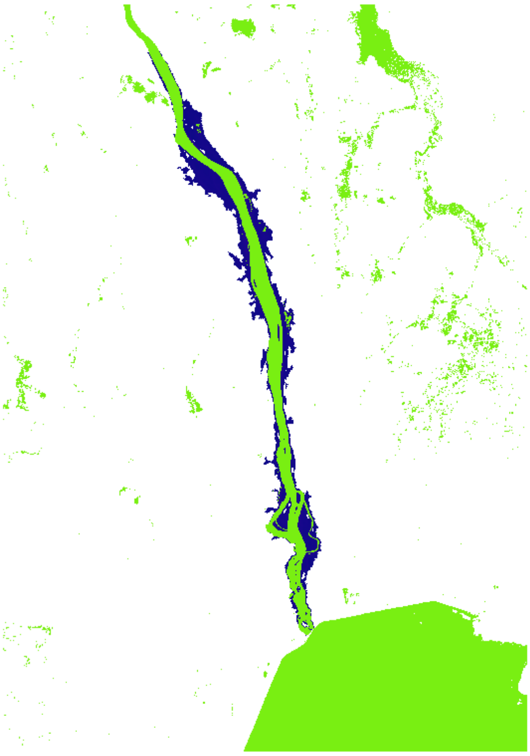


Figure 56 **Comparison between the simulated maximum flood extent for the T2 event (blue) and observed flood extent via satellite in 2020 (green) for the Rosieres area.**

Figure 56 shows that downstream of Rosieres dam, the simulated flood extent follows the satellite imagery (observed). This assertion is reinforced by the terrain topography which does not allow water to spread out of the main river channel and also by the lack of a well-defined floodplain.

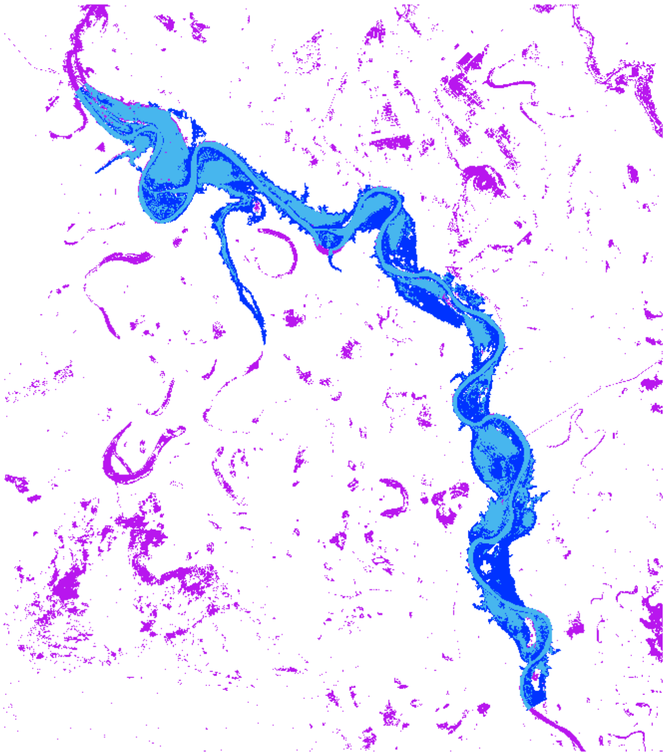


Figure 57 **Comparison between the simulated maximum flood extent (blue) and observed flood extent in 2020 (purple) for T500 for the Singa area**

Figure 57 above shows a comparison between the simulated T500 event and observed flood extents for Singa in 2020. Looking at various return periods and also different satellite imagery datasets, a good match between them is obtained. The main differences are found between the flooding observed in the floodplain and outside of main river channel. The water accumulation in the floodplain can be justified by water trapped in depressions during heavy rainfall.

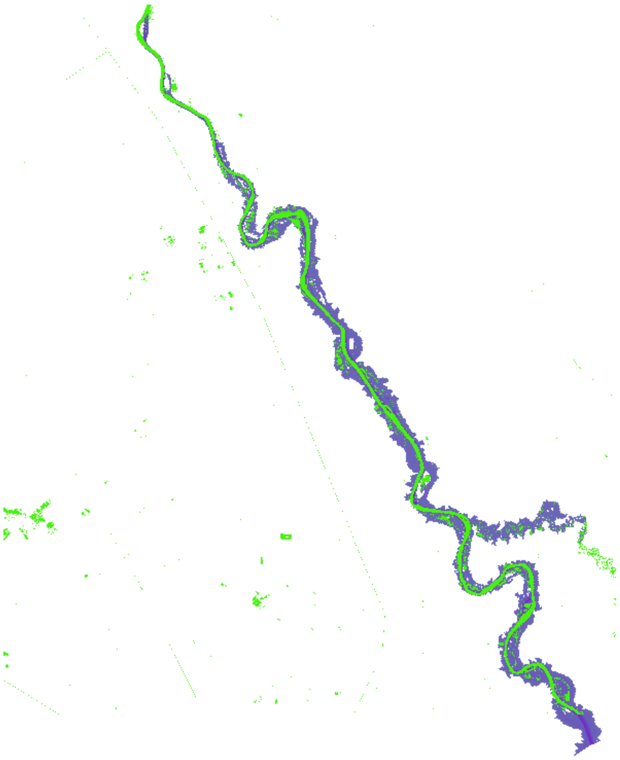


Figure 58 **Comparison between the simulated maximum flood extent (blue) and observed (green) flood extent in 2021 for Wad Medani for the T2 return period**

Figure 58 above shows the comparison between the simulated and observed flood extents around the Wad Medani area for the 2-year return period (T2). Looking at the observed data, it is clear that the satellite passed over the area during a period of time when there was no flooding occurring, thus capturing the water level in the river at a normal value. The simulated flood extent for the 2-year event agrees with the observed flood extent, but one has to consider the possibility of the discharge measured at the moment in time when the satellite was passing over, had it been measured, may be smaller than the 2-year event discharge used in the simulation. For this reason, the comparison is plausible and the observed flood extent could be narrower than the simulated one, even for the highest return period simulated.

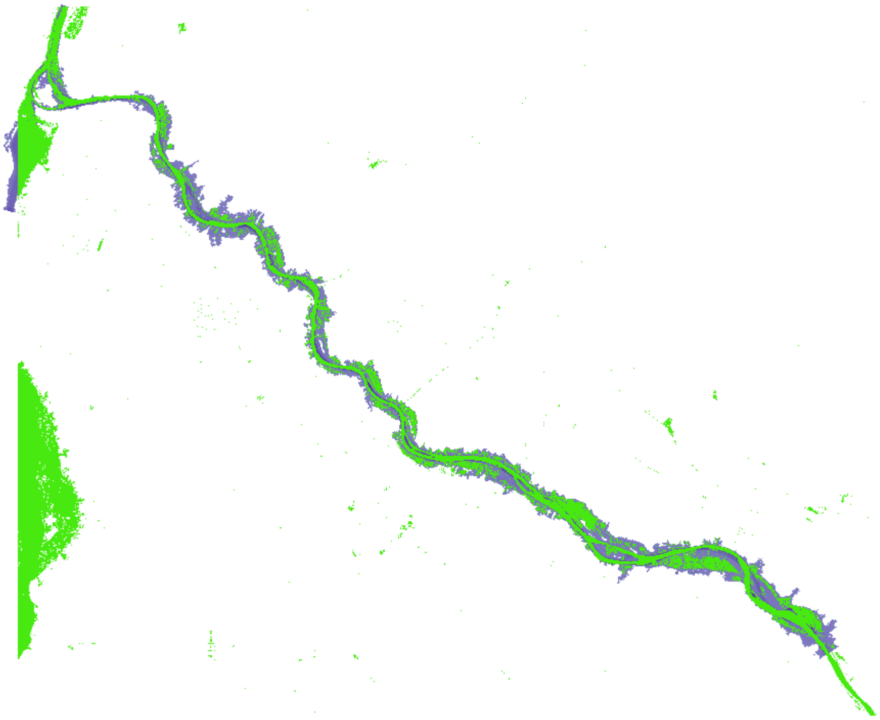


Figure 59 **Comparison between the simulated maximum flood extent (blue) and observed (green) flood extent in 2020 for Khartoum for the T2 return period.**

Figure 59 compares simulated and observed flood extents around the Khartoum area for the 2-year return period flood (T2). There is a match between the datasets, but the same arguments presented for the Wad Medani area can also be made in this case. The discharge during the satellite pass period could be lower than the theoretical 2-year event peak discharge, which could lead to a narrower extent. During high flows, the observed flood extent is similar to the simulated maximum flood extent in some areas, but the uncertainty regarding the moment in time when the flood has been captured becomes of great importance in this case, as the snapshot could be taken either during the ascension or recession of the flood event, while the modelled result shows the maximum extent.

5.3 Tana Basin

The statistical analyses and fitting of frequency distribution functions have been carried out for the following locations:

1. Ribb
2. Gumara
3. Dirma
4. Megech

The results – flow timeseries for selected return period at the above locations – are submitted in the Excel-workbook < Return period floods Tana.XLSX>.

As an example, the following chart shows the 100-year return hydrograph for Megech:

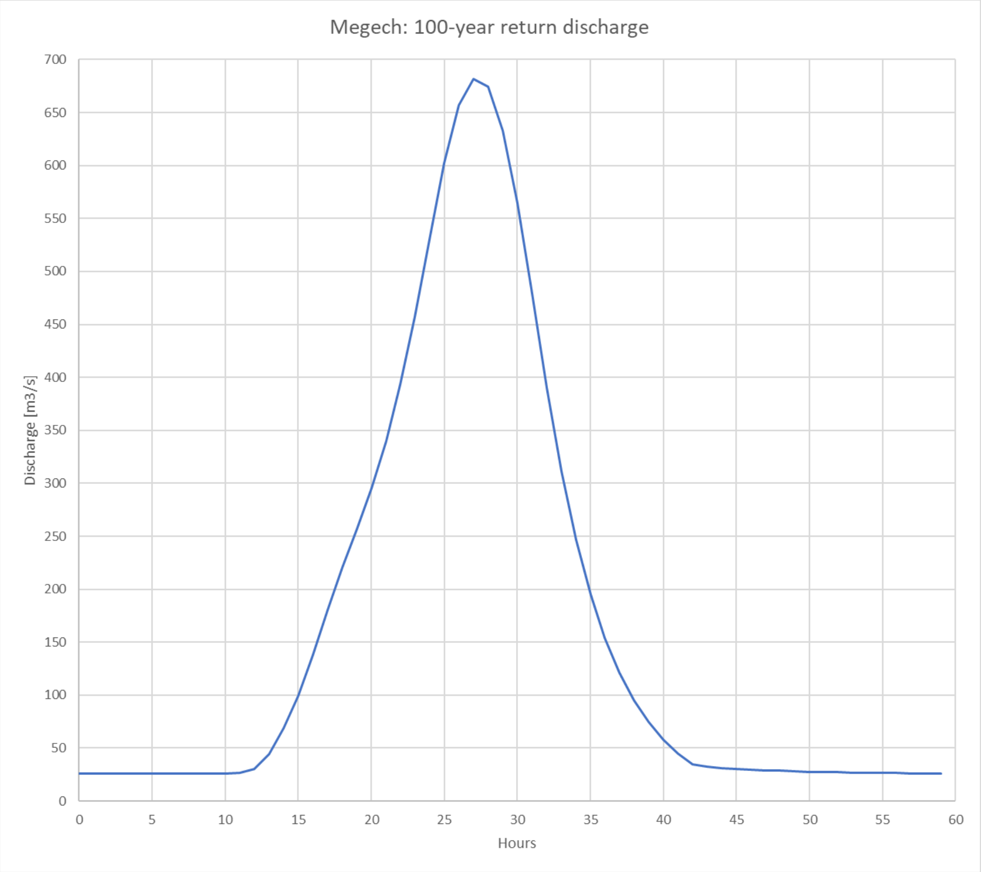


Figure 60 Discharge hydrograph for Megech for 100-year return period.

GIS result layers for all return periods simulated have been generated for the selected flood locations in this basin – see the respective files in <FEXT_Tana.ZIP>. As an example, the following image shows the extents for Dirma and Megech floodplains).

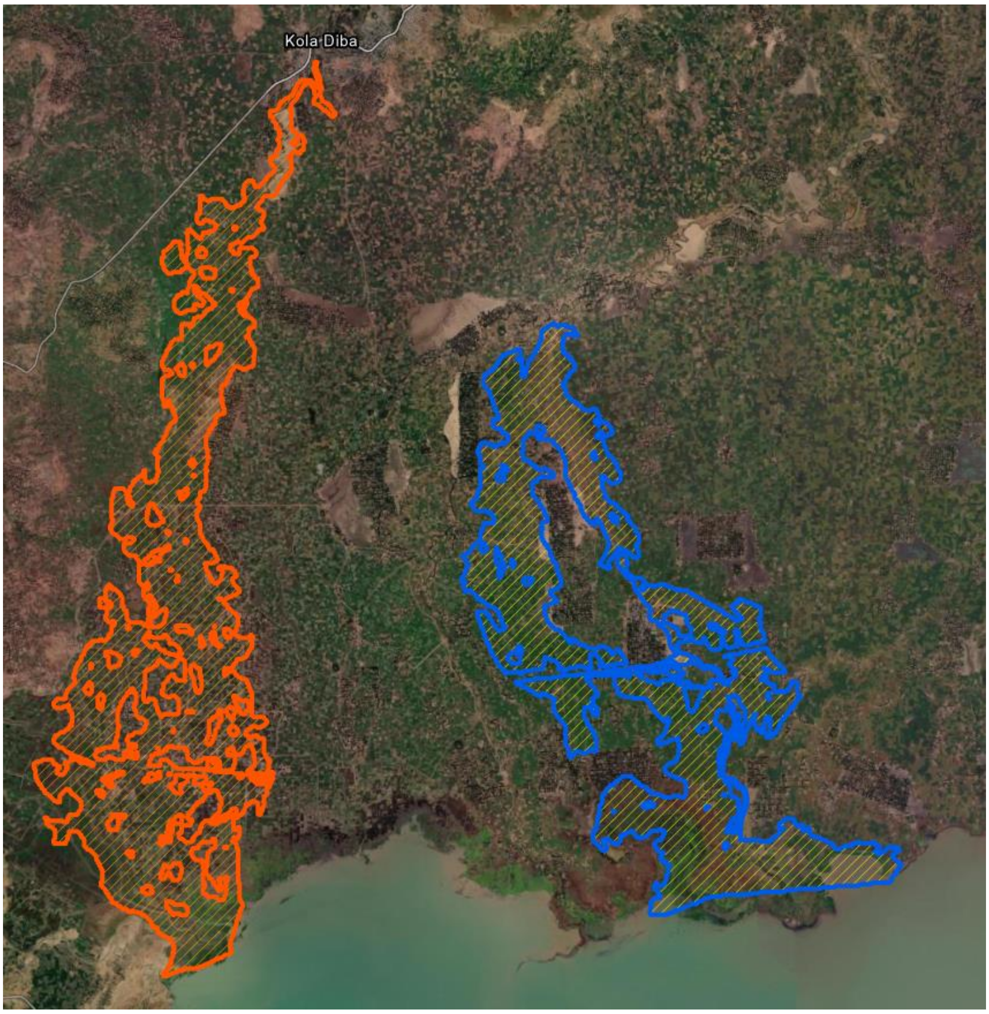


Figure 61 Maximum flood extent for the 100-year flood events for the Dirma (red) and Megech (blue) rivers.

The model results were compared to the Sentinel data in terms of the flood extent. The comparison shows resemblance between the model results and the observed data, as shown in Figure 62, Figure 63 and Figure 64.

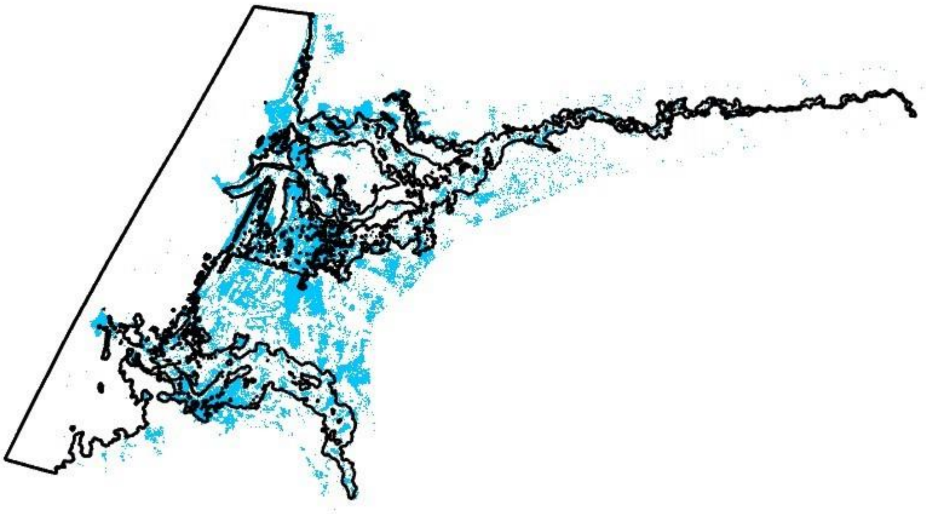


Figure 62 Comparison between the T500 maximum flood extent in black and the observed flood extents (blue) for Ribb and Gumara in 2018

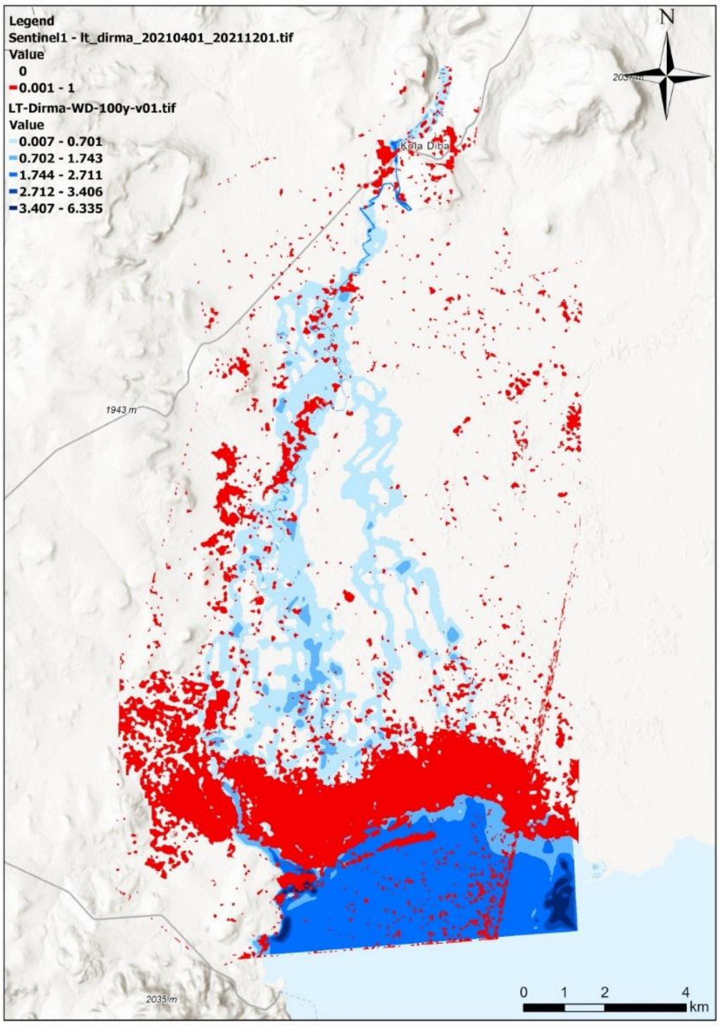


Figure 63 Comparison between the T100 maximum flood extent in blue and the observed flood extents (red) for Dirma in 2021.

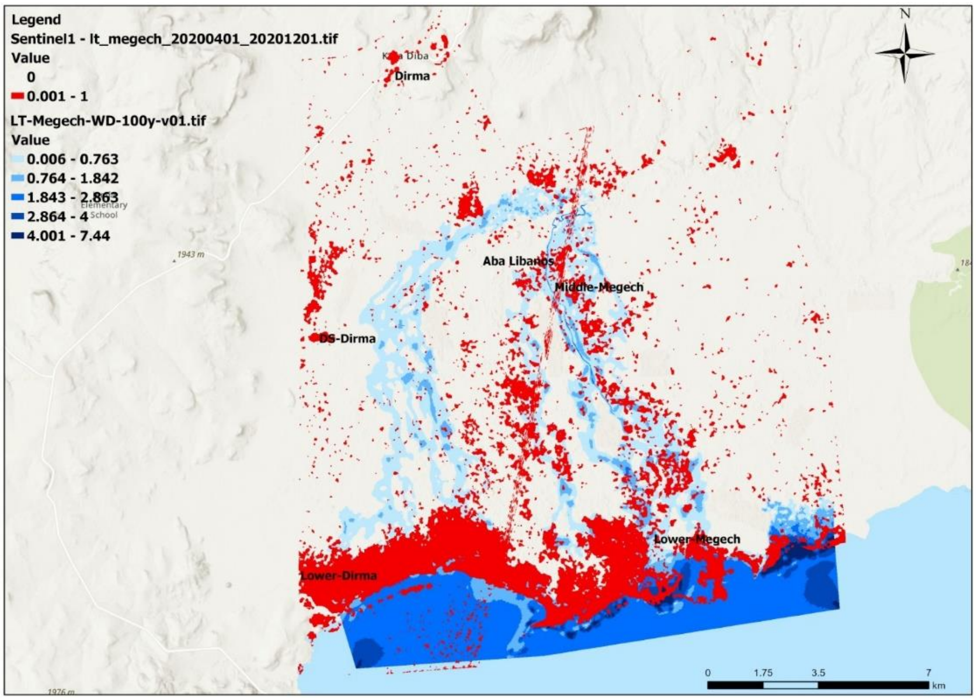


Figure 64 **Comparison between the T100 maximum flood extent in blue and the observed flood extents (red) for Dirma and Megech in 2020.**

The images above show that for Ribb and Gumara the match between the observed and simulated flood extents is good. There are some locations, such as the interfluvial area between Ribb and Gumara where the satellite imagery data shows some flooding, but this could be attributed to water accumulating in low areas and depressions during heavy rainfall.

For Dirma and Megech the observed data was found to have inconsistencies, with many small areas showing flooding which could be justified by the satellite passing over the area after the flood peak has gone and water puddling still showing just being water trapped in the depressions along the area.

5.4 Baro-Akobo-Sobat Basin

The statistical analyses and fitting of frequency distribution functions have been carried out for the following locations:

1. Gambela
2. Itang
3. Akobo
4. Nasir
5. Malakal
6. Pibor

The results – flow timeseries for selected return periods at the above locations – are submitted in the Excel-workbook <Return period floods BAS.XLSX>.

As an example, the following chart shows the hydrographs for Atbara (near the river's mouth).

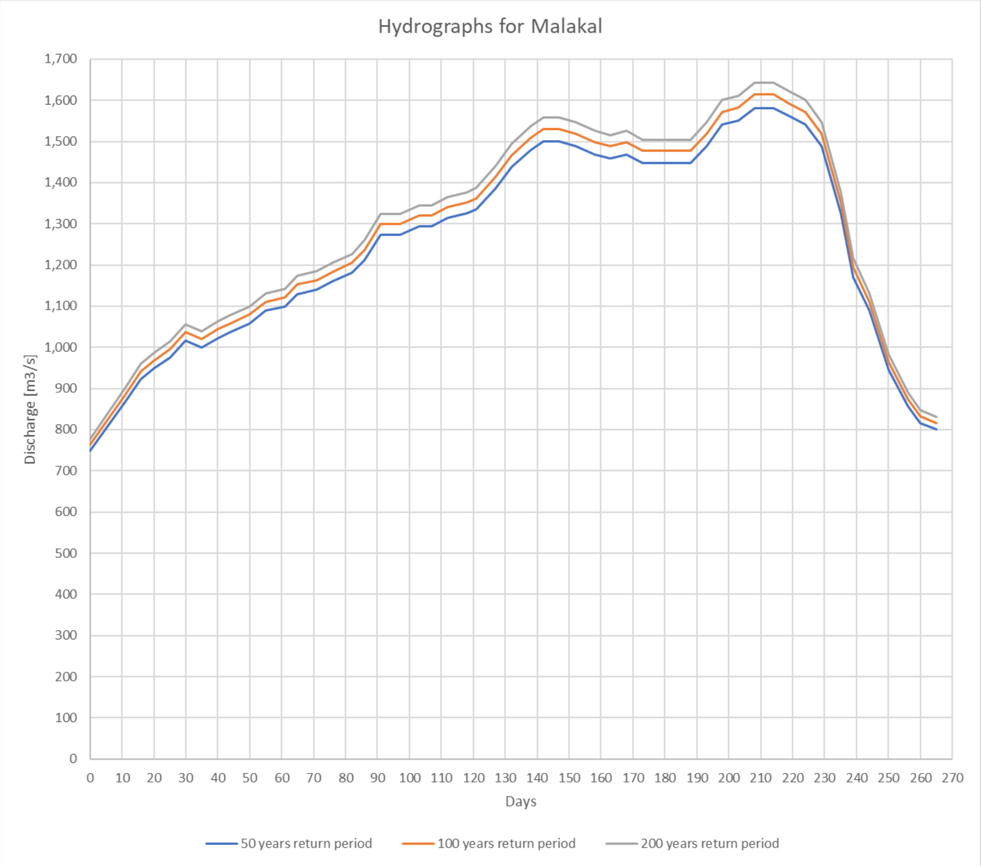


Figure 65 Discharge hydrographs for Malakal for return periods 50-year, 100-year, and 200-year.

GIS result layers for all return periods simulated have been generated for the selected flood locations in this basin – see the respective files in FEXT_BAS.ZIP

The model results were compared to the Sentinel data in terms of the flood extent. The comparison shows resemblance between the model results and the observed data, as shown in Figure 66.

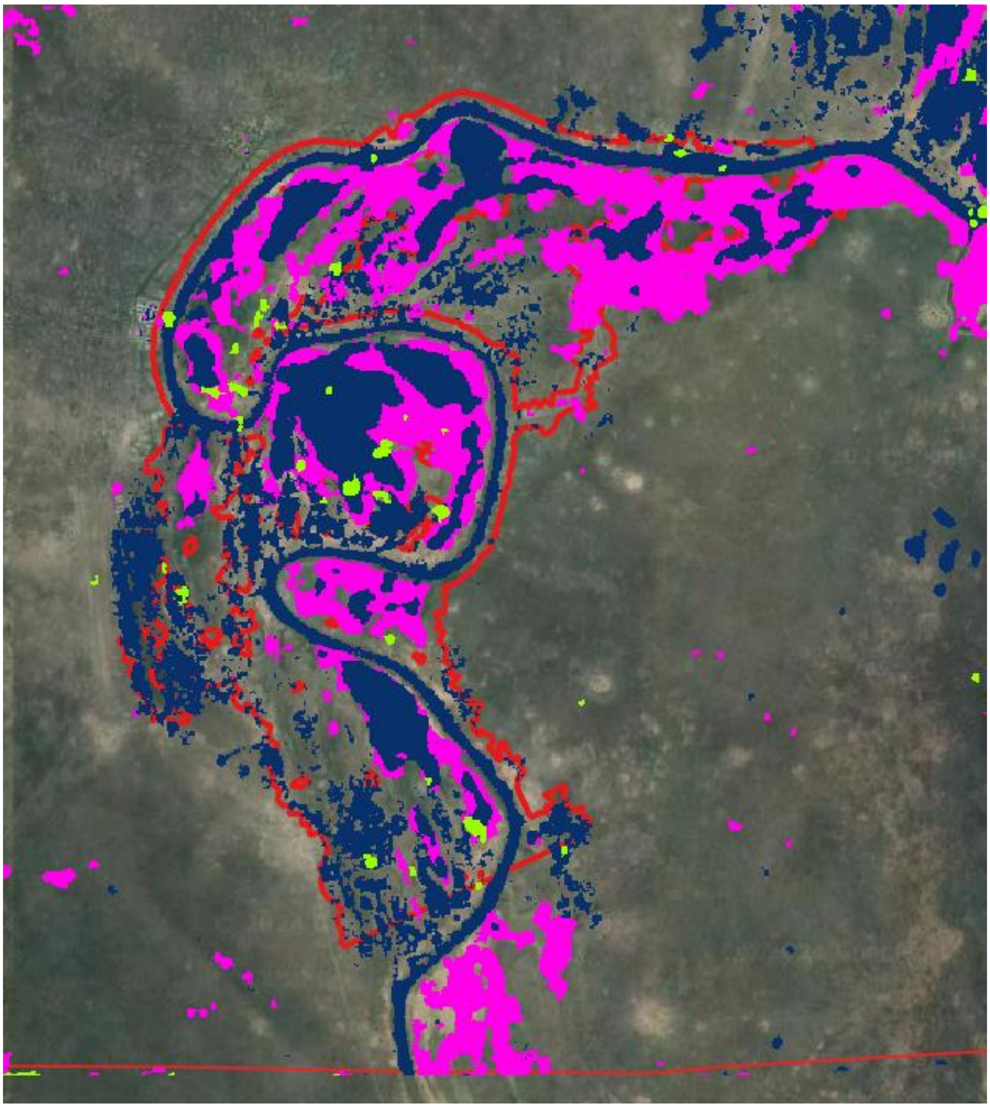


Figure 66 **Comparison between the Sentinel data (blue and pink – 2020 and 2021) and the simulated maximum flood extent (black) for Akobo for the 100-year return period.**

Figure 66 compares simulated and observed flood extents for Akobo for the 100-year return period. Overall, the flood extent is similar with several areas in the floodplain being flooded according to the observations. This can be justified by heavy rainfall accumulating in low areas. Also, the floodplain in the Baro Akobo Sobat area is quite flat and extended, so a possibility of the flooding occurring because of overflow from a nearby river still exists. The uncertainty in the Sentinel data is quite high, judging by the lack of water in the river channel (as seen on the aerial imagery shown above).

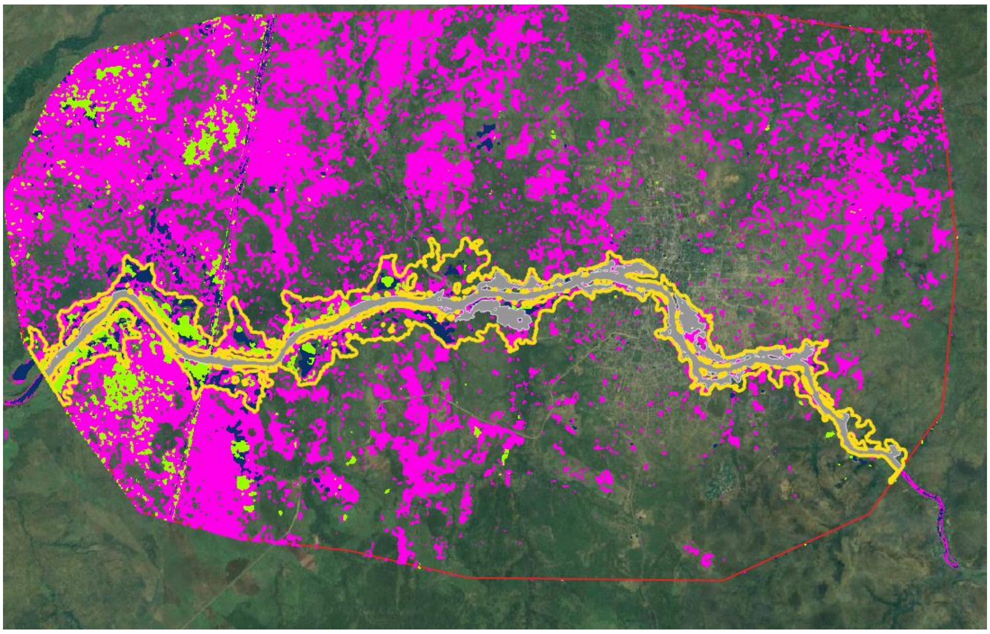


Figure 67 Comparison between the Sentinel data (blue, green and pink – 2020, 2018 and 2021) and the maximum simulated flood extent (yellow) for Gambela – 100-year return period.

The comparison above shows various Sentinel data overlapped on the simulated maximum flood extent. Depending on the moment in time when the satellite flew over the Gambela area, several areas of the flood extent show either no water in the floodplain or a very large inundation. The Gambela area, similar to the rest in the Baro-Akobo-Sobat area has extended floodplains where water can accumulate, appearing as puddles or even small lakes.

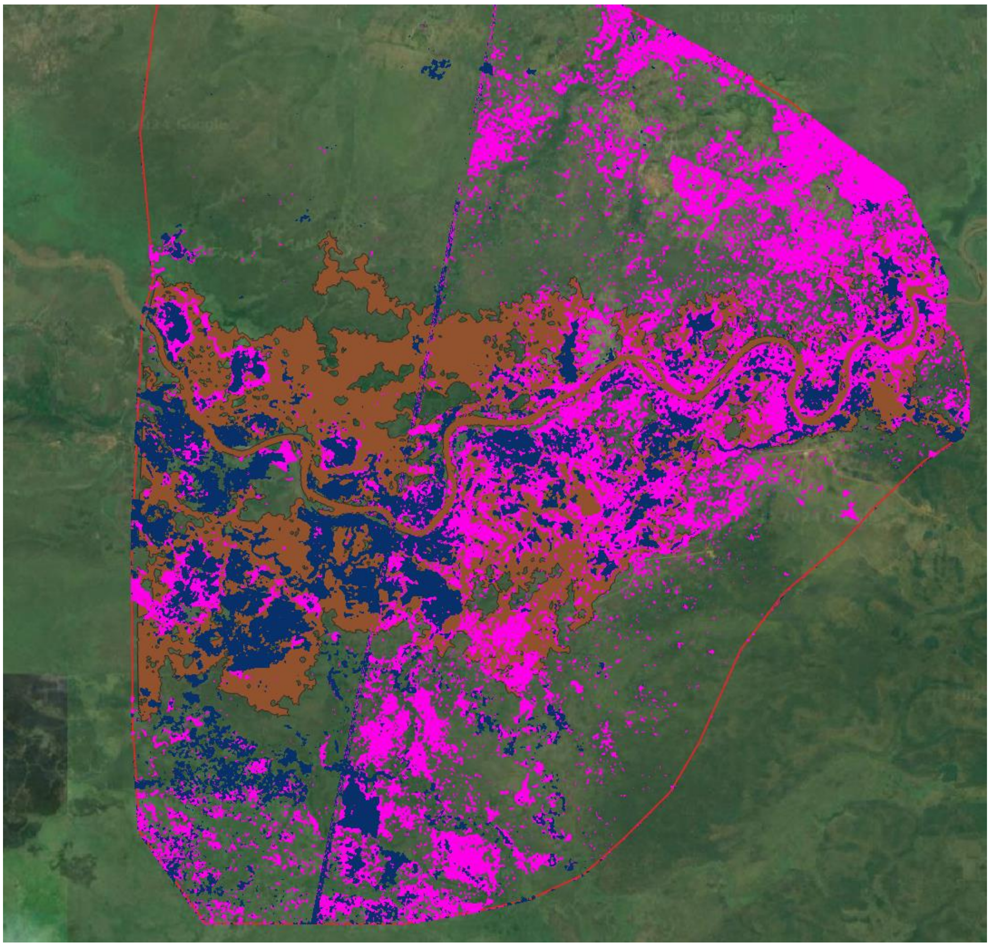


Figure 68 **Comparison between the Sentinel flood extent (blue and pink – 2020 and 2021) and simulated maximum (brown) flood extent for the 100-year return period for Itang.**

Figure 68 compares the simulated maximum and observed flood extents for the 100-year return period for Itang. The simulated flood extent is quite similar in the upstream region of the 2D domain, but it becomes larger in the modelled scenario compared to the observed data. The observed data has a degree of uncertainty which is further confirmed by the artifacts seen in the image (the flood extent seems to be cut off in the downstream area). Similar to the other locations, the moment in time when the satellite passed over the area is very important and plays a crucial role in estimating the quality and precision of the results provided by the 2D model.

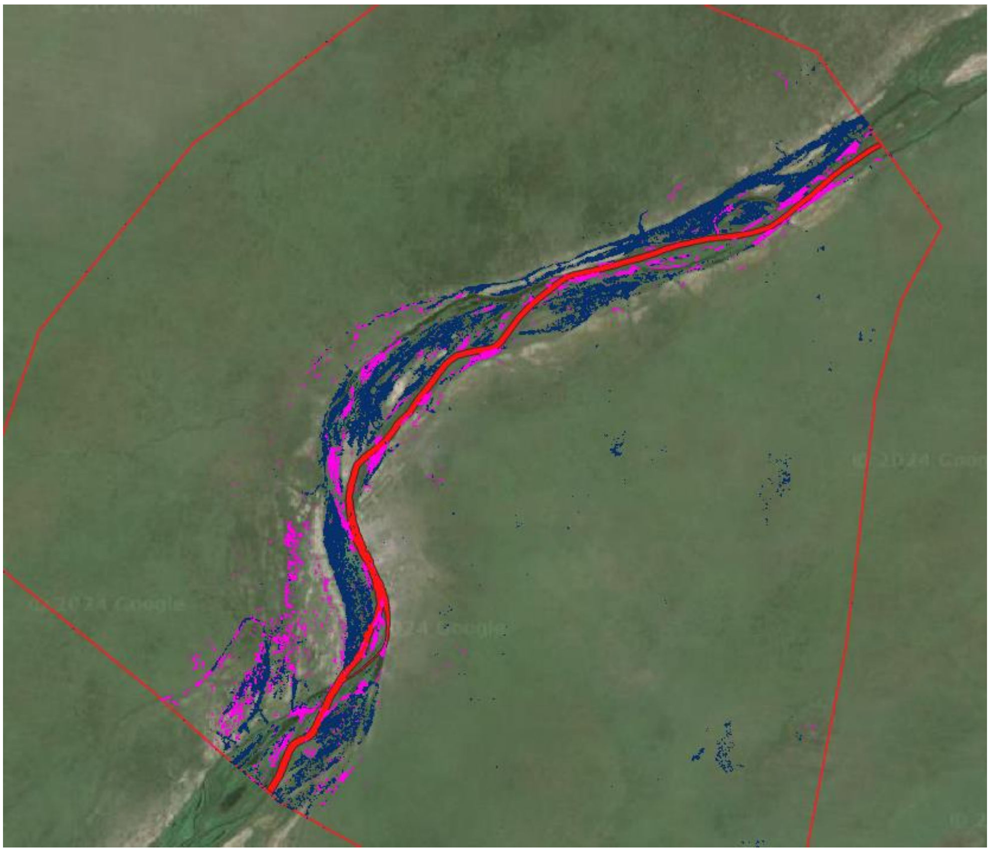


Figure 69 Comparison between the Sentinel data (blue and pink – 2020 and 2021) and the simulated maximum (red) flood extents for Malakal - T100.

Figure 69 shows the comparison between the observed and simulated maximum flood extents for Malakal for the T100 return period event. The simulated flood extent shows that the flood is contained inside the river banks with no overflow, while the Sentinel data shows some water accumulation along the river.

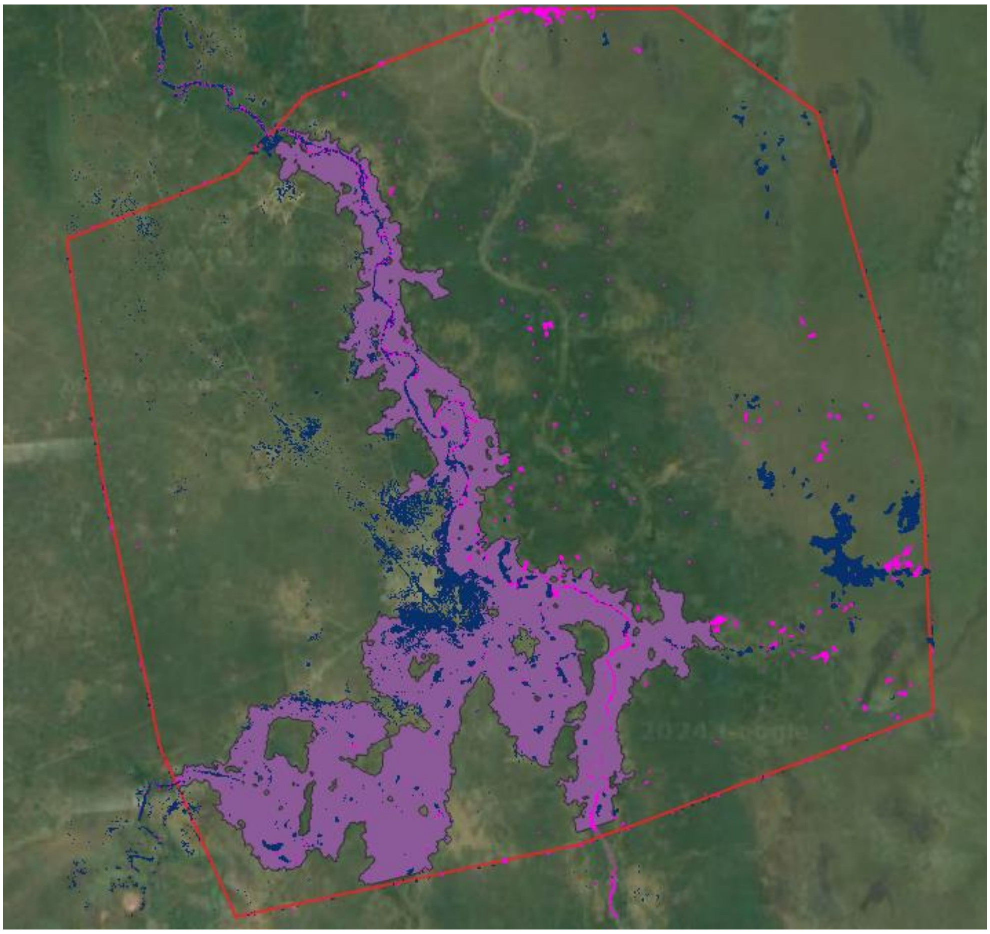


Figure 70 Comparison between the Sentinel (pink and blue - 2020) and simulated maximum (purple) flood extents for Pibor – T100 return period.

Figure 70 shows the comparison between the simulated and observed flood extents for T100 return period in the Pibor area. The Sentinel data, in this case, shows a large degree of uncertainty as there is little to no water in the river channel. Still, the Pibor city area shows some historical flooding which is in agreement with the flood extent obtained from the 2D model. One reason being the moment in time when the satellite has passed over the area captured the situation post-flooding.

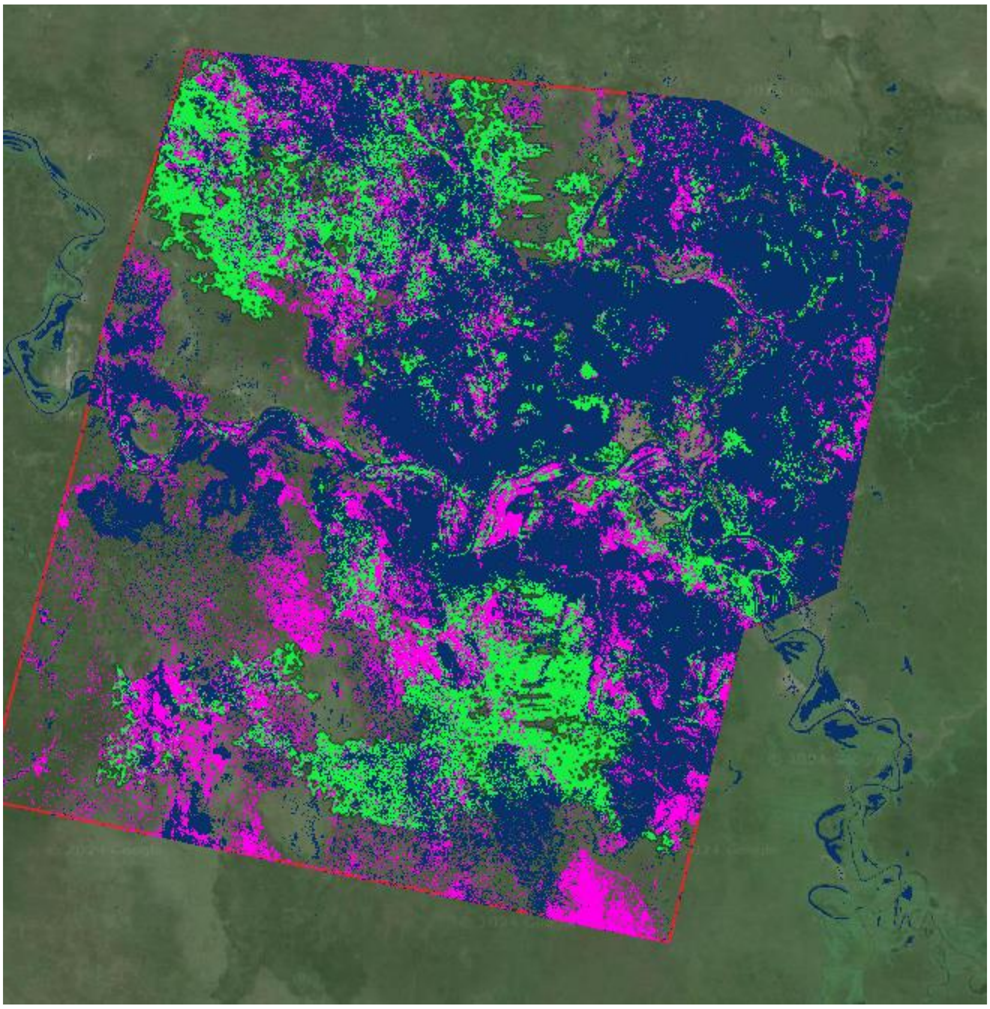


Figure 71 Comparison between the Sentinel (blue and pink – 2020 and 2021) and simualted maximum (green) flood extents for Nasir – T100.

Figure 71 shows the comparison between the modelled and observed flood extent for Nasir. It can be seen from the shape of the flood extent that there is no predefined flow direction and as soon as the transport capacity of the river channel is exceeded, the flood extent fills the entire floodplain and the Mashar Marshes. The image shows a good match of the datasets and confirms the overall flow direction.

6 Summary and Conclusions

The EN-FFEWS **software** has been (1) consolidated to one coherent system, (2) upgraded to the latest version of the forecasting system (MIKE Workbench in the backend + MIKE Operations Web in the front end), (3) optimized, and (4) migrated to a development site in the cloud. It still contains the original forecast models. The revised and enhanced forecast models will be embedded when they are finalized. This is the main remaining activity. Further remaining activities regarding the software system are: (1) configuration of thresholds for alerting purposes, (2) configuration of the dissemination system, (3) testing, and (4) migration to a cloud server of ENTRO's choice.

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 of this, the advantage of using GPM as input to calibrate the model has the advantage that data dissemination and performance evaluation of forecasts will become consistent. This is important because the purpose of the models is to serve for 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 a 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.
3. Tana Basin
   a. Cross-section geometries need to be further checked and revised where possible. This proved to be challenging due to the flat terrain.
   b. Model parameters are plausible and may need revisiting when cross-section geometries are made consistent.
   c. The hydrodynamic model produces plausible results. Including lake Tana as a structure in the model opens the possibility to

    fully integrate the model in FEWS and obtain the lake variation as a model result, as opposed to using a predefined boundary condition which might not provide the best results.

4. Baro-Akobo-Sobat Basin
    a. Cross-section geometries need significant corrections and adjustments. This has led to re-building the model from scratch and adding all necessary connections between the river channels and the floodplains
    b. Model parameters have been adjusted in order to calibrate the model in the available stations.
    c. The hydrodynamic model runs without errors and provides plausible results, thus it is ready to be fully embedded in the FEWS.

The **flood extents** for the selected flood locations in the basins have been produced on the basis of hydrological statistical analysis and hydrodynamic simulations with selected statistical discharges (e.g. for 100-year return period).

1. Tekeze-Setit-Atbara Basin:. 2D hydrodynamic models have been built and simulations executed which provide a better distribution of the water depths and velocities.
2. Blue Nile Basin: 2D hydrodynamic models have been built and simulations executed which provide a better distribution of the water depths and velocities.
3. Tana Basin: The 1D hydrodynamic models may have limitations for delineating flood extents in the flat terrain. It must be investigated yet, to what extent a high-resolution terrain model, if available, can improve the quality of the flood extents. To improve on the 1D model results, 2D hydrodynamic models have been built and simulations executed which provide a better distribution of the water depths and velocities. Also, in the case of Lake Tana models where the floodplains are quite flat, 2D models represent a better option for the flood wave propagation, as opposed to predefine the flow paths through the cross-sections.
4. Baro-Akobo-Sobat Basin: The BAS flood risk locations have been treated using 2D models which benefited from the WP1 DEMs and other sources of data such as IceSAT2 which provided valuable information regarding the water depth and bathymetry. The 2D models have been run and flood extents were generated which were then compared with aerial imagery data to confirm the validity of the model setup and results.