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Calibration of a Hydraulic Model for Seasonal Flooding in a Lowland River with Natural Diversions and Bathymetric Uncertainty, for Dam Downstream Impact Assessment

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Abstract: *A method is developed to generate bank-full river main channel geometry, to complement an open-source Digital Elevation Model (DEM) and produce a calibrated hydraulic model reproducing the extent of historically observed overbank flooding. This approach relies on limited surveyed cross section and flow rate information and is potentially suitable for projects in developing countries where the availability of measured data is limited. The method presented is applied to the case of the seasonal flooding of the Baro River in the Gambela floodplain in Ethiopia, modelled with a two-dimensional hydraulic model. The simulated flooding extent for the 1990 wet season is compared with the observed flooding from 1990 satellite imagery and the expected flow interaction patterns with the near Alwero River, showing good agreement. The calibrated model is also used to show the impact of the planned TAMS hydropower dam on the Baro River flooding.*

Keywords: *dams, downstream impact, river bathymetry, seasonal flooding, hydraulic modelling, remote sensing.*

1. INTRODUCTION

Dams are instream structures providing a wide range of services, including energy supply, drought and flood hazard mitigation, water supply, and recreation services (Graf, 1999, Bednarek, 2001, Biswas, 2012, Ansar et al., 2014). In particular, the importance of dams cannot be understated for developing countries (IRENA, 2020), where dam construction is expected to increase in the future to mitigate uneven distribution of fresh water in space and time (ICOLD, 2019) and to support economic and social development (Biswas, 2012).

On the other hand, the construction and operation of dams can cause different hydrological, social, economic, environmental, geomorphological and ecological impacts (Power et al., 1996, Magilligan and Nislow, 2005, Merritt and Wohl, 2006, Poff and Zimmerman, 2010, Marcinkowski and Grygoruk, 2017, Bejarano et al., 2019). Focusing on the area downstream of a dam, the hydrological impact, that is, the change, caused by the dam presence and operation, of the patterns of flooding magnitude, extent and duration, drives all the other types of impact (e.g., decrease in overbank flooding reduces wetland recharge). Energy production maximization while minimizing the negative downstream impact is the main evaluation principle in a hydropower dam project feasibility study; therefore, quantifying the dam downstream impact, particularly the hydrological impact, is crucial for hydropower project decision makers.

Numerical hydraulic models are keys to understand the hydrodynamics of a river system and its flooding patterns, before and after dam construction, to quantify and map the hydrological impact. On the other hand, model input uncertainties affect the accuracy of hydraulic models (Merwade et al., 2008, Bales and Wagner, 2009), and consequently affect the accuracy of the overbank flooding prediction. The availability of open-source Digital Elevation Models (DEMs) from remote sensing is crucial when developing hydraulic models for dam projects located in developing countries, where most of the hydropower projects are currently being designed and built. However, such DEMs do not contain accurate elevation information for the underwater river main channel. Typically, river main channel bathymetric information is collected by conducting topo-bathymetric surveys, and this information complements the elevation information from a DEM for the overbank areas. However, river bathymetry data collection is often expensive and time-consuming (Bures et al., 2019, Chénier et al., 2018) and, within specific projects in certain remote areas and with budget constraints, simply unfeasible.

Different methods have been proposed to estimate river bathymetry (longitudinal slope and cross-section geometry), based on different sources and techniques and the amount of information available. Some authors investigated the use of satellite images, such as assimilation of synthetic Surface Water and Ocean Topography (SWOT) water surface elevation to determine the channel depth and calibrate the roughness coefficient (Yoon et al., 2012, Häfliger et al., 2019) or the use of band ratio and multi-band models to extract satellite driven bathymetry from high-resolution satellite images (Chénier et al., 2018). These approaches, though promising, are still characterized by uncertainty, especially in absence of survey data for verification. Hostache et al. (2015) used a particle filter assimilation algorithm to extract the river bathymetry from GPS-equipped buoys, reporting a Root Mean Square Error (RMSE) of 36 cm; however, the study did not consider the effect of abrupt changes of topography in bathymetric estimation. Domeneghetti (2016) used a channel bank-full depth and slope break approach to generate the 140 km Po River (Italy) reach bathymetry from a 90m Shuttle Radar Topography Mission (SRTM) DEM, using linear statistical relationships to estimate both bank-full discharge and slope breaks from drainage area-bank-full depth and flow width-water surface elevation relationships, respectively. However, this method is not replicable for areas where there is not enough gauge station data to establish statistical relationship between channel bank-full discharge and drainage area as well as in the case of absence of high-resolution satellite data to establish flow width and water surface elevation. Caviedes-Voullième et al. (2014) proposed an algorithm to generate cross sections from 25 field surveyed cross sections and a 1m resolution LiDAR-based DEM available for the floodplain. Though the proposed algorithm is promising, the inconsistencies between DEM and the interpolated riverbed produced using the algorithm challenge its applicability. Bures et al. (2019) developed a mathematical model to represent the bathymetry of the Otava River (Czech Republic), with parameters estimated from 375 measured cross sections along the 1.75 km Otava River. Though the bank-full discharge is one of the most critical parameters in river bathymetry estimation, the study failed to consider the bank-full discharge and used instant Otava River flow as design discharge. The approach needs a significant amount of surveyed data to estimate the parameters of the model.

This paper presents and applies a method to calibrate a hydraulic model for flooding prediction that combines an open-source DEM and a procedure for bank-full cross-section geometry generation. The streamwise variation of the cross-sectionally-averaged depth is based on bank-full discharge estimation from stream gauge flow data, river width digitization from aerial imagery, streamwise river slope estimation from the DEM and uniform-flow calculations with friction coefficient determined from limited surveyed cross-section geometry, river photos and (Jarrett, 1985)'s method. The reconstructed main river bathymetry is then used to modify the available DEM within the river main channel region, to conduct two-dimensional (2D) hydrodynamics simulations. The reconstructed bathymetry is opportunely adjusted (calibrated) against historically observed river flooding extent. An application is presented for the Baro River in southwest Ethiopia, characterized by seasonal flooding (we focus here on the wet season) and complex overbank flow patterns in a lowland are where the absence of a clearly defined drainage divide in the left overbank area leads to water exchange between Baro River and Alwero River systems (natural river “diversions”).

2. MATERIALS AND METHODS

2.1. The study area

The Baro River in southwest Ethiopia is part of the Baro-Akobo river basin system, which contributes to the flow of the Sobat River, which in turn provides 48% of the White Nile flow (Wood et al., 2016). Except for the Baro River and the Alwero River, which joins the Baro River downstream of the Ethiopia-South Sudan border, all the other major rivers in the Baro-Akobo system, notably the Akobo River and the Gilo River, join the Pibor River, which is a tributary of the Sobat River.

Figure 1 shows the 29256 km^2 catchment of the Baro River, upstream of its confluence with the Alwero River. Figure 1 also shows the Baro River catchment location within the larger River Nile catchment.

While the upper part of the Baro River catchment is mountainous and forested, in the lower part of the catchment, starting from approximately 45 km downstream of the planned TAMS dam location, the river flows through lowland areas with meandering patterns. The Baro River right overbank area is relatively well constrained. On the contrary, the left overbank area is characterized by complex flooding patterns, also due to the vicinity of the Alwero and Adura rivers with the absence of a well-defined drainage divide, resulting in the natural water transfer (natural "diversions") between catchments during the wet season.

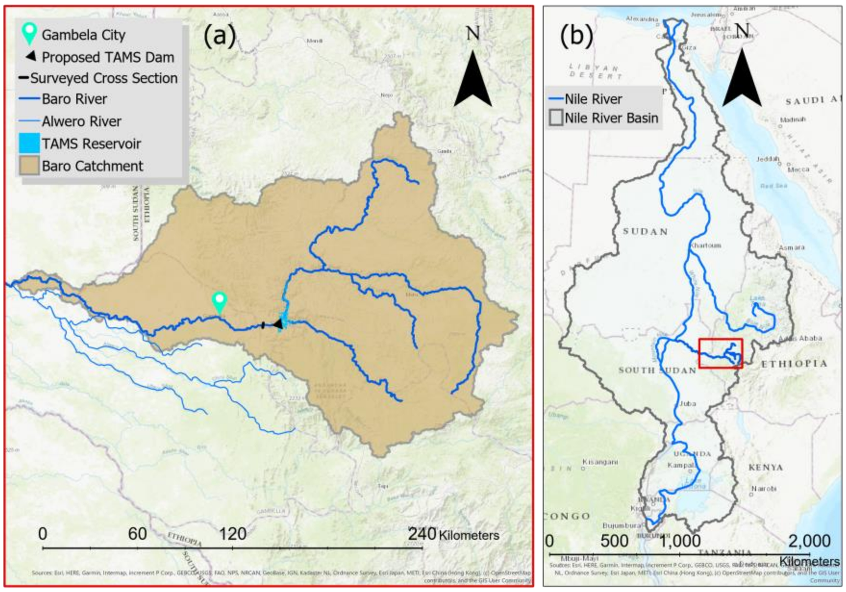

Figure 1 – (a) Baro River catchment and (b) its location within the Nile River catchment.

The weather in the Baro River region is significantly affected by tropical monsoons from the Indian Ocean; as a result, there is abundant rainfall during the wet season (May/early June to September/early October) and low precipitation in the dry season (December to April). The region presents a wide variety of ecosystems, such as wetlands, and activities such as navigation and recreation (Gambela National Park) (Wood et al., 2016). The average annual flow (1928-2009) of the Baro River, as measured at the stream gauge at Gambela (Figure 1) is 395 m^3/s, a value equalled or exceeded 39% of the year.

A number of hydropower and irrigation projects are either constructed or planned on the Baro-Akobo basin (Sileet et al., 2013). Notably, the hydropower TAMS dam (Figure 1) is planned for construction on the Baro River around 45 km upstream of Gambela. The dam height is 248 m, with a top-of-dam elevation of 730 m a.s.l. and length of 1335 m. The maximum and minimum pool elevations are 726 and 625 m a.s.l., respectively. The total storage capacity is estimated as 5868 Mm^3. The expected hydropower output is 2000 MW ($\approx$ 5.5 GWh/year), provided by eight turbines. In addition to hydropower generation, the dam is planned to provide irrigation water during the dry season to the fertile Gambela floodplain.

2.2. The hydraulic model

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) (Brunner, 2021) was used to develop a two-dimensional (2D) HEC-RAS hydraulic model (based on volume and energy conservation principles) for a longitudinal section of the Baro River stretching from the site of the planned construction of the TAMS hydropower dam to the Baro-Alwero river confluence, located about 243 km further downstream. This long reach of the Baro River was considered to model the area that will be affected by the construction of the TAMS dam, through overall flooding reduction, downstream of Gambela, and to capture the water exchange between Baro River and Alwero River catchments. The use of a 2D numerical modelling approach, instead of 1D, is important for the Baro River, characterised by overbank flooding during the wet season and complex flow patterns, especially in the lowland areas.

The freely available Shuttle Radar Topography Mission (SRTM) 30m DEM from the U.S. Geological Survey (USGS) was used as input for the model. A two-dimensional computational mesh, made of 100 m X 100 m computational elements, was used for the simulations. The finite volume solution scheme implemented by the HEC-RAS 2D modelling has the capability to use unstructured computational cells that may occur at the border of the computational domain. The default iterations number (20) for solution was used for each computational time step in the model setup. Breaklines were traced along both banks of the Baro River to capture the width variation of the river and refine the computational mesh in the river main channel area.

2.3. Estimation of bank-full discharge

Observed river flows (discharge at daily interval) in the Baro River flow are available at a stream gauge at Gambela for a period of 82 years, from 1928 to 2009, obtained from the Ethiopian National Meteorological Agency (NMA) and the Ministry of Water, Irrigation and Electricity (MoWIE) (ELC, 2017). A single, surveyed cross section is also available (Figure 2a), located about 5 km downstream of the proposed TAMS dam at Bonga (ELC, 2017). The measured river flow at Gambela was "transferred" to the measured cross section location using the drainage area ratio method (Williams, 1986, Emerson, 2005)

$$Q_U = Q_N * (A_U/A_N)^k \tag{1}$$

where Q_U is the unknown flow at the location of the surveyed cross section (m^3/s), Q_N is the known flow at Gambela (m^3/s), A_U is the catchment area at the location of the surveyed cross section (km^2), A_N is the catchment area at Gambela (km^2) and k = 0.82 is a region-specific exponent obtained from the analysis of 13 gauging stations located in the Baro River catchment upstream and downstream of the planned TAMS dam (ELC, 2017). Based on the flow rate time series generated at the measured cross section location, the bank-full discharge was estimated using flood frequency analysis techniques, as the value corresponding to a return period of two years, obtaining a value of 1179 m^3/s.

2.4. Reconstruction of the river main channel depth

As mentioned, a single Baro River cross section was surveyed by (ELC, 2017) 5 km downstream from the proposed TAMS dam location using an echo sounder Ohmex SonarLite (Figure 2a). This cross section was taken as reference to reconstruct the river main channel cross section, not provided by remote sensing techniques, at different locations (cross sections) in five different sub-reaches of the Baro River, each characterized by an average slope obtained from the available SRTM 30m DEM (Figure 2b).

At different locations along the Baro River, the bank-full discharge was estimated using Eq. (1) and the known value of bank-full discharge at the location of the surveyed cross section. For each of the five sub-reaches, a roughness Manning's coefficient was assigned based on Manning's values estimated for uniform flow based on the only surveyed cross section, literature values based on the river characteristics (Chow, 1959), or Jarrett (1985)'s equation. The latter equation was used for bed gradient higher than 0.002, as follows

$$n = 0.39 * S_b^{0.38} * R^{-0.16} \tag{2}$$

where S_b (ft/ft) is the riverbed slope and R (ft) is the hydraulic radius of the stream.

The width of the channel was estimated at each cross section considered along the River Baro from the DEM and satellite imagery. Finally, knowing riverbed slope, channel width, Manning's coefficient, and bank-full discharge, the reconstructed bank-full depth was computed for each cross section considered along the river reach. The river channel was assumed to be rectangular, because the channel carrying capacity is of interest here, more than the bathymetry-driven flow properties gradients within a given cross section. Additional interpolated scaled cross sections were generated to increase the number of cross sections (Caviedes-Voullième et al., 2014). From the reconstructed cross sections, a new terrain GeoTIFF was created in HEC-RAS Mapper and merged with the original terrain DEM to carry out the 2D simulations.

2.5. Model calibration

The inevitable uncertainty associated to the Manning's coefficient estimation, reflecting upon the river main channel bathymetry reconstruction, was finally mitigated by adjusting the resulting bathymetry from the steps described in sections 2.2 and 2.3 in a few sub-reaches. This was done by trial and error, to calibrate the simulated maximum flooded area against the historically observed flooded area for the flood event considered (in this case, the 1990 wet season). In this sense, the bathymetry produced, specifically the bank-full depth along the Baro River, was used as a calibration parameter for the hydraulic model to match the inundation maximum extent extracted from the Landsat 5 satellite imagery dated 4th October 1990.

3. RESULTS AND DISCUSSION

Five different sub-reaches of the Baro River were identified, each characterized by an average slope obtained from the available SRTM 30m DEM, ranging from 0.0001 m/m at the downstream end, towards the Baro-Alwero confluence, to 0.003 m/m upstream, at the TAMS dam location (Figure 2b). The dotted lines in Figure 2b are the linear best fit curves, and the points represent the minimum elevation of the cross section in the main channel. Using the procedures and inputs discussed above, the reach-wise Baro river main channel roughness coefficient was estimated, obtaining values in the range 0.024-0.053. The calculated Manning's coefficients were compared with typical Manning's coefficient values (0.025-0.06) suggested in the literature (Chow, 1959) for similar streams and showed good agreement.

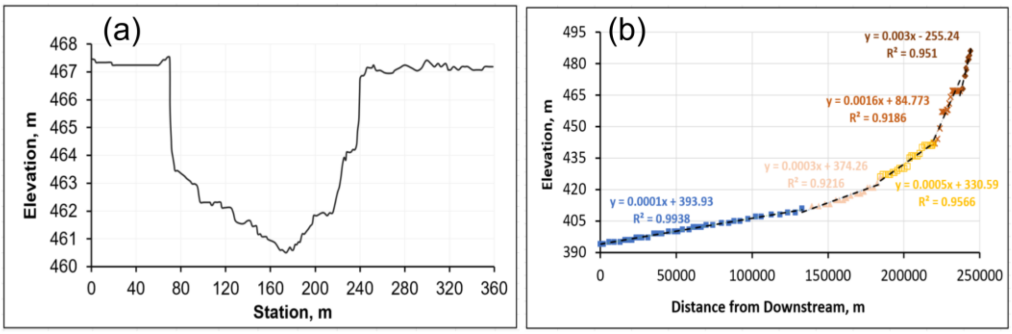

Figure 2 – (a) Surveyed cross section in the Baro River (ELC, 2017) and (b) Baro River bed profile.

As mentioned, the 1990 wet season was considered for our simulations. The 1990 wet season was the one characterised by the largest flows in the period 1928-2009. Our procedure was calibrated against satellite imagery from Landsat 5, dated 4th October 1990, from which the maximum extent of the flooded area was digitized, for comparison with the modelled maximum flooding extent.

Figure 3 shows a good agreement between modelled and observed maximum flooded areas. The figure focuses on the area downstream of Gambela In the right overbank area, the extent of flooding is relatively constrained by the floodplain topography, which is what is observed from the historical satellite imagery (Figure 3a). In the left overbank area, the absence of a drainage divides between Baro and Alwero causes water from the Baro River to flow into the Alwero system (Figure 3b). This is confirmed by the feasibility study conducted by Selkhozpromexport (1990), describing the area as "partially impounded" for large, low frequency, flood events, such as the one considered in this analysis, therefore suggesting communication between the different river systems in the lowlands downstream of Gambela.

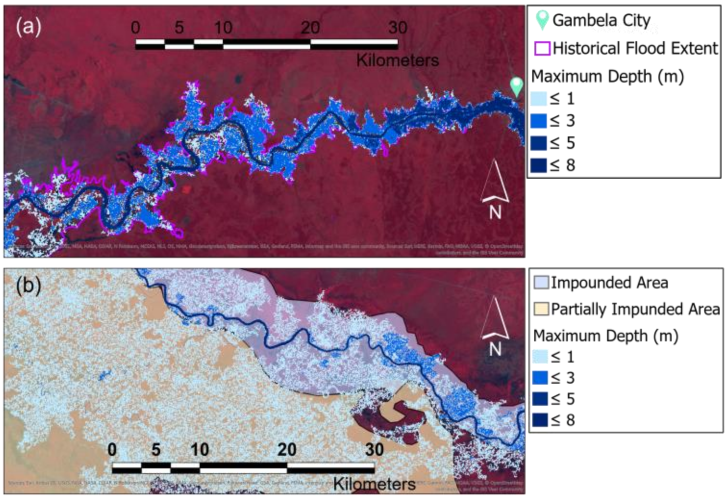

Figure 3 - Baro River 1990 flood extent in the Gambela floodplain. (a) Comparison of historically observed maximum flooded area from Landsat 5 imagery vs simulated flooded area downstream of Gambela and (b) Flooding in the left overbank downstream of Gambela, associated with Baro-Alwero water exchange.

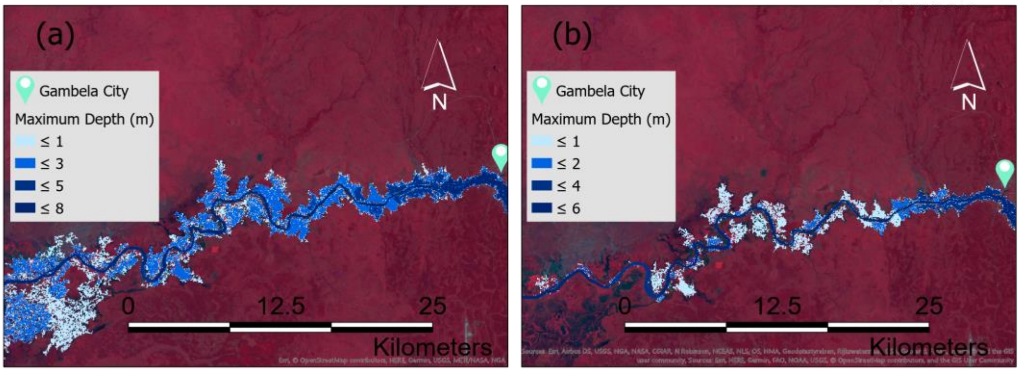

Figure 4 – Maximum flood extent comparison (a) without and (b) with the TAMS dam for the 1990 wet season.

Once a calibrated model is produced for the river in absence of dam, different TAMS dam operation scenarios (involving the opening/closing of spillways, bottom outlets, turbines) can be evaluated to model their impact on the downstream flooding (downstream dam hydrological impact). To illustrate this, the scenario with three spillways working simultaneously was considered here. The outflow hydrograph from the dam, developed using level pool routing techniques, was used as input hydrograph for the 2D model to simulate downstream flooding in presence of the dam. The peak flow rate from the dam decreased by 55% compared to the natural hydrograph in absence of dam and Figure 4 shows the resulting maximum flood extent comparison without or with dam for the reference 1990 wet season. As expected, the presence of the dam reduces the overbank flooded area, possibly having a negative ecological impact on wetlands along the Baro River; it also stops the water transfer from the Baro to the Alwero river system, at least for the protocol of dam operation considered here.

4. CONCLUSIONS

The method presented in this paper to reconstruct river main channel bathymetry uses limited data and considers bank-full depth as a calibration parameter for a hydraulic model simulating river flooding. The method was applied to the modelling of the seasonal flooding of the Baro River in the Gambela floodplain in Ethiopia, in lowlands characterised by multiple river systems and complex flow patterns including natural river diversions. The approach was shown to be able to capture the conveyance of the main channel, which is key to reproduce historically observed flooding extent. The agreement between simulated and observed maximum inundation area is satisfactory especially in the area immediately downstream of Gambela (Figure 3a); further downstream the agreement remains visually good, and deviations are explained by observing that the historical inundation extent was digitized from satellite imagery as a single polygon (in reality high ground areas exist, therefore not all areas inside the polygon will be flooded) and that some flooding downstream of Gambela is also due to sheet flow from the right side of the river (not captured by the model).

The hydraulic model produced in this study will be used to quantify and map the hydrological impact of the TAMS dam construction and operation and the consequent impact on the downstream wetlands and recession agriculture and fishing activities, all relying on the seasonal overbank flooding of the Baro River. A preliminary simulation of the impact of the dam on the downstream flooding extent has shown a significant reduction of the maximum inundation area (Figure 4b), with most of the flow contained within the main channel and generally lower main channel flow depths (30% less), compared with the scenario without dam.

5. ACKNOWLEDGEMENTS

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