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# An Improved Flood Forecasting Model of the Blue Nile River in Sudan

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**Abstract**: Reliable flood predictions with a reasonable lead time in the Blue Nile River in Sudan are vitally important to avoid catastrophic damages due to flooding of this river and the main River Nile. A HEC-RAS model was initially applied to the Blue Nile by representing the river as a single reach. The resulting original model was subsequently improved by including the two tributaries of the river, Rahad and Dindir, and also the two existing reservoirs, Rosaries and Sinnar, to the model. The original and the improved models were calibrated using 1988 flood data for the period from June to September inclusively. Then they were validated using flood data of 2009 and 2010 for the same period. The results clearly show the remarkable performance of the improved HEC-RAS model compared to the original HEC-RAS model. This also suggests that the complex behaviour of the Blue Nile River during floods cannot be only modelled by a simple model such as the original HEC-RAS model but it requires a more sophisticated model such as the improved HEC-RAS model. The improved HEC-RAS model can be used by the authorities to issue flood warnings to the affected areas before ample time to allow for proper preparedness.

**Keywords:** *Flood; Flow Routing; Hydrograph; HEC-RAS; Blue Nile; River Nile*

## 1. INTRODUCTION

The frequent occurrence of catastrophic flood events represents a major challenge for the River Nile riparian countries particularly those in the eastern region which include Ethiopia, Sudan, and Egypt where most of the floods occur. Many damages due to these floods could have been averted if accurate river flood forecasting system was in place. Such system is expected to effectively contribute to the existing flood forecasting warning response system and the planned flood preparedness programs that both could reduce any associated damages and loss of life. In Sudan major floods events mainly occur along the main River Nile and its tributary the Blue Nile River. The causes of floods in Sudan can be attributed to high water level, or to torrential rain, or to a combination of both. However in most cases the rises of water level particularly in the Blue Nile River can lead to major flooding in this river and also in the main River Nile. Therefore a proper flood forecasting model for the Blue Nile can be a viable tool to mitigate the River Nile flooding in Sudan.

Efforts to produce a robust flood forecasting system for the Blue Nile River have been ongoing for a long time and a number of studies have been carried out for this purpose. In most of the studies the data driven models or the black box models were used. The early attempt in developing Flood Early Warning System (FEWS) has started after the severe flood that occurred during August-September 1988 in Khartoum plains and the flood plains of Atbara River and the Main Nile [1]. The developed FEWS consists of three main components. Two of these components are used to process the rainfall and water level data, while the third component is used to route the water levels along the river channel. The weaknesses in the existing models in the FEWS, as reported by Shamseldin *et al*. [2], has motivated these authors to apply the SMAR model (O'Connell *et al*., [3]) in order to investigate the possibility of using this model as alternative or in parallel to the FEWS.

Mekawi [4] applied the Muskingum flood routing method to Blue Nile River in order to predict the flow hydrograph at Khartoum from knowing the flow hydrograph at Eddeim. In her study the Blue Nile has been modelled as a cascade of three sub-reaches. The results generally indicated that the Muskingum method produced good predictions for the flow hydrograph in the first reach while predictions of the flow hydrographs in the second and third reaches were extremely degraded. Other models including SLM (Nash and Foley, [5]), LPM (Nash and Barsi, [6]), and USGS Geospatial Stream Flow Model (Artan *et al*, [7]) have also been attempted at different studies for use in flood forecasting of the Blue Nile River.

In this study a hydraulic routing model for the Blue Nile River System from Eddeim to Khartoum was developed. The model was configured using the United States Corp of Engineer River Analysis System (HEC-RAS). The model predicts both the Water levels and flows at different desired locations along the Blue Nile River System.

## MATERIALS AND METHODS

### 2.1 Original Model

Firstly the HEC-RAS model of the Blue Nile River has been configured as a single reach from Eddeim to Khartoum. In this model the contributions of the river tributaries and the effects of the existing dams in the river were ignored. Regarding the boundary conditions the flow hydrograph at Eddeim was used as upper boundary condition and a normal depth boundary condition was adopted at Khartoum. No internal observed flow points were used. The performance of the resulting model was assessed based on the ability of this model in predicting the 2009 flood.

### 2.2 Improved Model

An improved version of the model was then produced where the two tributaries and the two dams were included in the model. Roseires dam was added as an inline structure with embankment and two gate groups, one for spillway and the other for deep sluices. To include the effect of the reservoir impoundment, storage area fully controlled by storage elevation relationship was added and connected to the end of the reach. As there are no cross sections along the reach from the border to the Roseires reservoir, the inflow to the reservoir was modeled by lateral inflow boundary condition and no flow modification is applied to Eddeim flow when entering the reservoir. Sinnar dam was also added as an inline structure with impoundment and three gate groups, one for spillways, one for deep sluices and one for Gezira and Managil canals. The effect of Sinnar reservoir impoundment was modeled using storage area fully controlled by storage elevation relationship connected to the downstream end of the Rosaries-Sinnar reach and the upstream end of Sinnar-Khartoum reach. This arrangement creates three reaches namely Eddeim-Rosaries reach substituted for in this model by lateral inflow hydrograph, Rosaries-Sinnar reach and Sinnar-Khartoum reach. The effects of Dinder and Rahad tributaries are accounted for by later inflow hydrographs at their confluences with the Blue Nile and no modification to the hydrographs is made.

In the improved model the upper boundary condition that specifies the inflow to the system was set as lateral inflow hydrograph, the downstream boundary condition at Khartoum is kept as normal depth. The effects of Rahad and Dindir were accounted for by lateral inflows at their respective confluences with the Blue Nile River. In addition, nine internal boundary conditions were set. These are observed stage and/or flow hydrographs at upstream and downstream of the two reservoirs. Namely Rosaries villages and wad Alaies in the Rosaries-Sinnar reach, wad Medani, Kamlin and Soba in the Sinnar-Khartoum reach.

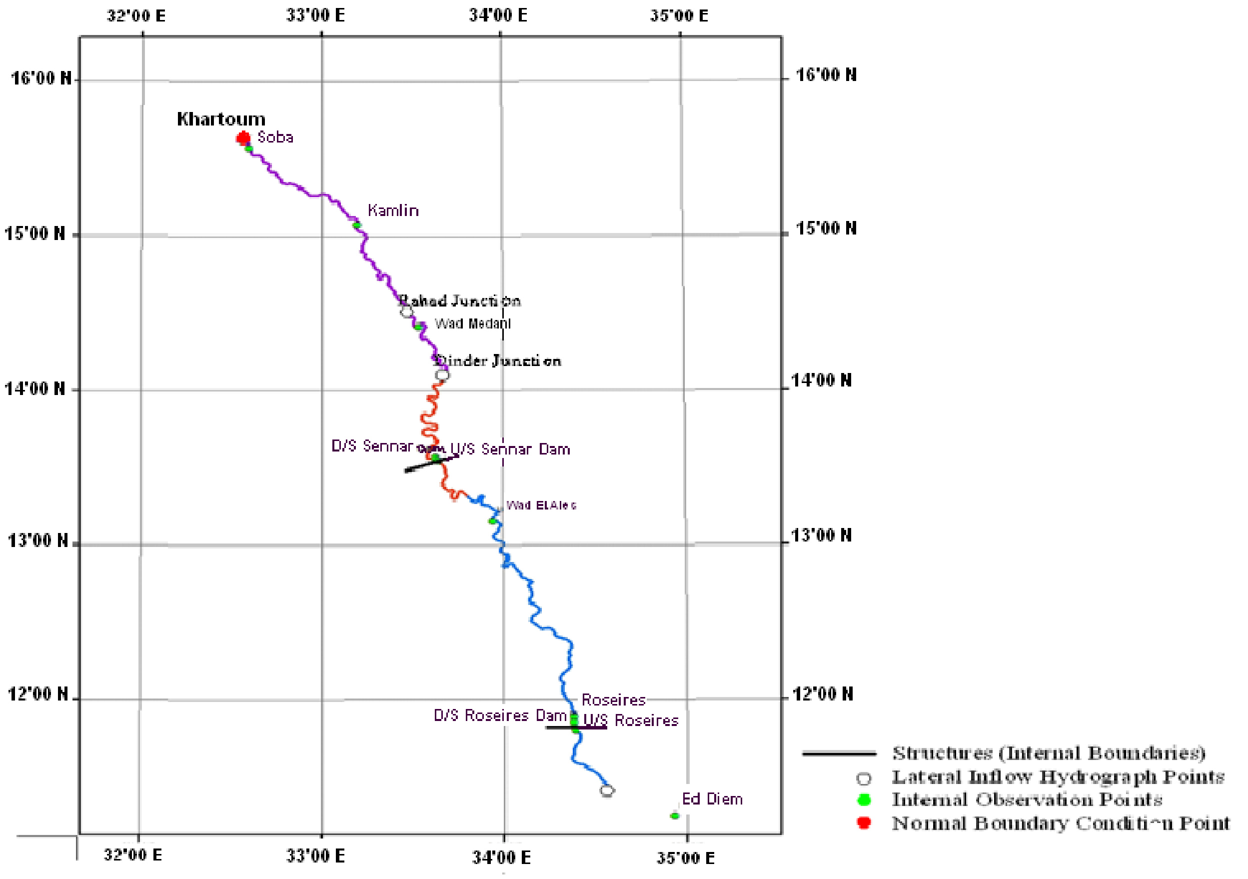


**Fig. 1.** Model schematics

Five initial conditions are required, one for each upstream end of a reach and one for each of the two storage areas. The initial conditions at the upstream ends of the reaches were specified as initial flow in $m^3/s$ and those at the storage areas were specified as initial water level in meters above mean sea level (amsl). Fig. 1 is a model schematic showing the boundary conditions, their types, river stations and the reach in which they reside.

### 2.3 Evaluation of Model Performance

There are various measures to express the accuracy of model forecasts, which are generally linked with the objective function used for optimizing or estimating the model parameters. A commonly used measure is the Nash and Sutcliff [8] efficiency criteria $R^2$ given by the Eq:

$$R^2 = \frac{F_0 - F}{F_0} \qquad (1)$$

where $F$ is the sum of squares of differences between the observed and the computed water levels and $F_0$ is the sum of the squares of the differences of the observed levels from their mean value over the calibration period.

## 2. RESULTS AND DISCUSSION

Both the original and the improved HEC-RAS model of the Blue Nile River have been calibrated using 1988 data for the period 1st May to 31st October. The 1988 flood was the highest recorded flood in Sudan and hence can logically be used as a base line to calibrate any flood forecasting model. Model validation was also undertaken using 2003 and 2010 data for the same period. Then the performance of the two models during calibration and validation has been assessed based on the two model results at different hydrometric stations along the Blue Nile River. Here in this paper results for the last downstream station in the river at Khartoum are only presented and also because Khartoum is the capital city of Sudan and the Blue Nile is passing by most of its populated towns. Therefore predication of floods at a longer lead time in the Blue Nile River at Khartoum station is very important for the authority to allow for efficient preparation to mitigate any

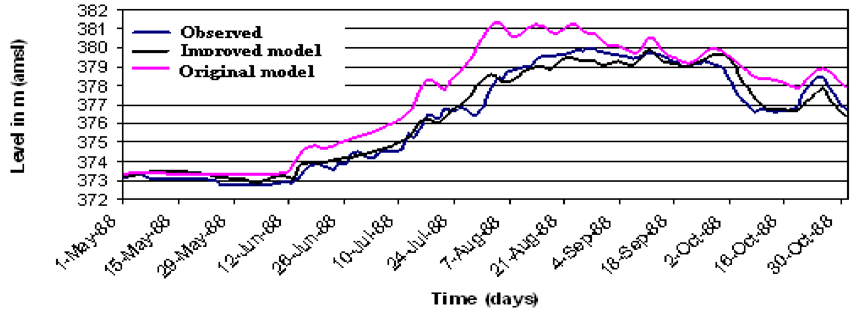


**Fig. 2**. HEC-RAS forecast results during calibration in 1988 for Khartoum

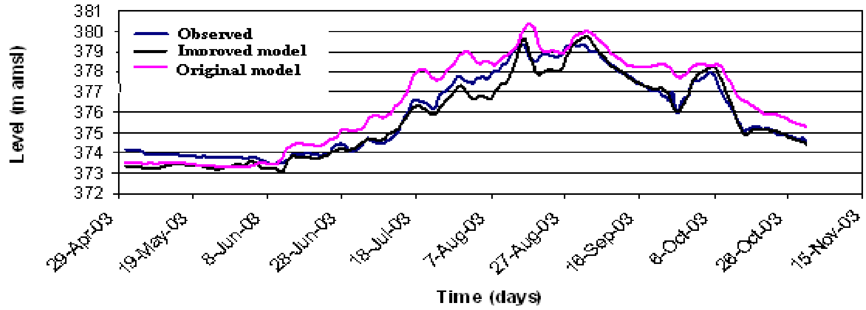


**Fig. 3.** HEC-RAS forecast results during validation in 2003 for Khartoum

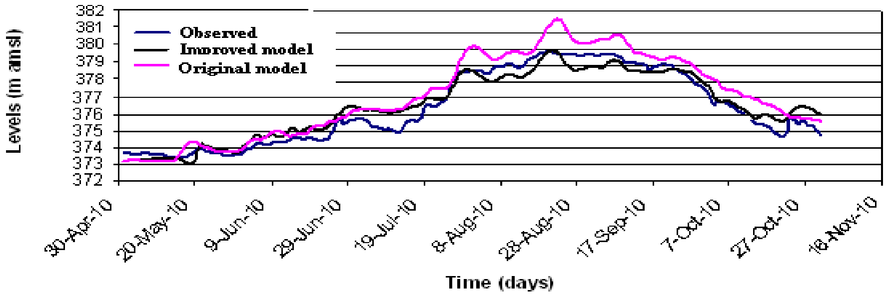


**Fig. 4.** HEC-RAS forecast results during validation in 2010 for Khartoum

**Table 1.** Nash and Sutcliff efficiency Measure

| Calibration or Validation period | Nash and Sutcliff efficiency $R^2$ (%) | |
|---|---|---|
| | Original model | Improved Model |
| Calibration in 1988 for Khartoum | 85 | 95 |
| Validation in 2003 for Khartoum | 89 | 97 |
| Validation in 2010 for Khartoum | 88 | 98 |

flood. Fig. 2 shows a comparison between the actual water level and the predicted values by the two models during calibration for the Khartoum Station. The same comparison is also shown for validation period in 2003 in Fig. 3 and for validation period in 2010 in Fig. 4.

Fig. 2 clearly shows that the original HEC-RAS model was considerably overestimating the actual water levels during calibration. Whereas the improved HEC-RAS model performed better and was able to produce reasonable prediction for the actual water levels. The good performance of the improved HEC-RAS model was also evident on the results of the model during the two validation periods as shown in Figs 3 and 4. Table 1 below gives the Nash and Sutcliff efficiency measure $R^2$ for the above cases. The results again show the superior performance of the improved HEC-RAS model over the original model

## 3. CONCLUSIONS

The outstanding results obtained from the improved HEC-RAS model clearly indicates that the complexity of flow routing in the Blue Nile River during floods cannot be represented by a simple model such as the original HEC-RAS model. The addition of the two tributaries of the river, Rahad and Dindir, has certainly contributed to obtain good estimations for the water balance in the river. Moreover the representation of the two existing reservoirs, Rosaries and Sinnar, has also resulted in a reasonable accounting for the storage in the river reach.

The results of the improved HEC-RAS model can be much better if actual river cross-sections at the missing locations along the river are used in the model. Moreover using the actual storage elevation relationship for the two reservoirs can also refine the results further.

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