



Calibration and Verification of the Hydraulic Model for Blue Nile River from Roseires Dam to Khartoum City

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ABSTRACT

This research represents a practical attempt applied to calibrate and verify a hydraulic model for the Blue Nile River. The calibration procedures are performed using the observed data for a previous period and comparing them with the calibration results while verification requirements are achieved with the application of the observed data for another future period and comparing them with the verification results. The study objective covered a relationship of the river terrain with the distance between the assumed points of the dam failures along the river length. The computed model values and the observed data should conform to the theoretical analysis and the overall verification performance of the model by comparing it with another set of data. The model was calibrated using data from gauging stations (Khartoum, Wad Medani, downstream Sennar, and downstream Roseires) during the period from the 1st of May to 31 of October 1988 and the verification was done using the data of the same gauging stations for years 2003 and 2010 for the same period. The required available data from these stations were collected, processed and used in the model calibration. The geometry input files for the HEC-RAS models were created using a combination of ArcGIS and HEC-GeoRAS. The results revealed high correlation ($R^2 > 0.9$) between the observed and calibrated water levels in all gauging stations during 1988 and also high correlation between the observed and verification water levels was obtained in years 2003 and 2010. Verification results with the equation and degree of correlation can be used to predict future data of any expected data for the same stations.

Keywords: calibration, verification, Blue Nile, Roseires dam, hydraulic model.

المعايرة والتحقق للنموذج الهيدروليكي لنهر النيل الأزرق من سد الروصيرص إلى مدينة الخرطوم

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الخلاصة

يمثل هذا البحث محاولة تطبيقية للمعايرة والتحقق من النموذج الهيدروليكي لنهر النيل الأزرق حيث تمت إجراءات المعايرة باستخدام البيانات المرصودة لفترة سابقة ومقارنتها مع نتائج المعايرة بينما يتم التحقق مع مقارنة البيانات المرصودة لفترة أخرى في المستقبل، ومقارنتها مع نتائج التحقق. يغطي هدف الدراسة وجود علاقة مع تضاريس النهر والمسافة بين النقاط المفترضة من فشل السد على طول النهر. يجب ان تتوافق القيم المحسوبة من النموذج والبيانات المرصودة مع التحليل النظري وأداء

التحقق الشامل للنموذج من خلال مقارنتها مع مجموعة أخرى من البيانات. وتمت معايرة النموذج باستخدام البيانات من محطات القياس (الخرطوم، ود المدني، موخر سد سنار، موخر سد الروصيرص) خلال الفترة من 1 ايار الى 31 تشرين الاول 1988 اما التحقق فقد تم من خلال استخدام بيانات لنفس محطات القياس للسنوات 2003 و 2010 لنفس الفترة. البيانات المتاحة المطلوبة لكل من هذه المحطات تم جمعها ومعالجتها واستخدامها في معايرة النموذج. تم إنشاء ملفات الإدخال للنموذج HEC-RAS باستخدام مزيج من نظام ArcGIS و HEC-GeoRAS حيث أظهرت النتائج ارتباط عالية ($R^2 > 0.9$) بين مستويات المياه الحقلية والمعايرة في جميع محطات القياس خلال عام 1988 وكذلك ارتباط وثيق بين مستويات المياه الحقلية والمتحققة لنفس المحطات وانفس الفترة لعامي 2003 و 2010 وبذلك يمكن استخدام النموذج للتنبؤ بالبيانات المستقبلية لاي معطيات متوقعة لنفس محطات القياس.

الكلمات الرئيسية: المعايرة ، التحقق ، النيل الأزرق، سد الروصيرص، النموذج الهيدروليكي.

1. INTRODUCTION

The Calibration of a hydraulic model aims to reflect the field measurements of water bodies that are to be used in the prediction of the system performance and to evaluate alternative projects. While the verification is to ensure that the adjustments done during calibration are appropriate and the calibrated model will give reliable results ,**Victore, 1995**.

For low flow rates, Manning's roughness coefficient and the associated data are used in model calibration and validation processes. The achieved calibrated coefficients are then used with the high flow rates ,**Federal Highway Administration, 1984**. Friction and turbulent diffusion/dispersion coefficients are also important parameters in most hydraulic models that affect water surface elevation calculations, velocity and salinity distribution ,**Chao and Guofu, 2000**. **Ming-Hsi Hsu, et al., 1999** had used a vertical two-dimensional model on a branched estuarine river system to study calibration procedures and verification requirements. The barotropic flow simulation model was used to calibrate and verify the friction coefficient while a salinity distribution model was used to calibrate the turbulent diffusion and dispersion coefficients. They found a qualitatively agreement of the computed and measured residual currents with theoretical analysis. **Peter, 2009** found that storm water models application have important considerations in calibration and verification processes. An infinite number of combinations and permutations of parameters that directly affect the behavior of the model appeared. Hence the results may be complex and daunting when used to evaluate the effectiveness of altering parameters.

May, et al., 2000 indicated the validation of the Hydrological Engineering centers River Analysis System (HEC-RAS). The water surface profile of the model was compared with two study models of straight uniform reaches with two different flow rates. **Crampton, 2007** studied the dam's failure result in potential flood risks which are tougher and can behave differently from the events of natural floods by using the unsteady HEC-RAS models for dam break analysis. Careful modifications were required to converse from a steady state flood study model to a dynamic dam break model with consideration of the differences in flood routing methodologies between the two model states. Flood inundation maps are created from models which include peak elevation, flood wave arrival time and flood wave time to the peak for both sunny day and storm in progress failures. **Al-Kazwini, et al., 2009** studied AlHusa'chi River which is one of three main branches of Al Ka'hla River in Moissan Governorate, Iraq with a length of 25 km. They ran a steady one dimensional hydraulic model at a location 1.5 km upstream its tail to simulate the flow in the river using the HEC-RAS software. The field measurements were used in the calibration and verification processes to obtain the maximum allowable flow rates and water surface elevation in the river. **Khassaf and Ameera,**



2015 used HEC-RAS to develop the hydraulic model for Al- Kahlaa river system, south of Iraq using the observed weekly stage and flow data .The results showed that a good agreement is achieved between the model predicted and the observed data. The model demonstrated that in the case of high flow discharges, it is found that cross sections flooded are inadequate for such flows and the flows remained within the cross section extents during the drought season.

UNESCO-CWR, 2011 performed a field survey to supplement the available data and verify the accuracy of existing river cross-sections. The United States Corp of Engineers River Analysis System Model (HEC-RAS) was utilized to develop the hydraulic routing model for the Blue Nile River to reveal the shape of Roseires dam failure which covered the shape of the failure and its relationship with the dam height. It also included the capacity of the canal at the end of the dam. The objective of this study to evaluate the calibration and verification of the unsteady flow model through available field data for four gauging stations (Khartoum, Wad Medani, D/S Sennar, D/S Roseires) of Blue Nile River.

2. MATERIAL AND METHODS

2.1 Study Area Description

River Nile consists of three main tributaries, Atbara, White Nile and Blue Nile Rivers. The Blue Nile River system in this study covers about 76% of the total irrigated agriculture of the three Nile tributaries. **Fig.1** illustrates Blue Nile River system schematically of the study area ,**Ministry of Irrigation and Water Resources Sudan's, MOIWRs, 2014**. Blue Nile River has a major characteristic of a remarkable seasonality flow. More than 80% of the Blue Nile River flow is during the period from June to October, which is the flood period .Two Dams were built across the Blue Nile River, Sennar in 1925 and Roseires in 1966 ,**Ministry Of Irrigation Sudan, 1968**. The two dams control the flow, that irrigate about 1.134 million hectares of the Sudan agriculture area, as well as supplying more than 40% of the total hydropower generation in Sudan. The Roseires dam, which spans the Blue Nile River, is at 630 km upstream of Khartoum, it is 1000 m long and 68 m high concrete dam with the crest at 482.2 m amsl (above mean sea level). The dam was completed in 1966 with an initial capacity of 3.024 km³ at level 480 m amsl to be used for irrigation water as the first priority, and hydropower generation as the second priority. The dam contains five deep sluices and a gated spillway, consisting of seven units, with a maximum discharge capacity of 16500 m³/s at 480 m amsl. The hydro-electrical generation power approaches 212 MW. Sennar Dam is the second dam on the Blue Nile River near Sennar Town, as shown in **Fig. 2**. It was built by the British engineer, (desert explorer and adventurer), Stephen "Roy" Sherlock, under the direction of Weed man Pearson. The dam is 3025 meters long, with a maximum height of 40 meters. It provides water for crop irrigation in the Gezira scheme. ,**UNESCO-CWR, 2011 and ENTRO 2013**.

2.2 Requirements and Data Collection

Analysis of the system requires upper boundary conditions that specifies the inflow to the system which is considered as lateral inflow hydrograph. Eddiem gauging station, 170 km upstream Roseires dam observes the flow which is used as the upper boundary condition. The downstream boundary condition at Khartoum was taken as the downstream end of the study area which was considered the normal depth. The effects of Rahad and Dindir Rivers, the tributaries of the Blue Nile River were accounted as lateral inflows at their respective confluences with the Blue Nile River. In addition nine internal boundary conditions were observed stages, flow hydrographs at upstream, flow hydrographs at downstream of the two reservoirs, Roseires village, Wad Alaies village in the Roseires-Sennar reach, Wad Medani, Kamlin, and Soba in Sennar-Khartoum reach. **Fig. 3** shows location and type of each flow gauging station for



modeling purpose. The required available data for each of these stations were collected by the Ministry of water resources and electricity. These data were processed and used in the model calibration, **Dam Implementation Unit, 2012, Sudan.**

3. HEC-RAS MODEL APPLICATION METHOD

The geometry input files for the HEC-RAS models were created using a combination of ArcGIS and HEC-GeoRAS. The Blue Nile River centerline, bank lines, flow paths, and cross sections were digitized in HEC-GeoRAS. The Blue Nile River centerline was digitized to simulate the proposed field channel centerline as indicated by the field survey. This was necessarily supplemented by reference to satellite images. The bank lines represented the point where the river was considered as a flood plain and the Blue Nile River was accessing its flood plain for active flow. In addition, these lines determine the change in Manning's roughness coefficients (n) in the hydraulic model and the possibility to be adjusted in the model, **Federal Highway Administration, 1984.** The channel bank lines were also digitized using the field survey as a reference. Three flow path lines were setup in HEC-GeoRAS to represent the direction of flow within the channel centerline and banks in the left and right flood plains. These lines also determine the cross sections limits of the stations together with the right and left overbank flow between these cross sections. Finally, the cross sections were oriented perpendicular to the flow and located to represent areas in the reach where physical changes occur, **HEC-RAS, 2005 and USGS, 2004.**

The steps followed in configuring the HEC-RAS Model for the Blue Nile River could be summarized as follows, **HEC-RAS, 2005.**

Step 1: Validate geometric data and time series to be used in the model

- a- Pre-process time series data using HEC-DSS (Data Storage System) to check for missing data, unit conversion and create an input time series file in DSS format.
- b- Pre-process geometric data with the aid of ARC-GIS and Excel, to establish Left Over Bank (LOB), Right Over Bank (ROB) locations for each section, and decide on ineffective areas to be included as part of each section. This also includes decision on roughness coefficients, contraction and expansion coefficients. The purpose of this is to examine the coverage of the field surveyed cross-section and establish the need for modeling meandering effect and bend for certain reaches in the HEC-RAS model.

Step 2: Configure the River basin schematically and input geometric data for the Blue Nile River:

- a- Using the geometric data editor in HEC-RAS establish the connectivity and draw the schematic river basin for the Blue Nile River.
- b- Enter the reach length for the LOB, ROB for the channel.
- c- Enter Station - Elevation data for each cross section.
- d- Establish the frictional loss coefficient, expansion and contraction loss coefficient for each cross-section.

Step 3: Determine the initial condition for the model by running HEC-RAS under steady state version.

Step 4: Establish upstream and downstream boundary conditions. The upstream boundary condition is chosen as the daily time series discharge hydrograph at Eddiem station and the downstream boundary condition is taken as the rating curve for Khartoum Station.

Step 5: Perform Unsteady State Simulation.

- a- Decide on the time step used for the simulation (1 hr)
- b- Decide on the time step used in producing the output results (1 Day).



4. RESULTS AND DISCUSSION

Hydraulic models are used to estimate hydraulic characteristics of the flow in the rivers and channels that would result from passing the discharge through them. Running a steady state model may take seconds, while unsteady flow simulations can take many hours. The results of a model are validated by calibrating one or more known events. Observed points can be entered into the model as inputs for direct comparison with prototype results. The scaled model output should match the prototype output observed points. To arrive at a fully calibrated model the input that has the most uncertainty must be adjusted. Once the digitization process is complete, the HEC-GeoRAS data are imported into HEC-RAS. The transition between the pre-processor and the hydraulic model should be smoothed. The results identical to that created in the pre-processor were visualized in the model presentation, as shown in **Fig. 4**.

One of the main challenges of hydraulic modeling in areas with broad flood plains adjacent to rivers are to represent accurately the conveyance of water and the extent of inundation through hydraulic connections with the river channel. In many cases, there is a direct and continuous connection between the river and the flood plains. In other cases, there is an interruption in the water surface. For the flow to access a floodplain area beyond a high point in the topography, it must be accessible to the main channel or another area of the floodplain from either an upstream or a downstream cross section. This can best be determined through an iterative process of simulating the flow, generating an inundation map, and then adjusting hydraulic constraints in the model to limit or extend flow to areas that can be observed as hydraulically connected. **Fig. 5** and **Fig. 6**, show the relationship between cross sections and inundated areas for connected and disconnected flow areas. They also demonstrate how inundation mapping can provide guidance on placement of hydraulic model constraints. The hydraulic model builders use judgment to define three conditions. The first case is when the levees flow does not enter the flood plain until it exceeds the height of the levee. The second case is when the flow is not simulated. The third case when there are ineffective flow areas that may be inundated but do not contribute to conveyance in the river system, **HEC-RAS, 2005 and HEC, 1995**.

The model was calibrated using data of each stations (Khartoum, Wad Medani, downstream D/S Sennar, D/S Roseires) during the period from the 1st of May to 31st of October 1988. The results of the model are shown in a comparative manner in **Figs. 7a to 10 b**. The results revealed high correlation ($R^2 > 0.9$) between the observed and calibrated water levels in all gauging stations. The verification was done using the data of the same gauging stations in years 2003 and 2010 for the same period. The results of the model are shown in a comparative manner in **Figs. 11a to 14b**. Also high correlation ($R^2 > 0.9$) between the observed and verification water levels was achieved. Verification model performed by comparing the results derived and observed data to predict the equation and degree of correlation, also can be used for future prediction. The study revealed the relationship with the terrain of the river and the distance between the gauging stations of the dam failure on the rivers length. Also it was clearly observed in the downstream direction where terrain became higher there was no effect on both bank sides.

6. CONCLUSION

The HEC-RAS models were used to evaluate the calibration and verification of the unsteady flow model through available field data for four gauging stations (Khartoum, Wad Medani, D/S Sennar, D/S Roseires) of Blue Nile River. The results of the model showed:



1. The study revealed the relationship with the terrain of the river and the distance between the gauging stations of the dam failure on the rivers length. Also it was clearly observed in the downstream direction where terrain became higher there was no effect on both bank sides.
2. High correlation ($R^2 > 0.9$) between the observed and calibrated water levels in all gauging stations during 1988.
3. High correlation ($R^2 > 0.9$) between the observed and verification water levels for years 2003 and 2010.
4. Verification results with the equation and degree of correlation can be used to predict future data for same stations.

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Figure 1. Blue Nile River system schematic in the study area.



Figure 2. Location of the Sennar dam within Blue Nile River.

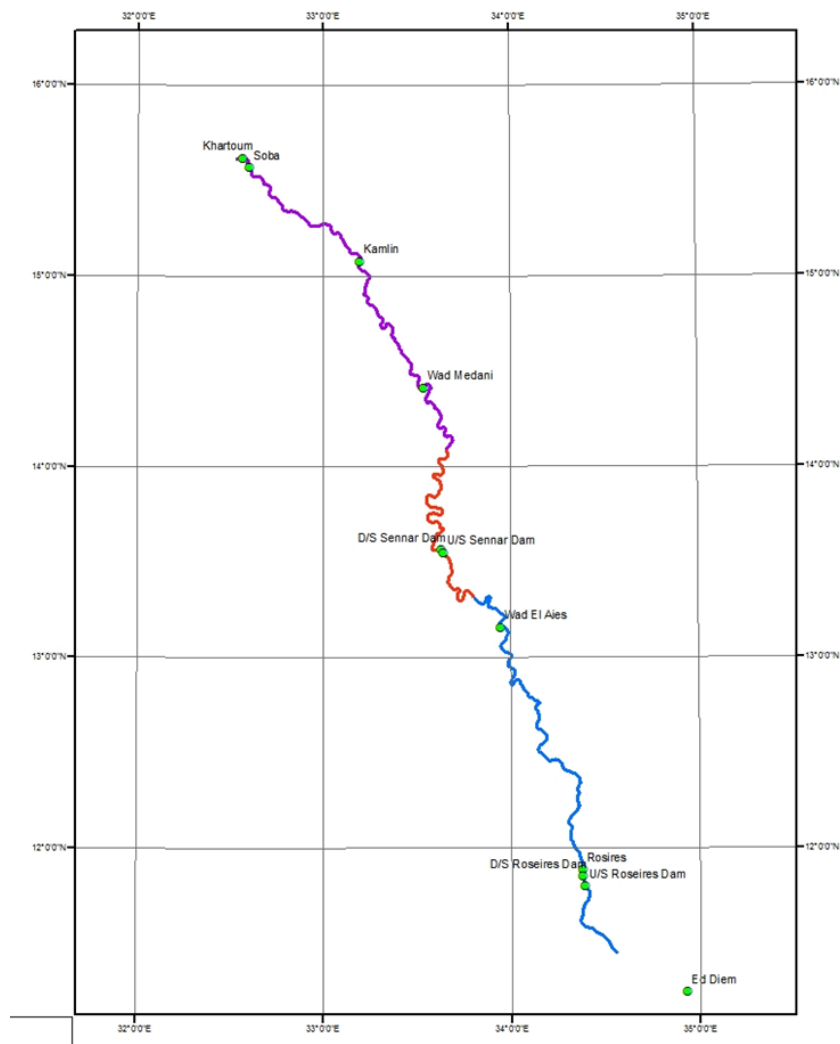


Figure 3. Location and type of each flow gauging station for modeling purpose.

- Structures (Internal Boundaries)
- Lateral Inflow Hydrograph Points
- Internal Observation Points
- Normal Boundary Condition Point

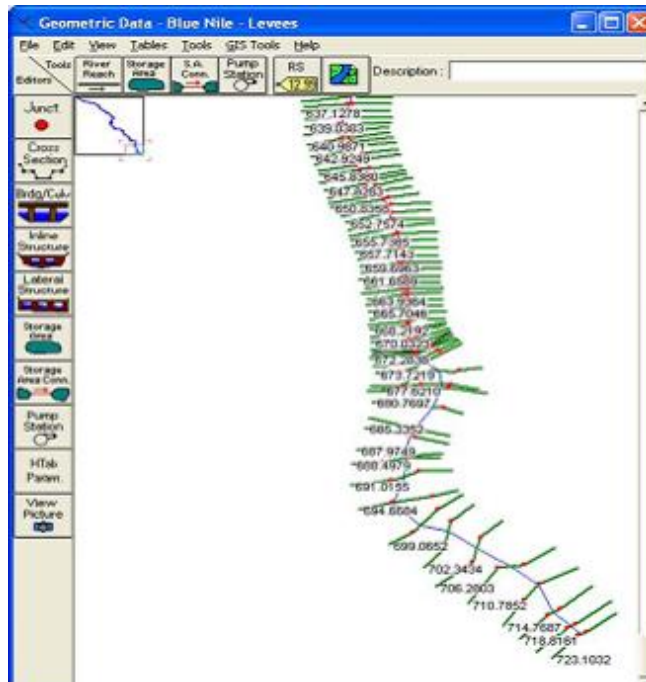


Figure 4. Illustration of HEC-RAS model development.

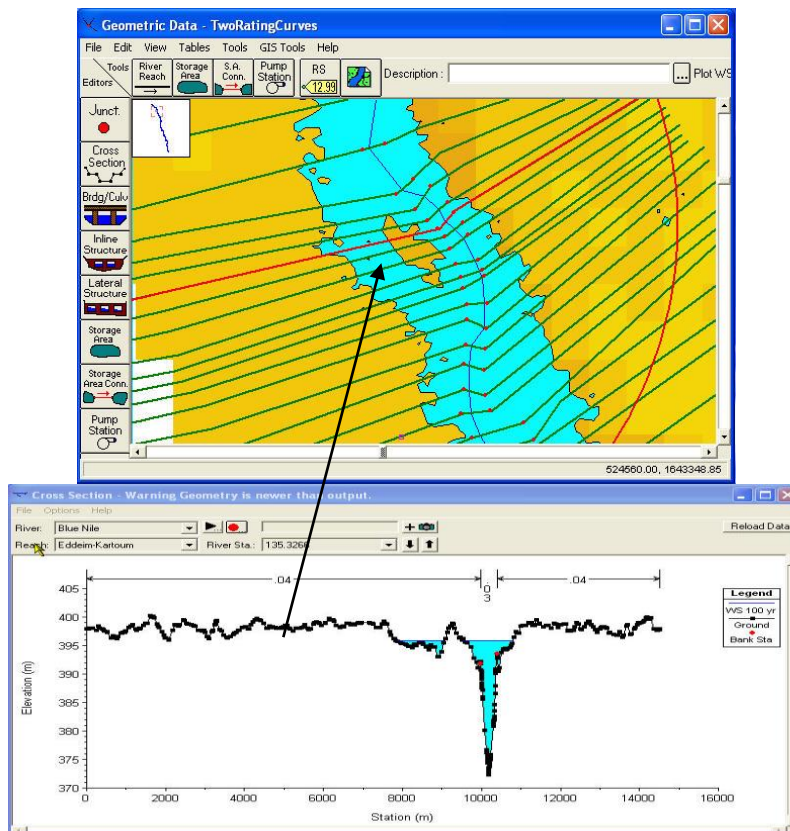


Figure 5. Example of hydraulic connected area.

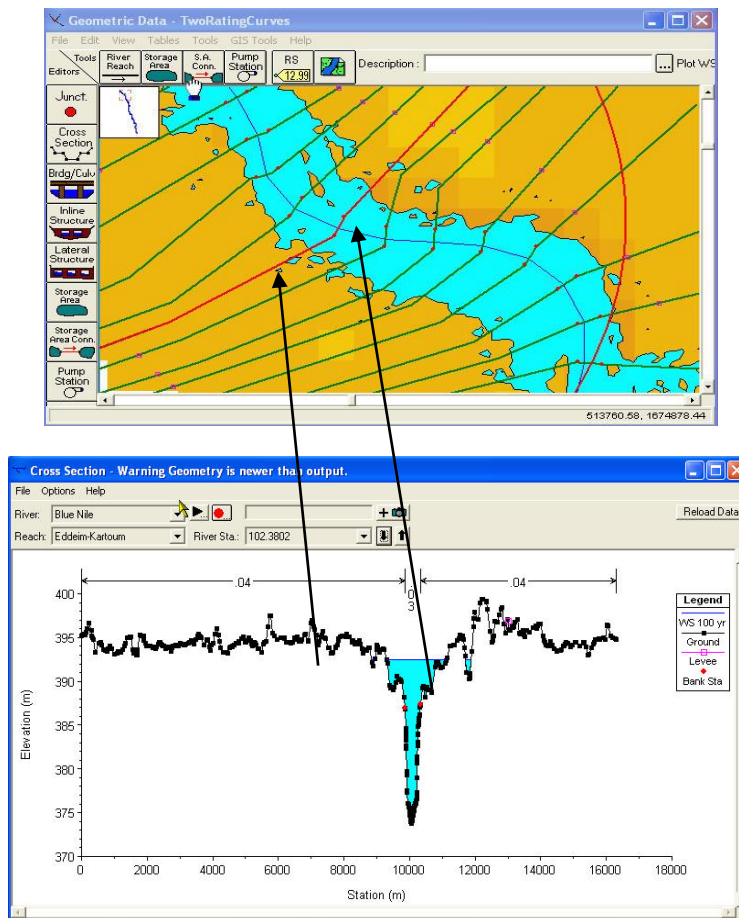


Figure 6. Example of a lack of hydraulic disconnected area.

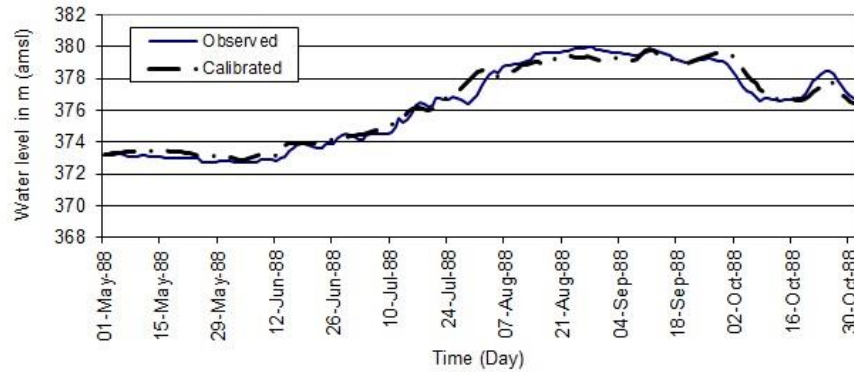


Figure 7a. HEC-RAS forecast calibration for Khartoum, 1988.

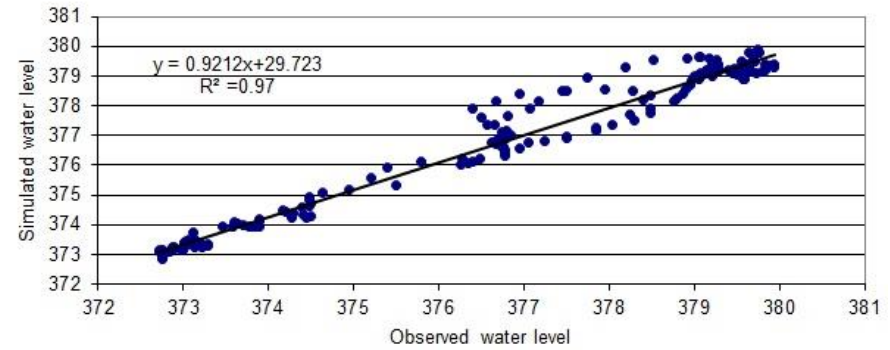


Figure 7b. HEC-RAS calibration-observed flows for Khartoum, 1988.

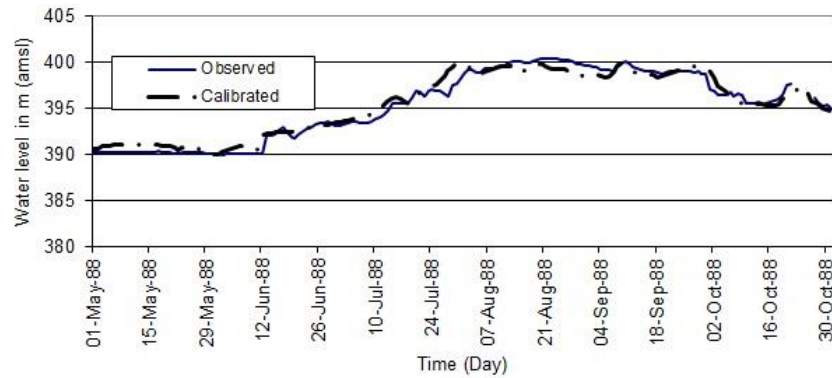


Figure 8a. HEC-RAS forecast calibration for Wad Medani, 1988.

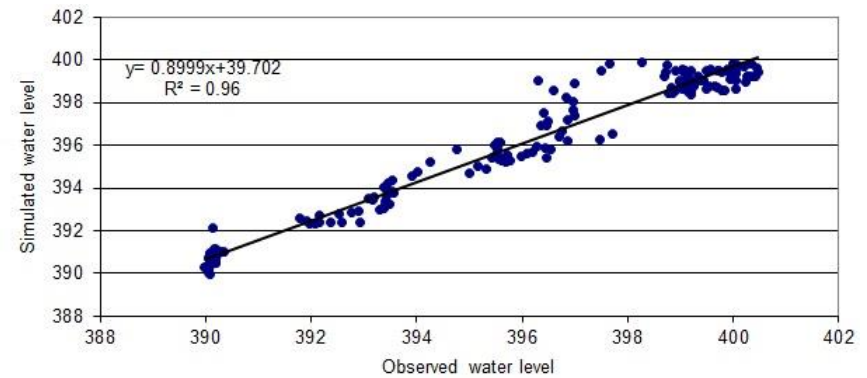


Figure 8b. HEC-RAS calibration-observed flows for Wad Medani, 1988.

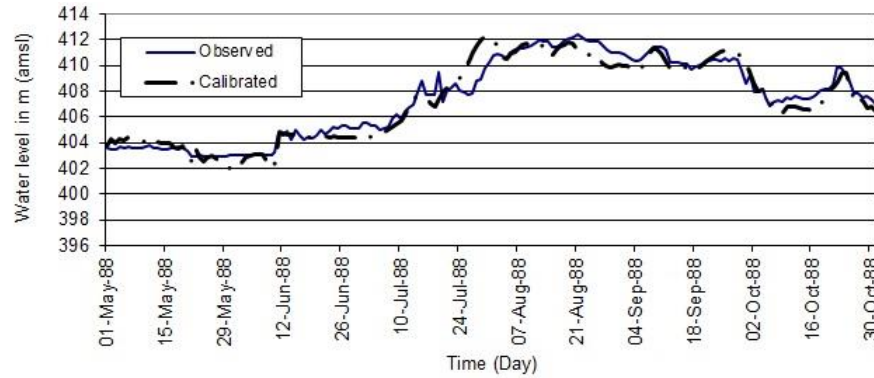


Figure 9a. HEC-RAS forecast calibration for D/S Sennar, 1988.

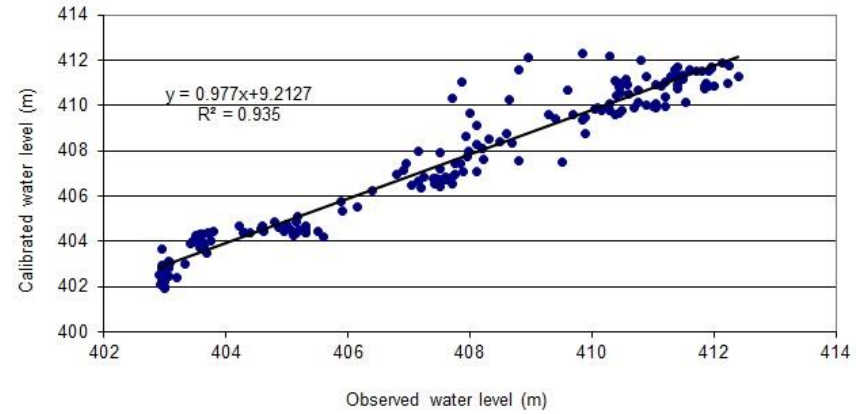


Figure 9b. HEC-RAS calibration-observed flows for D/S Sennar, 1988.

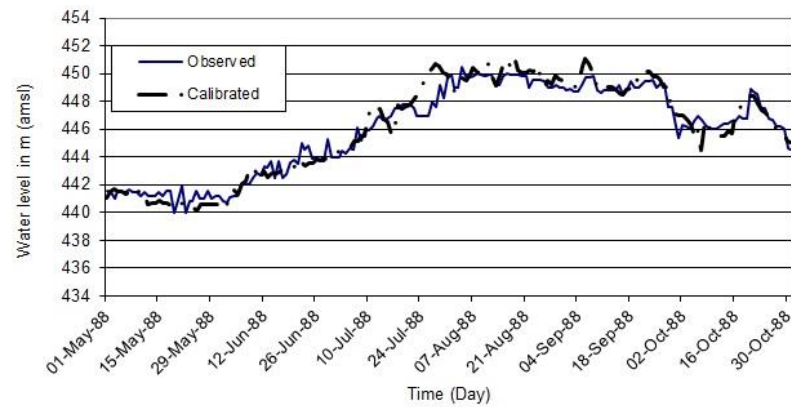


Figure 10a. HEC-RAS forecast calibration for D/S Roseires, 1988.

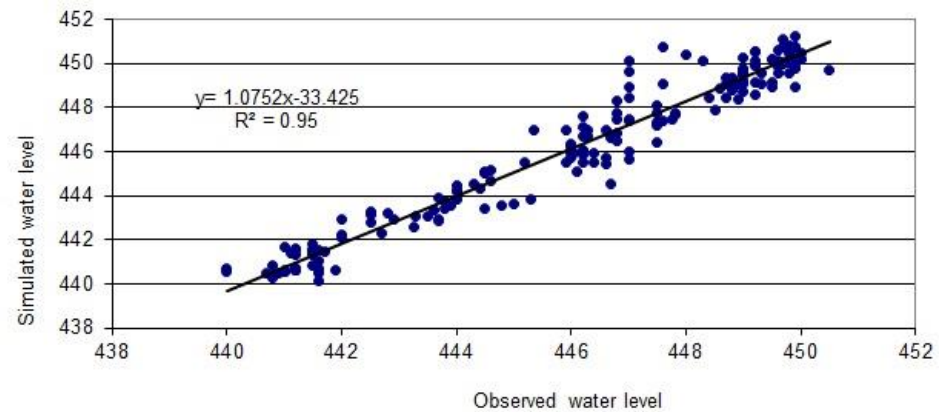


Figure 10b. HEC-RAS calibration-observed flows for D/S Roseires, 1988.

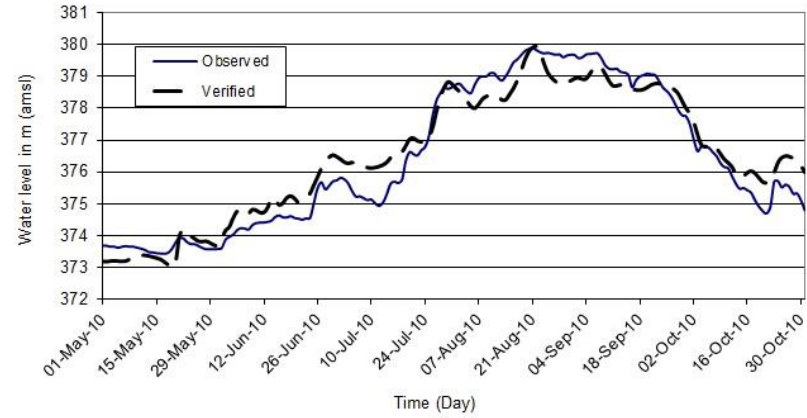
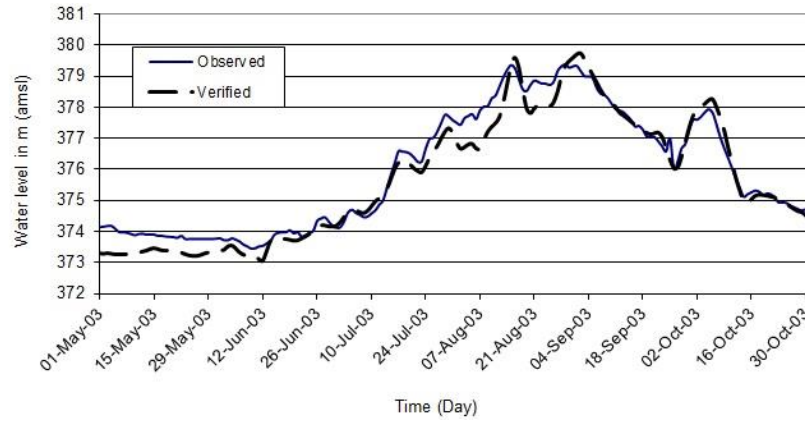


Figure 11a. HEC-RAS forecast verification results for Khartoum during 2003 and 2010.

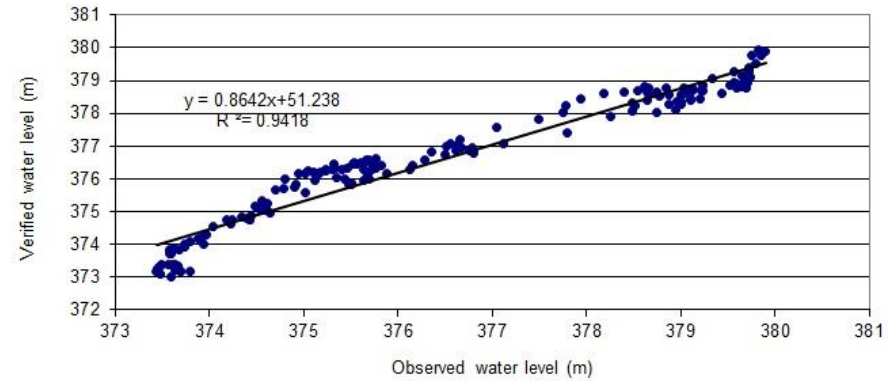
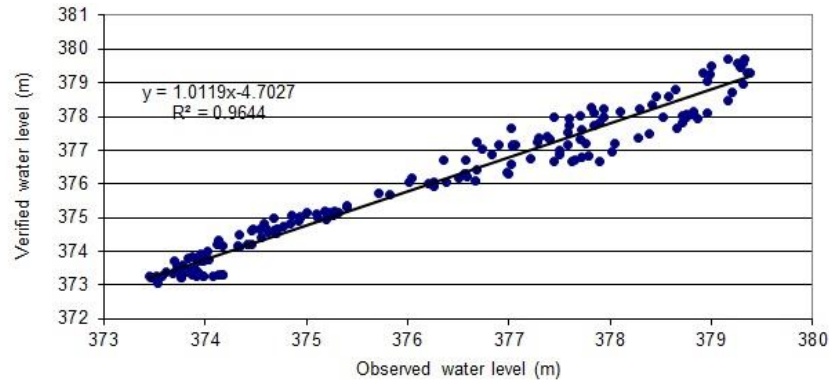


Figure 11b. HEC-RAS verification- observed flows results for Khartoum during 2003 and 2010.

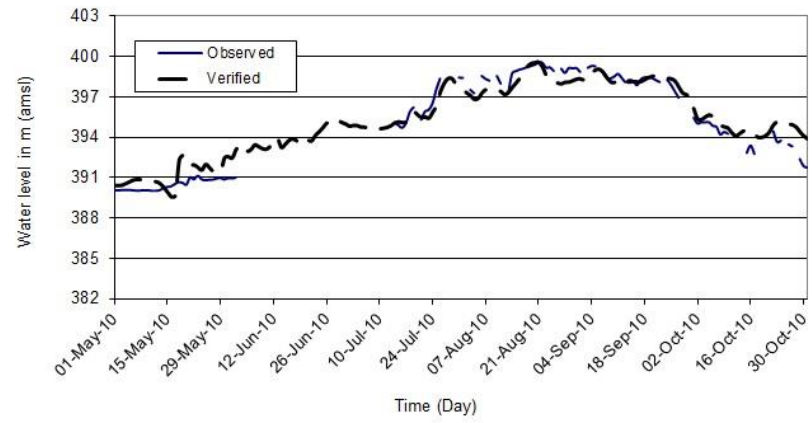
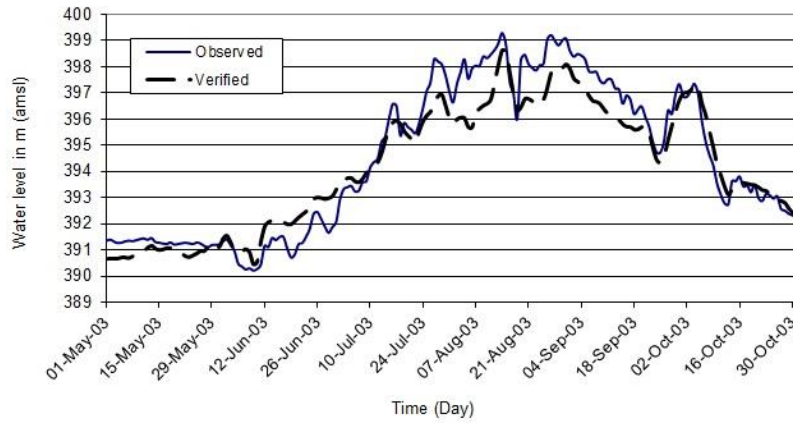
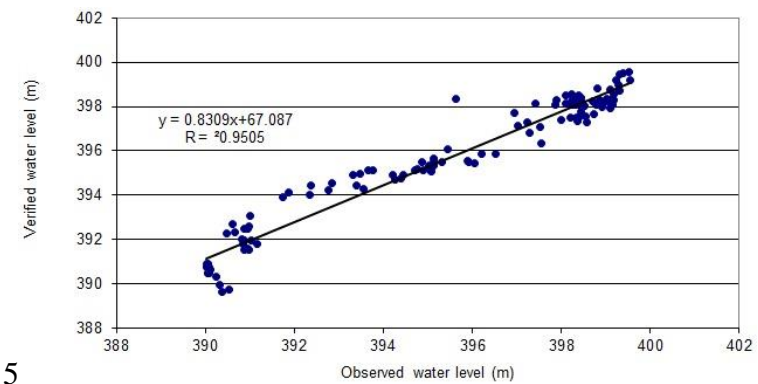
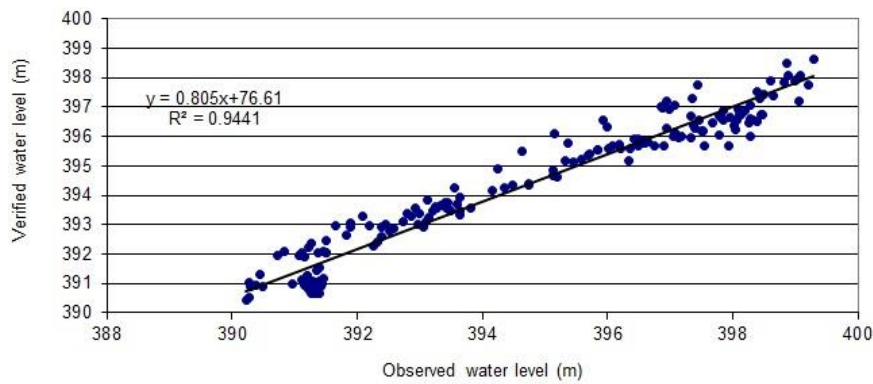


Figure 12a. HEC-RAS forecast verification results for Wad Medani during 2003 and 2010.



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Figure 12b. HEC-RAS verification-observed flows results for Wad Medani during 2003 and 2010.

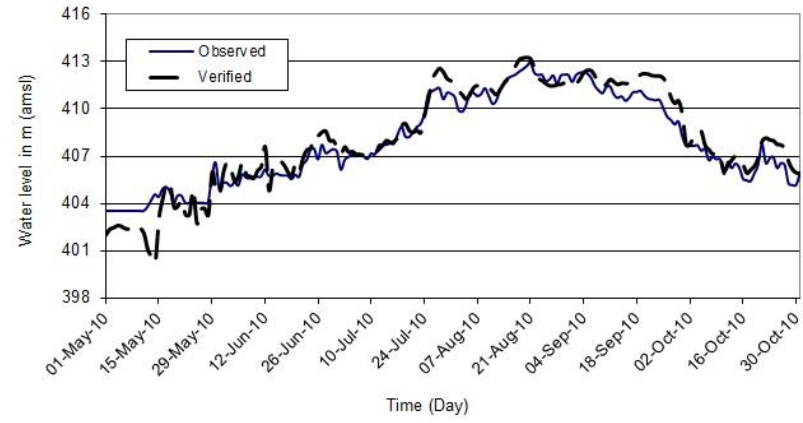
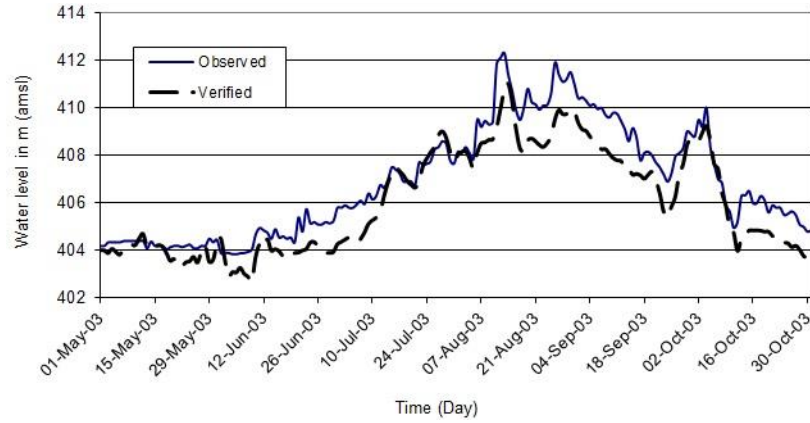


Figure 13a. HEC-RAS forecast verification results for D/S Sennar during 2003 and 2010.

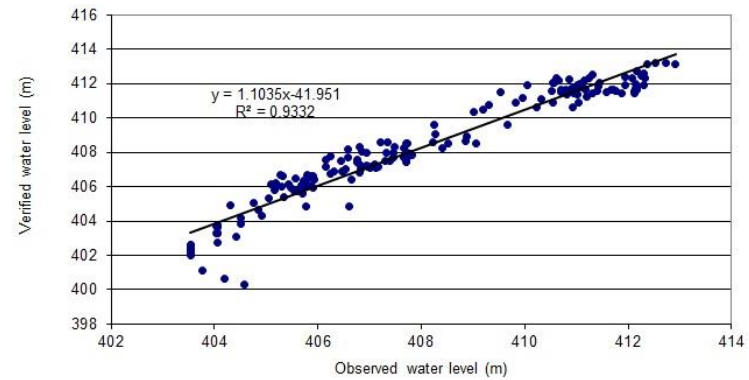
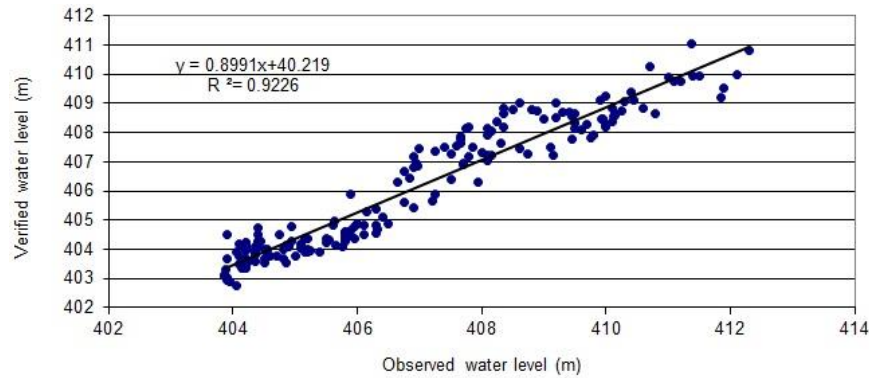


Figure 13b. HEC-RAS verification-observed flows results for D/S Sennar during 2003 and 2010.

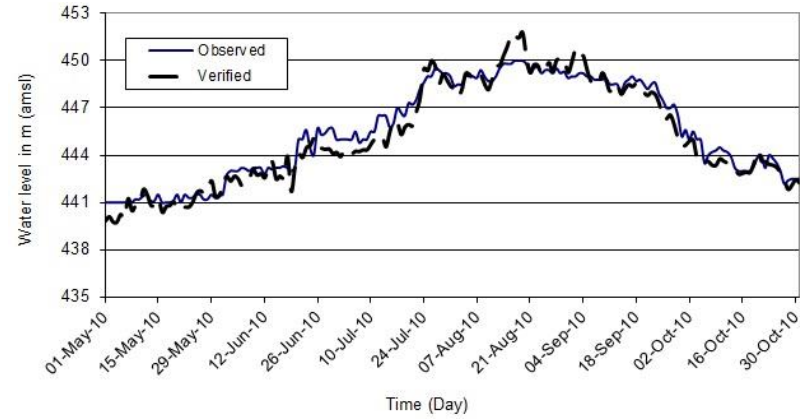
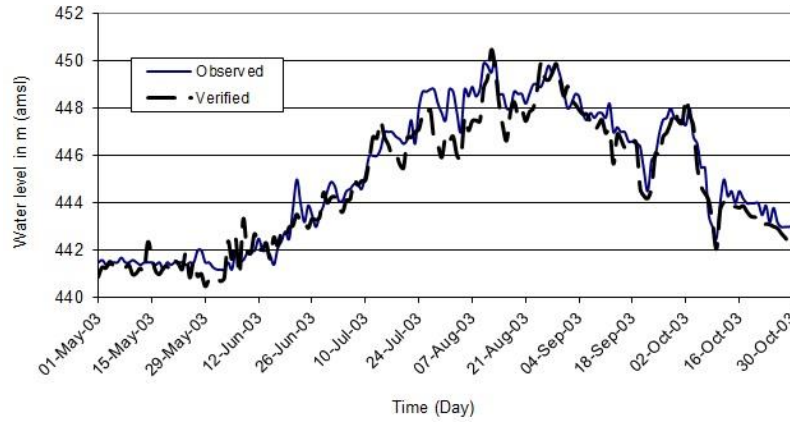


Figure 14a. HEC-RAS forecast verification results for D/S Roseires during 2003 and 2010.

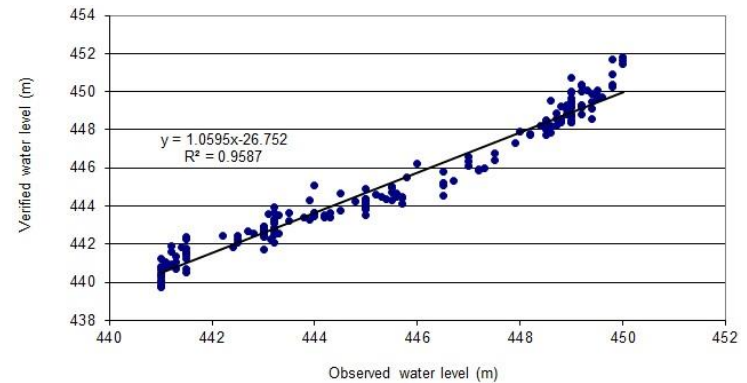
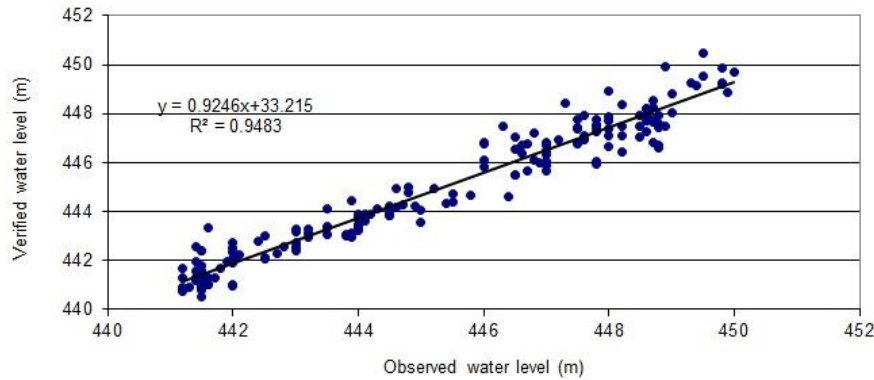


Figure 14b. HEC-RAS verification-observed flows results for D/S Roseires during 2003 and 2010.