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Virtual Failure Influence of Roseires Dam on Khartoum City Using HEC-RAS Hydraulic Simulation Modeling

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ABSTRACT - Dam break is series phenomenon that can result in fatal consequences and loss of properties. Unfortunately, the observed consequences can only be available after the dam breaks. Therefore, it is important to anticipate what will happen prior to dam break to issue suitable warning and locate the possible risk areas. This study attempts to simulate the case of dam break in Blue Nile at Roseires dam and see its consequences downstream. Roseires dam lies at a distance of 630 km south of Khartoum, Sennar dam lies at about 260 km downstream of Roseires dam. In this study hydraulic model is developed based of Hydraulic Engineering Centre (HEC), River Analysis System (RAS), and HEC-RAS. The HEC-RAS based model is calibrated and validated using observed data of the Blue Nile for several flood years. The calibrated and validated model is used to analyze the impact of flood wave due to dam break failure of Roseires dam to provide the following information: the maximum discharge, the maximum water level, the maximum velocity, the velocity and depth profiles, the flooding extent, etc. Several dam break scenarios that cover the possible failure modes were considered and the scenario that gives the worst situation is present in this paper. Piping is considered as failure mode with different failure parameters. It was found that failure of Roseires dam result in overtopping failure of Sennar dam due to the inability of the Sennar reservoir and dam to withstand the flood wave. The results also indicated that the maximum flood wave resulting from the failure of Roseires dam reaches Khartoum in 4, 6, 7 and 9 days when the maximum flow is 33105, 14724, 13249 and 12443 m3/s respectively the cities (Roseires, Sennar, Wad Medani and Khartoum). The respective water surface level of flood wave is 481.01, 428.37 and 382.5 m in Roseires, Sennar and Khartoum and the wave speed at Khartoum is 8.97 m/s.

Keyword: *Roseires, Sennar, Blue Nile River, failure, Hydraulic Modeling.*

المستخلص - انهيار السد هو ظاهرة متسلسلة والتي تؤدي إلى عواقب وخيمة وخسائر في الممتلكات .ان العواقب والاضرار التي يمكن ان تحدث من انهيار السد خطيرة ، وبالتالي، فمن المهم استنباء ما سيحدث قبل انهيار السد لاطلاق تحذير مناسب وتحديد مناطق الخطر المحتملة .هذه الدراسة تهدف لمحاكاة حالة انهيار السد في ولاية النيل الأزرق في سد الروصيرص وملاحظة تاثيره في المناطق الواقعة اسفل السد ،سد الروصيرص يقع على مسافة 630 كم جنوب الخرطوم وسد سنار يقع على بعد 260 كم اسفل سد الروصيرص. في هذه الدراسة تم تطوير نموذج هيدروليكي بالاعتماد على المركز الهيدروليكي للمهندسين (HEC)، النظام التحليلي للانهر (RAS)، و-HEC RAS ، ونموذج ال(HEC-RAS) يعتمد على المعايرة والتحقق من صحة البيانات المستخدمة لنهر النيل الازرق المسجلة لعدة سنوات..التحقق والمعايرة للنموذج يستخدم لتحليل صدمة الموجة وحساب التصريف ، اعلى منسوب للماء،اعلى سرعة جريان ومقطع السرعة والعمق للموجة وتاثير الفيضان .واجريت عدة سيناريوهات لتمثيل حالة الفشل للسد وتم تحديد السيناريو الذي يعطي اسوأ وأشد حالة فشل في هذه الورقة ،والفشل الانبوبي هو النوع الذي تم اعتماده في هذه الحالة وبمعاملات مختلفة. وقد تبين أن فشل سد الروصيرص يؤدي الى عبور موجة الفيضان فوق سد سنار بسبب عدم قابلية سد سنار على صد موجة الفيضان .كما أشارت النتائج إلى أن موجة الفيضان القصوى الناتجة من فشل سد الروصيرص تصل الخرطوم في (4،6،7،9) أيام عندما يكون أقصى تدفق هو(33105، 14724، 13249و 12443 م^3/ ث)على التوالي في مدن الروصيرص ،سنار ، ود مدني والخرطوم .(واعلى مستوى لسطح الماء الناتج من موجة الفيضان هو(481.01، 428.37 و 382.5م) في الروصيرص، سنار والخرطوم وسرعة الموجة في الخرطوم هي 8.97 متر / ثانية.

INTRODUCTION

Hydraulic modeling is employed to estimate the hydraulic characteristics of flow in the rivers and channels that would result from passing the discharge through them. Sky and Hanif [1] collected experimental data of dam break flows by a new procedure using electronic digitization of video images to record water levels in the downstream channel and found dam removal time was approximately 0.05 sec for an upstream reservoir level of 0.3 m and 0.02 sec for a reservoir level of 0.1 m while Spinewine and Zech [2] performed experimental dam break with sediment bed channel. The surge of water and eroded sediments was recorded by fast digital cameras, tracking techniques were used to follow each particle of bed and obtain detailed measurements. The influence of the varying levels on the surge speed, front height, water levels and bed levels will be investigated. As well, Froehlich [3] developed a best-fit regression equation for prediction of peak discharge based on reservoir volume and head, using data from twenty two case studies for which peak discharge data were available. He also presented a computational procedure for determining confidence intervals and identifying hidden extrapolation in the estimates. Wahl and Cheng [4] studied the characteristics method of hypothetical sudden failures (full and partial) of a dam. Laboratory data on dam- break flood waves were used in the verification of the model the smaller the size of the breach, the poorer the agreement of the computed and the measured results, and the depth ratio at the breach (after and before removal of the dam) increases from 0.44-0.51 for n from 0.009 to rough surface.

The important characteristics for the flood risk mapping study include water surface elevation, flow depth, and flow velocity. Globally, Sam Crampton [5] stated that the potential flood risk caused by dam failure is often more severe and can behave very different to that of natural flooding events. The tragedy of dam failure is all too familiar to Georgia with the failure of the Kelly Barnes dam near Toccoa Georgia which resulted in 39 deaths in the early hours of November 6th 1977. Cameron and Gary [6] provided an analysis of dam failure models and scenario generating tool for identifying the resulting hazards. Floodplain managers and emergency personnel may then utilize the resulting contingencies to protect against the loss of life and property damage. HEC-RAS can be used with HEC-GeoRAS to develop dam failure model. Eastern Nile Technical Regional Office (ENTRO) [7] studied the dam safety risk assessment through various literatures and published project reports review, also the approaches to the demonstration of safety have been outlined, together with some of the strengths and weaknesses of each approach. The report has also assessed the current dam safety practice in the Eastern Nile countries in comparison with the international practices, the study has focused on the Embankment dams in the Eastern Nile countries and has develop a baseline data and dam safety assessment toolkit using of Excel applications. The toolkit contains information about the existing and proposed dams on the region. A case study has been undertaken to test the toolkit and explain the inundation map for the case steady.

MATERIAL AND METHODS

Blue Nile River

The Blue Nile sub system in this respect accounts for 76% of the total irrigated agriculture on the three Nile tributaries Atbara, White Nile and Blue Nile as shown in Figure 1 Ministry of Water Resources and Electricity, Sudan, MoWRE [8]. A major characteristic of the Blue Nile discharges is the remarkable seasonality of its flow, and more than 80% of the river discharge flows during the flood months, (June–October) two dams were built across the river (Sennar, 1925 and Roseires, 1966) to partially control the flows [9].

The Roseires dam, which spans across the Blue Nile at about 630 km upstream of Khartoum to the south, is a 1000 m long and 68 m high concrete dam with the crest at 482.2 m before heightening. The dam was completed in 1966 with an initial capacity of 3.024 km^3 at 480 m above mean sea level to be used for irrigation water supply as first priority, and hydropower generation comes secondly.

The Sennar Dam is a dam on the Blue Nile near the town of Sennar, Sudan. It was built in 1925 by the British engineer, desert explorer and adventurer, Stephen "Roy" Sherlock, under the direction of Weetman Pearson. The dam is 3025 meters long, with a maximum height of 40 meters. The dam extended over about 3.10m, i.e. over 3 km (3,025 meter) in length, and of a maximum height of 40- 45m**.** Figure 3 shows Stage-Volume-Area relation for Roseires- reservoir.

The Data

Hydraulic analysis needs cross section profiles along the river reach with suffient number to accurately represent the hydraulics in the river channel. An inventory of the existing available topographic and cross-section data collection was performed in order to identify data gaps and the need for additional field surveys. The field surveyed data of the Blue Nile River of 1992 used in the configuration of the Flood Early Warning System (FEWS) developed for the River Nile were retrieved. A total of 87 cross-sections were available from this survey. In 2007 a bathymetric survey was performed by the Dam Implementation Unit (Sudan) in association with Ministry of Irrigation and Water Resources (MOIWR Sudan). This survey covers a 25 km reach between Khartoum and Bagair and is a very dense bathymetric survey collected at an interval of 100 m. In 2007, the Dam Implementation Unit in association with MOIWR performed bathymetric survey for Roseires Reservoir. The survey covered a reach of about 110 km upstream of Roseires dam with geo-referenced data. The data were pre-screened to check for the right datum projection (WGS-UTM84) and a number of referenced points were utilized to verify the accuracy of the data.

Field Survey performed by Riverside Technology (RTi, 2010) and UNESCO Chair in Water Resources (UNESCO-CWR) [10] to supplement the available data and verify the accuracy of existing river cross-sections. The Unite States Corp of Engineers River Analysis System Model (HEC-RAS) is utilized to develop the hydraulic routing model for the Blue Nile.

Field Survey, 2013 during this study and for the sake of training three cross sections around Khartoum were done. These cross sections were used for check the validity of the existing ones. Materials used include: Global Positioning System (GPS) device used to locate positions of each cross-section along the river centerline. Theodolite, ADCP, and GPS instruments were used by the surveying working team.

Reservoir characteristics were collected from the dams' directorate of the Ministry of water resources and electricity and the operation policy for each reservoir is also collected (Ministry of Water Resources and Electricity, Sudan, 1968).

Analysis of the system requires upper boundary condition that specifies the inflow to the system which is considered as lateral inflow hydrograph. So, for this study, Eddiem observed flow is used as upper boundary. The downstream boundary condition at Khartoum as the downstream end of the study area is set 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 to be considered. These are observed stage and/or flow hydrographs at upstream and downstream of the two reservoirs, Roseires village and wad Alaies in the Roseires-Sennar reach, wad Medani, Kamlin and Soba in the Sennar-Khartoum reaches. The required available data for each of these stations were collected for the Ministry of water resources and electricity. The collected data were processed for use in the model calibration.

Description of the HEC-RAS Model

Overview of HEC-RAS Model Capabilities

HEC-RAS [11] is an integrated system of software, designed for interactive use in a multi-tasking environment. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities. The current version of HEC-RAS system contain one-dimensional hydraulic analysis components for: (a) steady flow water surface profile computations; (b) unsteady flow simulation; and (c) movable boundary sediment transport computations. A key element is that all three components will use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the three hydraulic analysis components, the system contains several hydraulic design features that can be invoked once The basic water surface profiles are computed. The current version of HEC-RAS supports steady and unsteady flow water surface profile calculations (Hydraulic Reference Manual, version 4.1.0).

HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. The following is a description of the major capabilities of HEC-RAS. The user interacts with HEC-RAS through a graphical user interface (GUI). The main focus in the design of the interface was to make it easy to use the software, while still maintaining a high level of efficiency for the user. The interface provides for the following functions:

1 -File management.

2 -Data entry and editing.
3 -Hydraulic analyses.
4 -Tabulation and graphical displays of input and output data.

Data storage is accomplished through the use of "flat" files (ASCII and binary), as well as the HEC-DSS (Data Storage System). User input data are stored in flat files under separate categories of project, plan, geometry, steady flow, unsteady flow, and sediment data. Output data are predominantly stored in separate binary files. Typically, for a steady flow model, frequency events (i.e, 100-year, 20-year, etc.) are used as inflow boundary controls. In unsteady models, inflow hydrographs, representing a time-series of flows (real or fictitious) are used to define the inflow boundary control. Outlet boundary controls include normal depth, critical depth, rating curves, and flow and stage hydrographs (Hydraulic Reference Manual, version 4.1.0).

RESULTS AND DISCUSSIONS

The study area model is developed under the HEC-RAS. The model is calibrated and validated using several observed flood years. The result of calibration using 1988 observed flood validated using 2003 floods at Khartoum is shown in figures 4and 5. In both cases the model accounted for more that 96% of initial variance reflected in giving R^2 of above 0.96. Therefore, the model can be used for further analysis.

The calibrated and validated HEC-RAS model was used to analyze the dam break hypothetical failure at AL Roseires dam. The main input to the model is the observed 2013 data for the period 1st August to 31st August at Eddiem station.

Several scenarios that cover the possible dam break failure modes were tried and the results presented here is only for the worst scenario. The piping failure mode at Roseires dam is assumed. The failure is triggered when the reservoir is full. The model results at downstream Roseires dam, Sennar dam, Wad Medani, Kamlin, Soba and Khartoum at distances of 0.34, 256.34, 438.34, 498.34, 590.34 and 600.34 km respectively were obtained. The breach parameters for the concrete structure of the Roseires dam were produced by using parametric Description of Dynamic Breach (PDDB) Spreadsheet, developed by ENTRO as shown in Fig 6.

The breach parameters obtained from PDDB is used to run the HEC-RAS model. Fig 7 shows the water flow hydrograph at the different stations along the reach. It can be seen that the dam break flood is attenuated as it progresses downstream. The maximum flow obtained at Roseires dam, Sennar dam, Wad Medani and Khartoum are 33105, 14724, 13249 and 12443 m^3/sec respectively.

Figure 8 shows surface water profile along the river channel of the Blue Nile in the area of Roseires to Khartoum. The maximum water level at Sennar is 428.37 m and that at Khartoum is 382.5 m. It is clear from the figure that Sennar dam experiences an overtopping failure due to the piping failure of Roseires.

The velocity profile shown in Figure 9 indicates that the velocity at Khartoum can reach as high as 9 m/s which is with depth of water can create a great risk. The inundation can be seen in Fig 10 which shows the X-Y-Z perspective plot of water surface area.

CONCLUSIONS

For the mathematical model the calibrated HEC-RAS model was used. The worst situation occurred during scenario five with the following parameters: the failure mode was selected as piping mode, the failure is triggered at water level of 481, the real observed flow of 2013 for August was used, the initial breach center dam of 583.4 m was used, the breach parameters for Scenario five is width 546 meters, depth 19 meters and time 5.6 hours.

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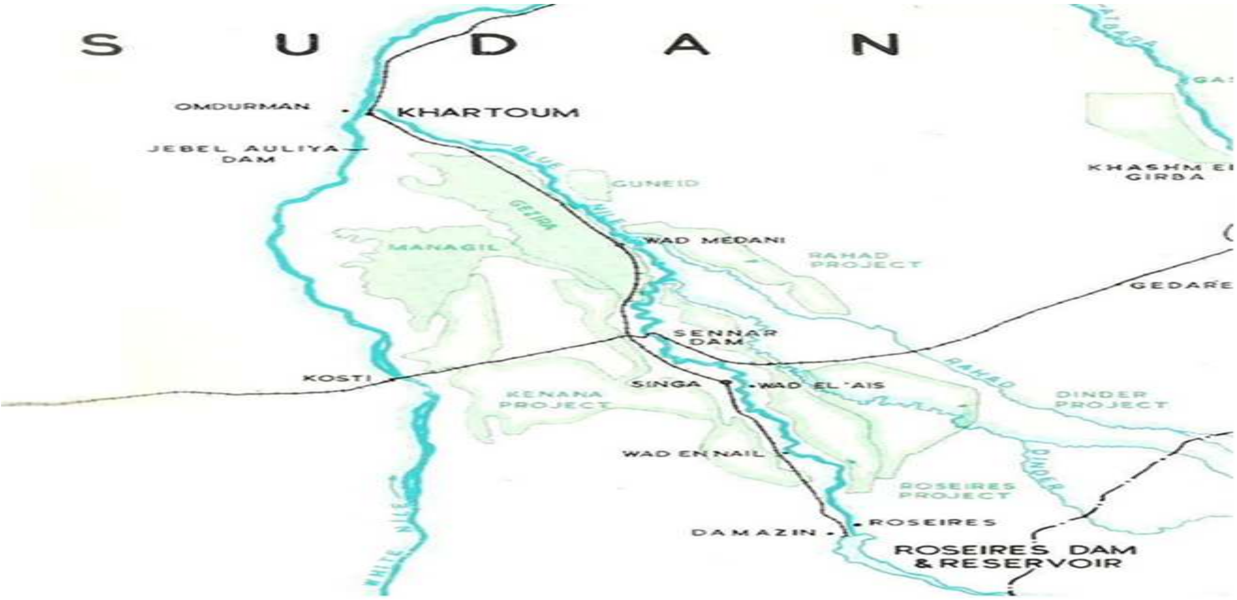


Figure 1: Blue Nile River system schematic in the study area

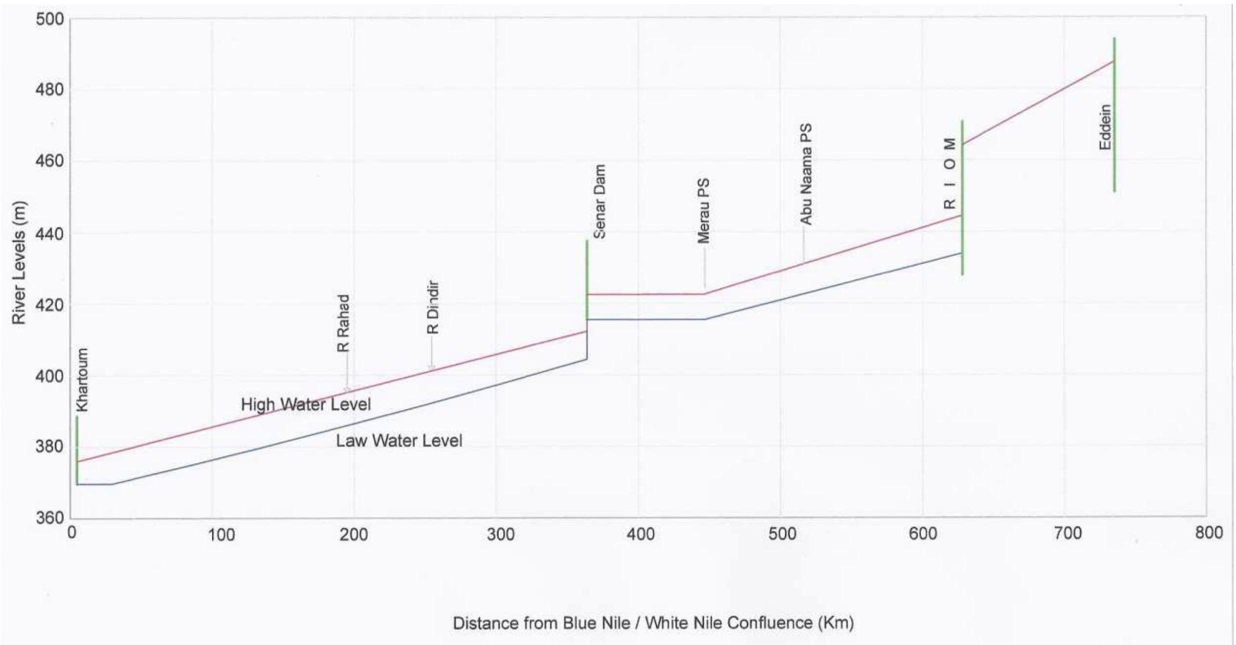


Figure 2: Longitudinal profile of the Blue Nile River from Roseires dam to Khartoum

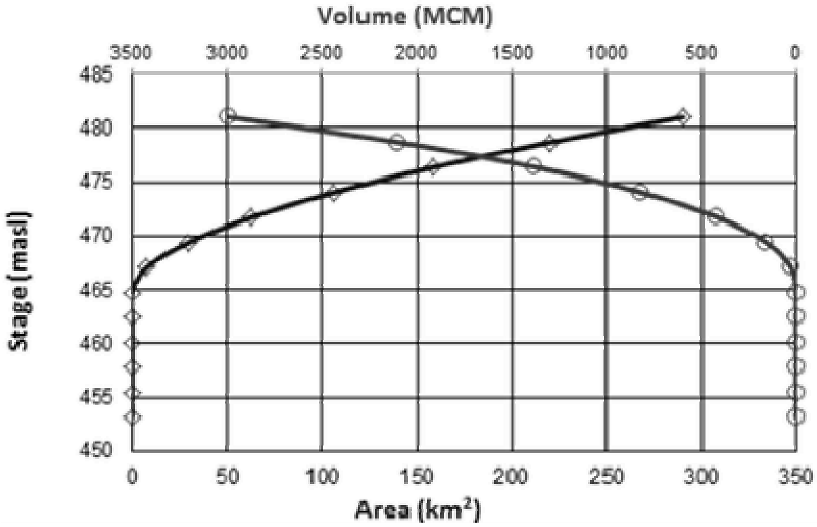


Figure 3: Stage-Volume-Area relation for Roseires- reservoir

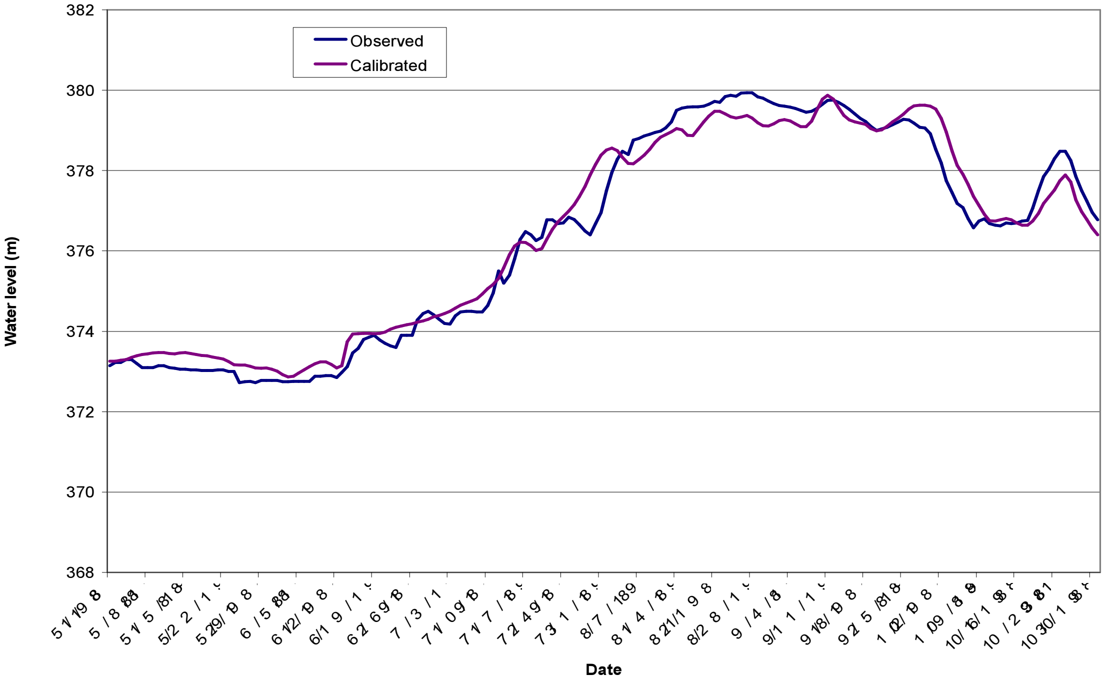
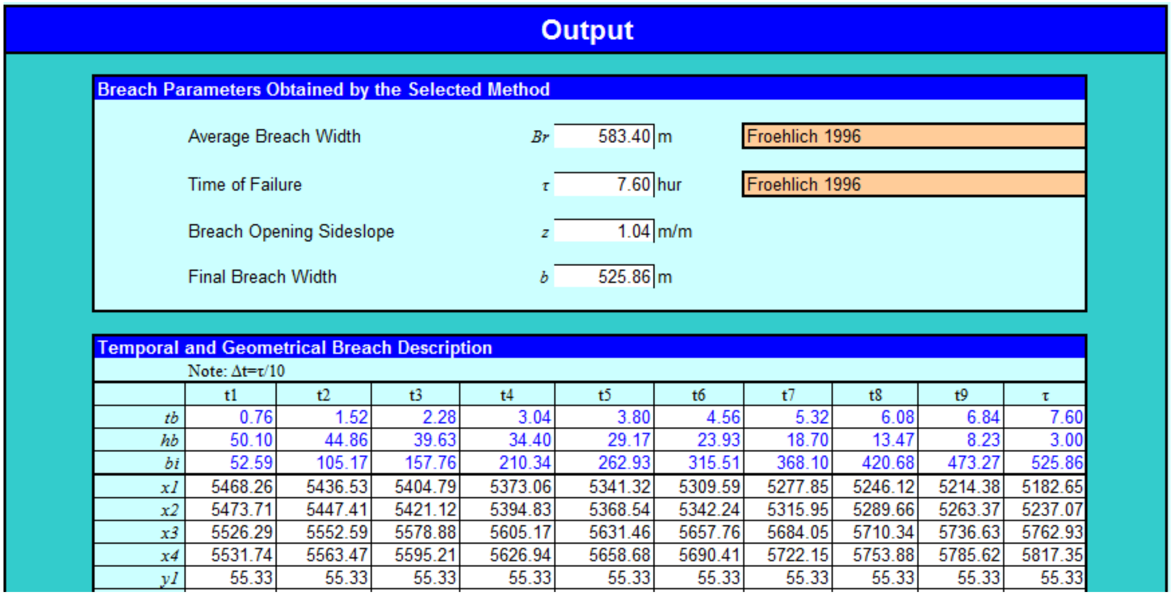


Figure 4: Observed and simulated water level at Khartoum during calibration

Figure 5: Observed and simulated water level at Khartoum during validation



Output

Breach Parameters Obtained by the Selected Method

Average Breach Width	*Br*	583.40	m	Froehlich 1996
Time of Failure	*τ*	7.60	hur	Froehlich 1996
Breach Opening Sideslope	*z*	1.04	m/m	
Final Breach Width	*b*	525.86	m	

Temporal and Geometrical Breach Description

Note: Δt=τ/10

	t1	t2	t3	t4	t5	t6	t7	t8	t9	τ
tb	0.76	1.52	2.28	3.04	3.80	4.56	5.32	6.08	6.84	7.60
hb	50.10	44.86	39.63	34.40	29.17	23.93	18.70	13.47	8.23	3.00
bi	52.59	105.17	157.76	210.34	262.93	315.51	368.10	420.68	473.27	525.86
x1	5468.26	5436.53	5404.79	5373.06	5341.32	5309.59	5277.85	5246.12	5214.38	5182.65
x2	5473.71	5447.41	5421.12	5394.83	5368.54	5342.24	5315.95	5289.66	5263.37	5237.07
x3	5526.29	5552.59	5578.88	5605.17	5631.46	5657.76	5684.05	5710.34	5736.63	5762.93
x4	5531.74	5563.47	5595.21	5626.94	5658.68	5690.41	5722.15	5753.88	5785.62	5817.35
y1	55.33	55.33	55.33	55.33	55.33	55.33	55.33	55.33	55.33	55.33

Figure 6: Parametric description of dynamic breach (PDDB)

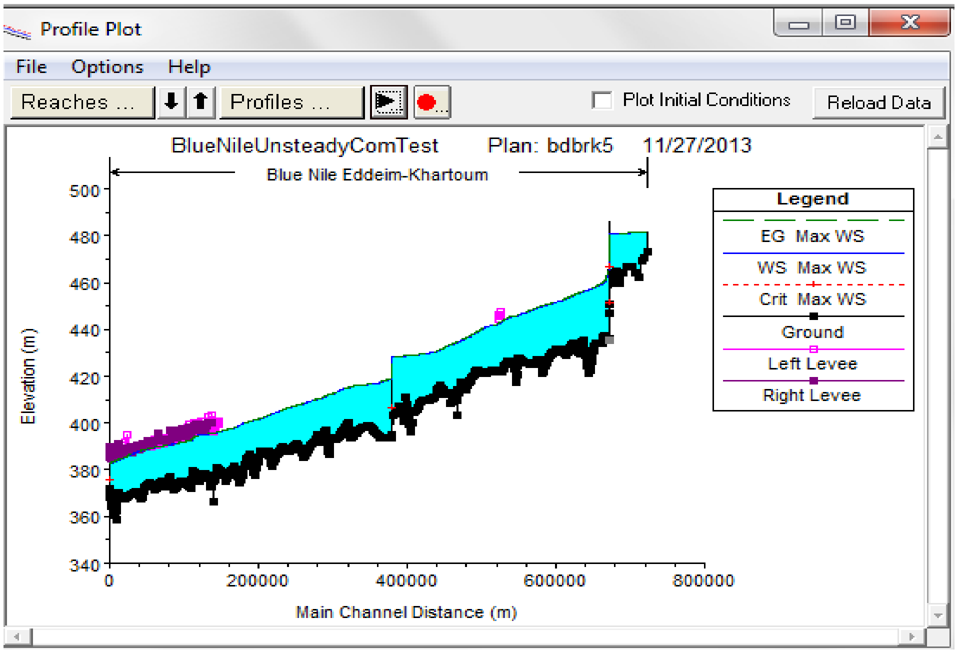


Figure 7: Dam breach flood wave attenuation (piping and overtopping)

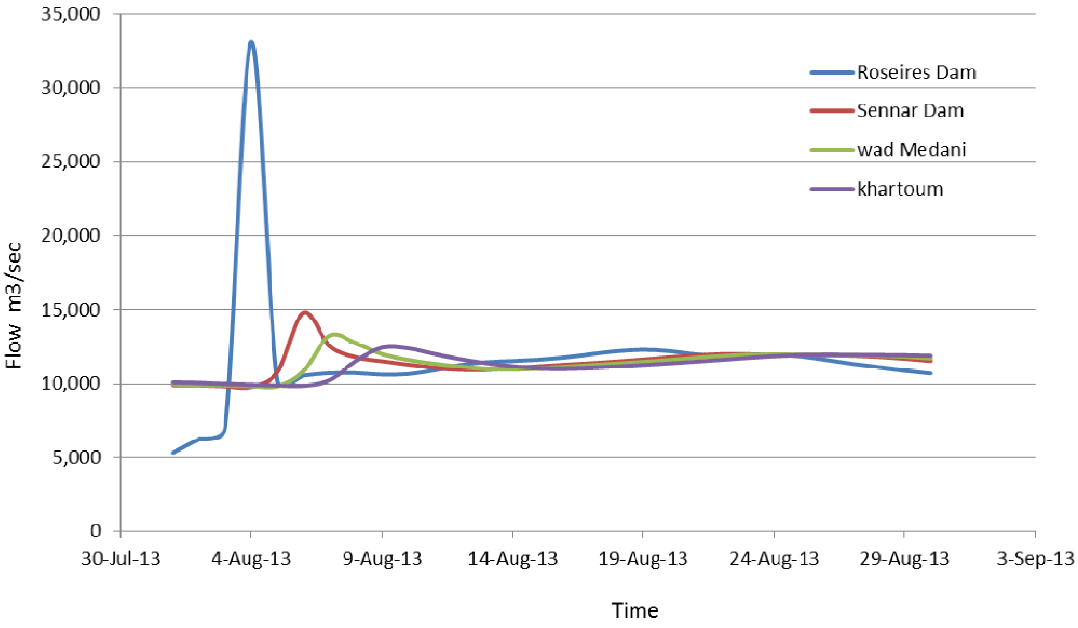


Figure 8: Water profile after Dam break

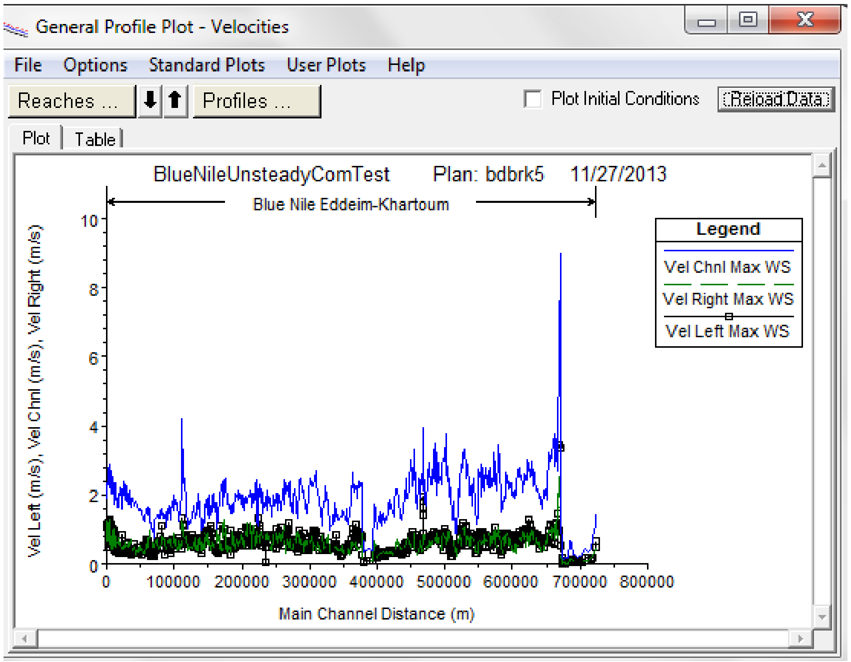
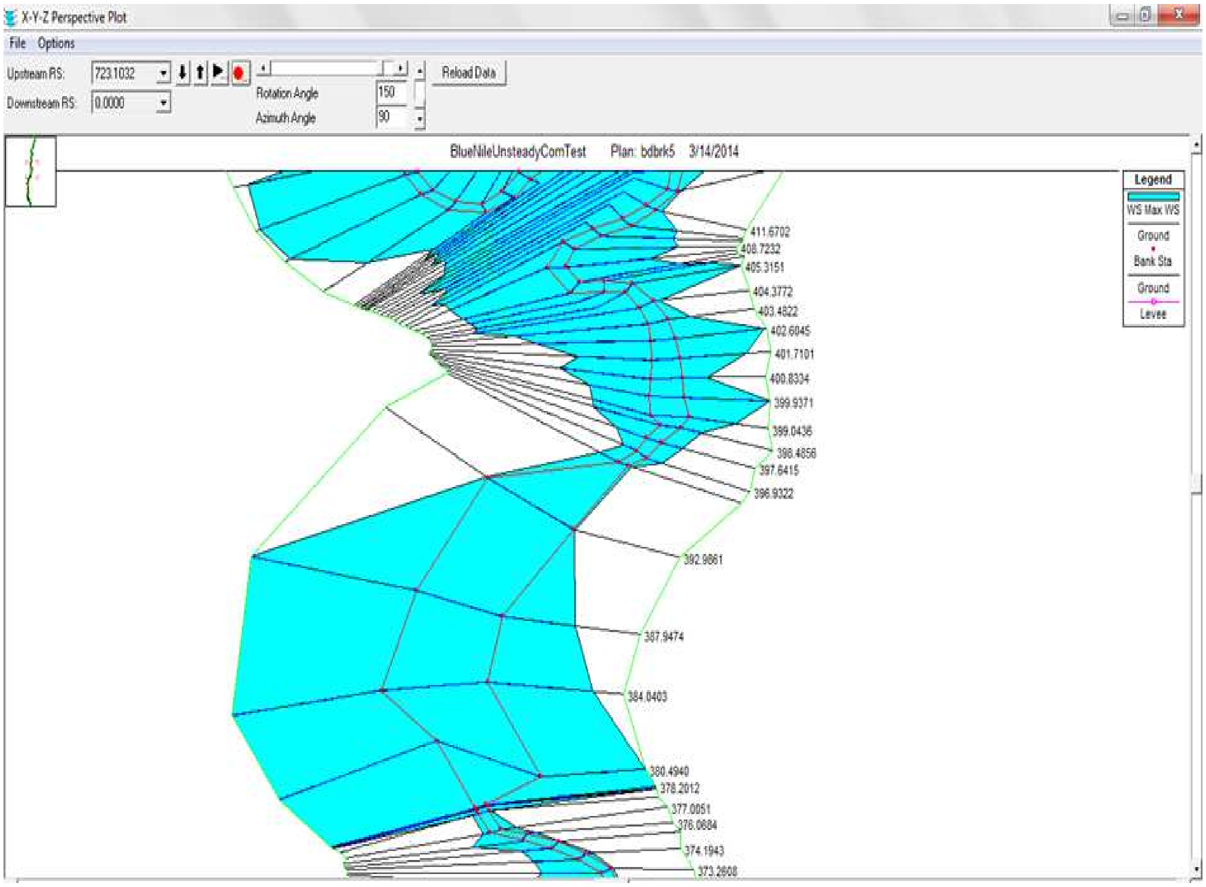


Figure 9: General profile plot – velocities


Upstream RS: 723.1032

Downstream RS: 0.0000

Rotation Angle 150

Azimuth Angle 90

Figure 10: X-Y-Z perspective plot