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Auteurs: Authors:	Eman AlQasimi, & Tew-Fik Mahdi
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Flooding of the Saguenay Region in 1996: Part 1- Modeling River Ha! Ha! Flooding

Eman AlQasimi and Tew-Fik Mahdi[*]

Polytechnique Montreal, Department of Civil, Geological and Mining.C.P.6097, Succ. Centre-Ville, Montréal, Québec, H3C 3A7. Canada

Abstract. This paper presents an application of the model UMHYSER-1D (Unsteady Model for the HYdraulics of SEdiments in Rivers One-Dimensional) to the representation of morphological changes along the Ha! Ha! River during the 1996 flooding of the Saguenay region. UMHYSER-1D is a one-dimensional hydromorphodynamic model capable of representing water surface profiles in a single river or a multiriver network, with different flow regimes considering cohesive or noncohesive sediment transport. This model uses fractional sediment transport, bed sorting and armoring along with three minimization theories to achieve riverbed and width adjustments. UMHYSER-1D is applied to the Ha! Ha! River (Quebec, Canada), a tributary of the Saguenay River, for the 1996 downpour. The results permit forcing data verification and prove that some cross sections are not the right ones. UMHYSER-1D captures the trends of erosion and deposition well although the results do not fully agree with the collected data. This application shows the capabilities of this model and predicts its promising role in solving complex, real engineering cases.

Keywords: Saguenay flood 1996; One-dimensional model UMHYSER-1D; Data validation; Ha! Ha! River

1 Introduction

Precipitation-runoff floods and dam failure floods result in unusually rapid water surface rises and high-velocity outflows through the downstream river. The inundation of riverbanks may cause significant

[*] Corresponding author: Tewfik.Mahdi@polymtl.ca

erosion and important riverbank retreats and creates potentially unstable embankments, as those observed in the aftermath of the Saguenay floods in 1996 (Lapointe et al., 1998).

From July 18 to 21, 1996, unusually heavy rain affected the Saguenay region of Québec, Canada, between Lake St. Jean and the St. Lawrence River (Figure 1). These torrential rains are the largest meteorological event recorded in Québec for almost a century. Between 150 and 280 mm of rain fell during more than 48 hours over a territory of several thousand square kilometers, affecting the watersheds of the southern part of the Gaspe Peninsula, Charlevoix, Haute-Mauricie, Haute-Côte-Nord and Saguenay-Lac-Saint-Jean, leading to widespread flooding and damage including extensive erosion in the region, significant riverbank retreat and destruction of many run-of-the-river dams on rivers discharging into the Saguenay River and Saguenay Fjord.

The Saguenay-Lac-Saint-Jean region was affected the most. For example, water discharge to the Kenogami Reservoir Lake reached 2780 m^3/s on July 20, 1996, while the historical maximum observed before this event was 997 m^3/s.

The situation was particularly dramatic for a few rivers and streams: the Saint-Jean River at Anse-Saint-Jean, the Petit Saguenay River in the municipality of the same name, the A Mars River in the municipality of La Baie, the Ha! Ha! River in the municipalities of La Baie and Ferland-et-Boilleau, the Moulin River in the municipalities of Laterrière and Chicoutimi, the Belle River in the municipality of Hébertville, the Chicoutimi River in the municipalities of Laterrière and Chicoutimi and the Aux Sables River in the municipality of Jonquière. Major damage affected local populations (houses flooded, buildings destabilized and washed away, infrastructure torn apart, etc.) and other effects had negative impacts on rivers through multiple repercussions: riverbeds were lowered, riparian and aquatic vegetation was destroyed, loose soil suffered deep erosion, great amounts of sediment were deposited in some places, multiple beds were created, the majority of habitats were destroyed, aquatic fauna were washed away and so on.

This paper analyses the Ha! Ha! River 1996 floods through modeling by using a newly developed numerical model, UMHYSER-1D (One-Dimensional Unsteady Model for the HYdraulics of SEdiments in Rivers) (AlQasimi and Mahdi, 2018). The second section presents UMHYSER-1D, and section 3 describes the study case, a reach of the Ha! Ha! River, which is a tributary of the Saguenay River, along with the available data; section 4 includes the results and discussion of the simulations, followed by the conclusion.

2 Overview of UMHYSER-1D

UMHYSER-1D is an unsteady one-dimensional model that represents the water and sediment phases by solving the one-dimensional de Saint-Venant equation for the water phase and the Exner/one-dimensional convection-diffusion equation for the solid phase. UMHYSER-1D performs five groups of operations: water phase, stream tubes, sediment phase, riverbank stability analysis and cross section adjustments.

UMHYSER-1D uses the continuity equation and the energy equation when there are no changes in the flow regime, while the momentum equation is used with the continuity equation when there are changes from supercritical to subcritical flows, or vice versa. In the case of steady flow, for backwater computations, the standard step method is used (Henderson, 1966), and the friction losses are computed by a uniform flow formula as generally admitted (Jain, 2000). Under steady-state conditions, the capabilities of UMHYSER-1D are similar to those of the MHYSER model developed by Mahdi (2009). The de Saint-Venant equations are used for unsteady flow computations. Irregular cross sections can be handled regardless of whether the river reach consists of a single channel or multiple channels. For the latter case, the variables related to the cross-sectional geometry are computed for each subchannel and are summed to obtain the total values. Moreover, internal conditions such as weirs, falls and sluices are modeled by rating curves. UMHYSER-1D uses the NewC scheme (Kutija and Newett, 2002), which assures numerical stability in the transition between different flow regimes.

After the water surface characteristics are calculated, the cross sections are divided into sections of equal conveyance or stream tubes. These stream tubes act as conventional one-dimensional channels with known hydraulic properties where sediment routing can be carried out within each stream tube almost as if they were independent channels. Once the top widths are determined, the velocities of the stream tubes are calculated by giving a crosswise velocity distribution for every cross section.

Stream tube locations are allowed to vary with time. Therefore, although no material is allowed to cross stream tube boundaries during a time step, lateral movement of sediment is described by lateral variations in the stream tube boundaries. For noncohesive sediment transport, UMHYSER-1D uses the transport functions of Meyer-Peter and Müller (1948) and Parker (1990), Laursen (1958), modified Laursen (Madden, 1993), Toffaleti (1968), Engelund and Hansen (1972), Ackers and White (1973), modified Ackers and White (HR Wallingford, 1990), Yang (1973, 1979. 1984) and Yang et al. (1996). When the unsteady term of the suspended sediment transport continuity equation is ignored, the Exner equation is solved to update the bed changes. Both the spatial and temporal derivatives are approximated by first-order finite difference operators (Hirsh, 1990).

UMHYSER-1D deposition of cohesive sediment is based on Krone's equation (1962), while particle and mass erosion are based on the work of Parthenaides (1965) and adapted by Ariathurai and Krone (1976). For the convection-diffusion equation, the Lax-Wendroff TVD scheme is used to discretize the convective term; a central difference scheme is used for the diffusion term (Tannehill et al.,1997), and the source term discretization is similar to the one used by Vetsch et al. (2017).

For bed changes, the sediment transport is computed for each individual sediment size fraction within each stream tube. The bed changes are computed as a sum of the bed change due to each particle size. To maintain numerical stability, the time step is determined by a Courant-Friedrichs-Lewy (CFL) condition (Cunge et al., 1980). Since the kinematic wave speed of the bed changes is not easily quantified, numerical experimentation is required to determine a suitable time step to be used for a simulation.

UMHYSER-1D uses the method of Bennett and Nordin (1977) for the bed composition accounting procedure by dividing the bed into conceptual layers. The top layer, or active layer, contains the bed material available for transport, beneath which is the storage layer or inactive layer, and finally the undisturbed bed. The active layer is the most important layer in this procedure. Erosion of a particular size class of bed material is limited by the amount of sediment of this size class present in the active layer. At the end of each time step, bed material is calculated in each stream tube. At the beginning of the next time step, after the new locations of the stream tube boundaries are determined, these values are used to compute the new layer thickness and bed composition.

Finally, UMHYSER-1D offers the choice of 3 minimization theories for the determination of depth and width adjustments, at a given time step: minimization of the total stream power (Yang, 1972), minimization of the energy slope (Chang, 1988) and minimization of the bed slope.

3 Application: the 1996 Lake Ha! Ha! flood

3.1 Site description

The study area is an 8.4 km reach of the Ha! Ha! River, the most severely affected river during the 1996 floods. This river drains a catchment of 610 km^2. The Ha! Ha! River links Lake Ha! Ha! to the Ha! Ha! Bay, an arm of the Saguenay Fjord (Figure 2). The study reach extends from the Cut-away dike at Lake Ha! Ha! to the first falls encountered, 6 km beyond the village of Boilleau (8.4 km from the Cut-away dike that broke during the events).

On July 19, 1996, the watershed of the Ha! Ha! River began to receive an exceptional rain: on average, more than 210 mm of rain fell on this mountain basin of 608 km^2 and increased the contributions to Lake Ha! Ha! from 10 to 160 m^3/s.

Lake Ha! Ha! is impounded by a concrete dam that suffered minor damage during the flood. The dam maintained a high elevation in the water body (380 m) and allowed only a small spill (less than 30 m^3/s).

Lake Ha! Ha! was impounded by three structures: the concrete dam as the main dam, the evacuator, and two secondary dikes (Left Bank and Cut-away). The crest elevation of the Cut-away dike was 380.65 m, 40 cm lower than that of the main dam and 35 cm lower than the Left Bank dike (Nicolet Commission 1997).

The rising water level of the lake under the effect of the increased inputs and their partial retention caused on July 20, at approximately 6:00 am, an overtopping on the Cut-away dike, leading to its gradual erosion. The dike breach that developed during the morning of July 20 led to its failure.

As a result, the incision of a new outlet channel occurred, bypassing the concrete dam and leading to rapid drainage of the main lake. Due to the incision, the lake level dropped from a level of 381 m to a new level of 370 m (above average mean sea level). Further details of the flood and the corresponding damage are given by Brooks and Lawrence (1999). They estimated the peak outflow to be in the range of 1080-1260 m^3/s at a surveyed cross section 27 km downstream from the dike.

3.2 Available data

The 37 km river reach, from the Cut-away dike to the Ha! Ha! Bay (Figure 1), is discretized into 370 cross sections before and after the flood, and the rock elevations along the river (Figure 3) are provided by Capart et al. (2007).

The hydrograph of the breach flood (Figure 4) and a size gradation curve (Figure 5) for the first 10 km of this river reach are provided by Mahdi and Marche (2003). This sediment distribution is assumed to be valid for the entire river. Note that to ensure numerical stability, a time step of 10^{-4} s is used.

4 Results and discussion

As the available data cover the river's cross sections before and after the flood, the only interesting results are the longitudinal profile and the comparison of the cross sections to the observations.

4.1 Cross sections data validation

Performing data validation of the cross sections reveals that not all the available cross sections provided by Capart et al. (2007) and covering the entire river can be used. Figure 6 shows an example of a cross section that cannot be used for the simulation. After removing several similar cross sections, the first simulations aimed to model the whole Ha! Ha! River, since the available cross sections covered the entire river. Figure 7 shows an example of a simulated thalweg and the observed one (Capart et al., 2007). As shown, major differences between the simulated and observed thalwegs are noted approximately 22 km downstream from the Cut-away dike.

These major differences, appearing at a specific zone and reaching a maximum value of 20 m, cannot be attributed to modeling errors. As seen from Figure 2, approximately 22 km downstream of the Cut-away dike and just upstream of Perron Falls, a new river path was created during the 1996 flood. The available initial cross sections are along the old riverbed, and the available postflood cross sections are along the new river path. Hence, in this zone, the preflood cross sections of Capart et al. (2007) are not the right ones to use for the simulations. Once this river zone is excluded, only the upper reach, 8.4 km long, can be modeled.

4.2 Longitudinal profile

Figure 8 shows the initial, simulated and observed final longitudinal profiles. UMHYSER-1D captures the trends of erosion and deposition well, although the simulated profile underestimates erosion for almost the whole river reach, except at the first cross section and the last 1.2 km (Figure 9). For the first cross section, the predicted thalweg is 1.5 m (12%) deeper than the observed one.

4.3 Evolution of the cross sections

Figures 10 to 14 show examples of simulated and measured cross sections after the flood passage. Using UMHYSER-1D, the trends of cross sections' evolution are well captured, although the erosion is underestimated for all the cross sections except those of the last 1.2 km. Note from Figure 11, the unusual shape of the observed final cross section where the right riverbank experienced sediment deposition of more than 40 m.

5 Conclusion

Several river systems could suffer extensive catastrophic floods in the event of a dam break. This paper presents UMHYSER-1D, a newly developed one-dimensional hydromorphodynamic model that solves the de Saint-Venant equations, the sediment Exner equation and a convection-diffusion equation for suspended sediments. The model handles subcritical and supercritical regimes and cohesive and noncohesive sediments. Moreover, UMHYSER-1D allows modeling of a single natural channel or multichannel looped networks with different types of internal boundaries. Applied to the Ha! Ha! River (Quebec, Canada) for the 1996 flood, UMHYSER-1D predicts the trends in the river changes well. Furthermore, based on a set of simulations, a doubt was raised about the quality of the cross sections used along a reach of 3 km. This question was confirmed after finding evidence in the literature that the Ha! Ha! River overflowed from its original channel to a secondary valley just before Perron Falls. Thus, the original cross sections used cannot be considered as they belong to the old river path and do not cover the secondary valley where the postflood river flows. Although UMHYSER-1D captures the main features by predicting the evolution trends of the longitudinal river profile and cross sections, the numerical results are not in full agreement with the observations. Several reasons can explain this shortcoming. First, UMHYSER-1D is a one-dimensional model based on the de Saint-Venant equations, which assume small bed slopes and neglect vertical accelerations. Second, the sediment transport equations used in the model are developed under quasi-uniform and steady flow conditions with small water velocities, which was not the case during the 1996 Ha! Ha! River flooding. Finally, several assumptions were used for the input data: some cross sections had bizarre shapes, a single gradation curve was used for the entire river reach with a single roughness coefficient, and debris flows were ignored. Indeed, after the breaching of the Cut-away dike, water flowed in a forest, and a new channel was created after trees were uprooted. UMHYSER-1D was used in an extremely complicated case and was able to predict the trends of deposition/erosion using simplified assumptions for the input data. Knowing the different sources of sediment transport uncertainty, the performance of UMHYSER-1D is encouraging. The application of UMHYSER-1D to the 1996 Ha! Ha! River flooding shows the capabilities of this model and predicts its promising role in real engineering cases.

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Figures Captions

Figure 1. Location map showing Ha !Ha! River and the Ha! Ha! Reservoir (Brooks and Lawrence, 1999).

Figure 2. Study area: reach of 8.4 km downstream of the Ha! Ha! Lake (modified after Couture and Evans, 2000 and El Kadi and Paquier, 2004)

Figure 3. Longitudinal river profiles: (a) evenly spaced valley cross-sections, numerals in km indicat distance from breached dyke; (b) width changes induced by the flood (pre-flood and post-flood corridors); and (c) elevation data: pre-flood thalweg profile (thin line), post-flood thalweg profile (thick line), surveyed high-water marks (dots), and reconstructed bedrock surface (grey); (Capart et al., 2007)

Figure 4. Outflow discharge hydrograph (Mahdi and Marche, 2003).

Figure 5. Sediment particle size distribution (Mahdi and Marche, 2003)

Figure 6. Example of an invalid initial cross-section: cross-section 263 from Capart et al. (2007).

Figure 7. Example of observed and simulated thalwegs.

Figure 8. Initial, observed and simulated longitudinal profiles.

Figure 9. Difference between simulated and observed erosion.

Figure 10. Simulated and observed first cross-section (0 km).

Figure 11. Simulated and observed cross-section 23 (2.2 km from upstream).

Figure 12. Simulated and observed cross-section 42 (4.1 km from upstream).

Figure 13. Simulated and observed cross-section 62 (6.8 km from upstream).

Figure 14. Simulated and observed last cross-section (8.4 km from upstream)

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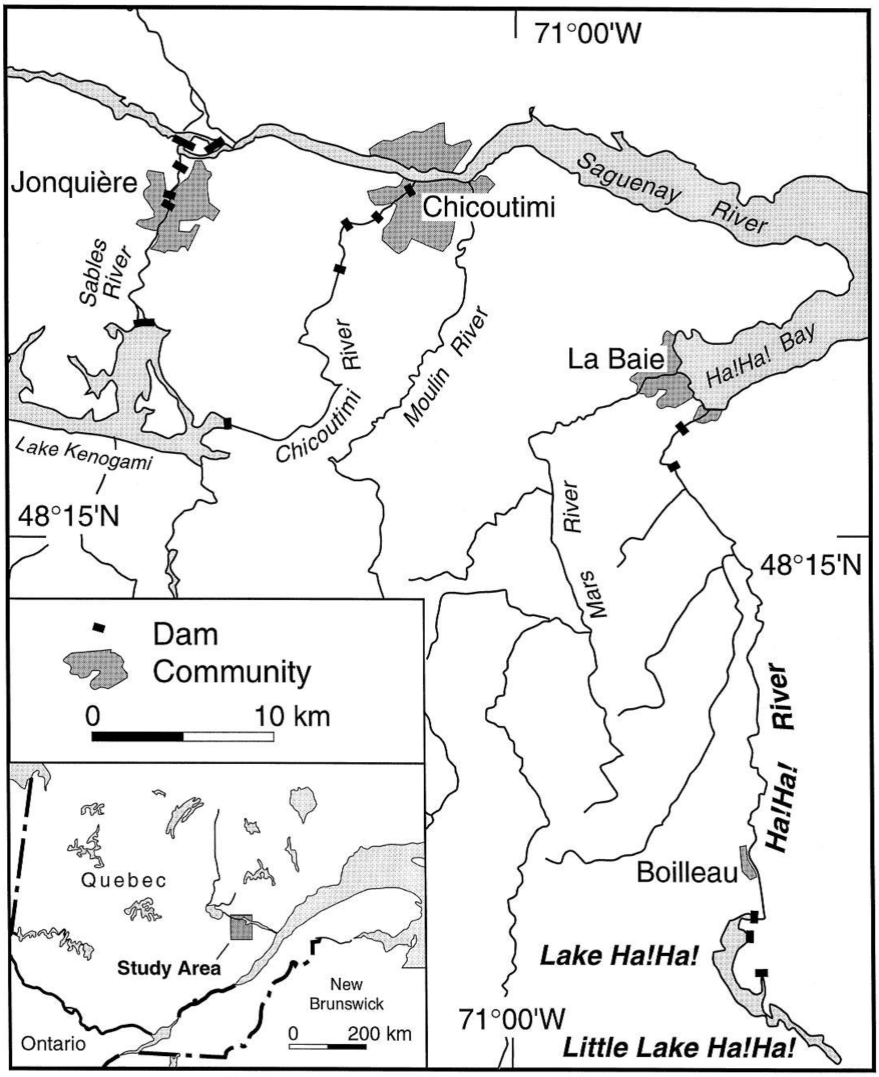

415 Figure 1.

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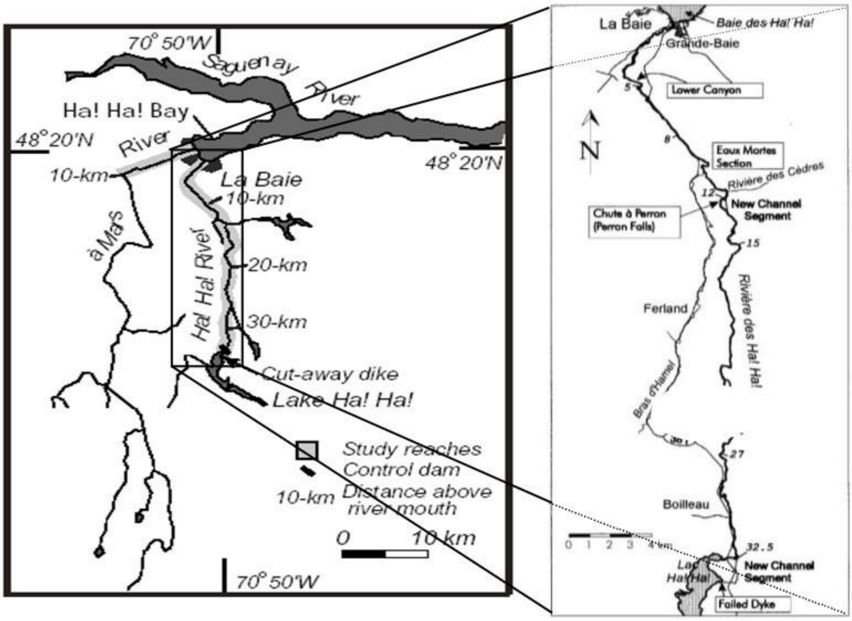

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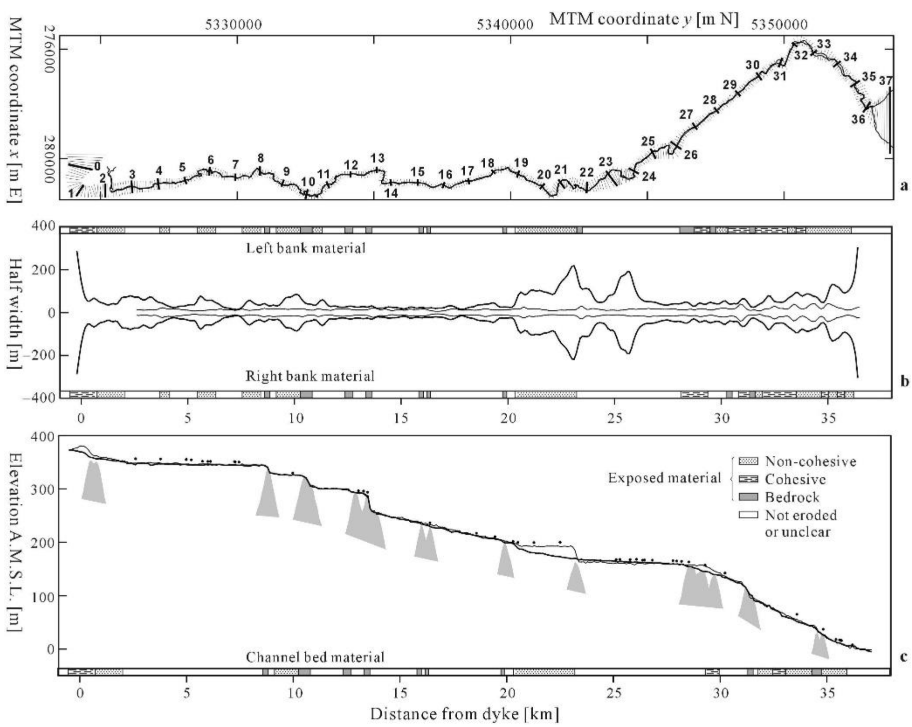

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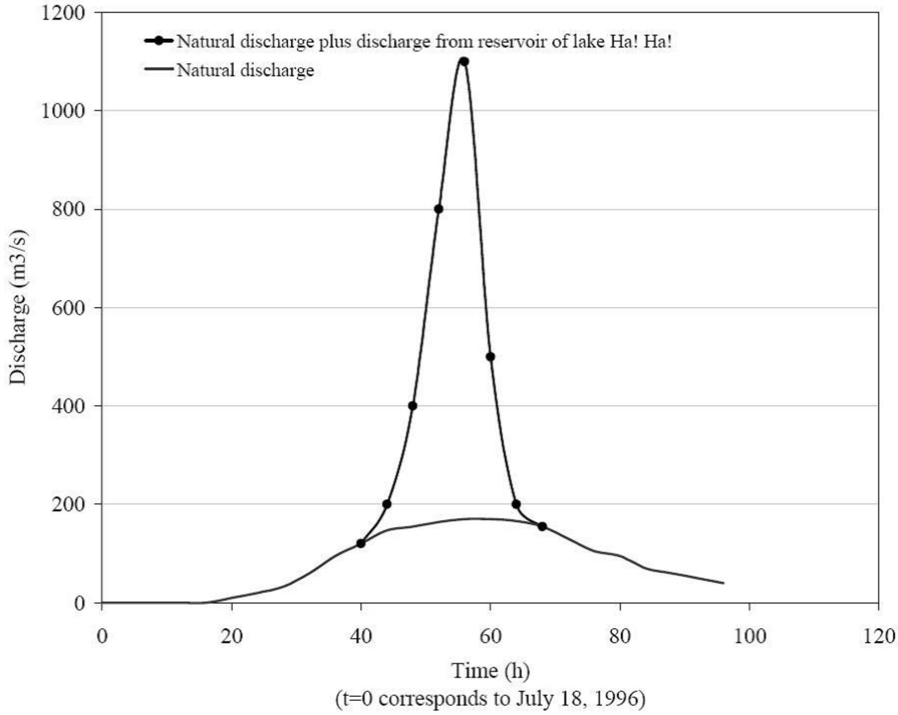

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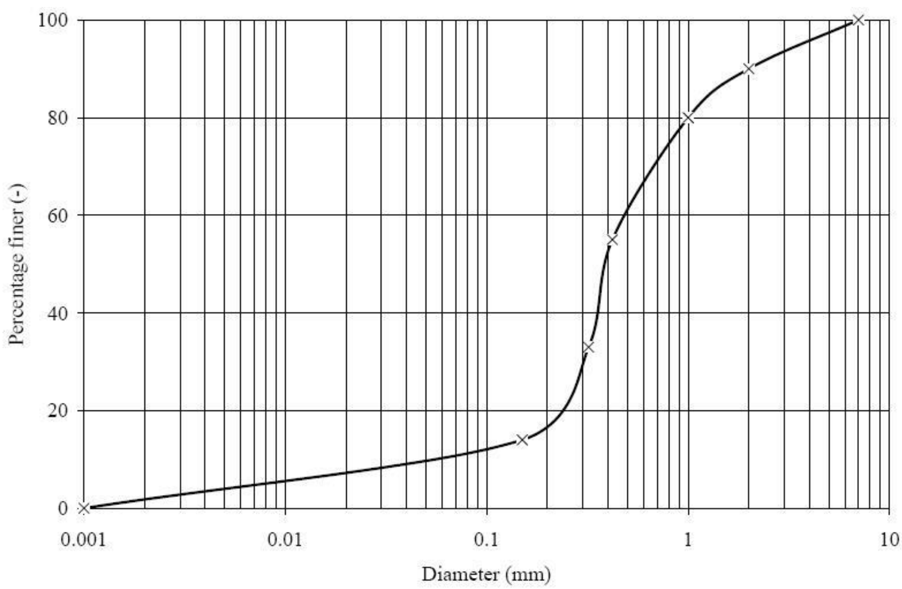

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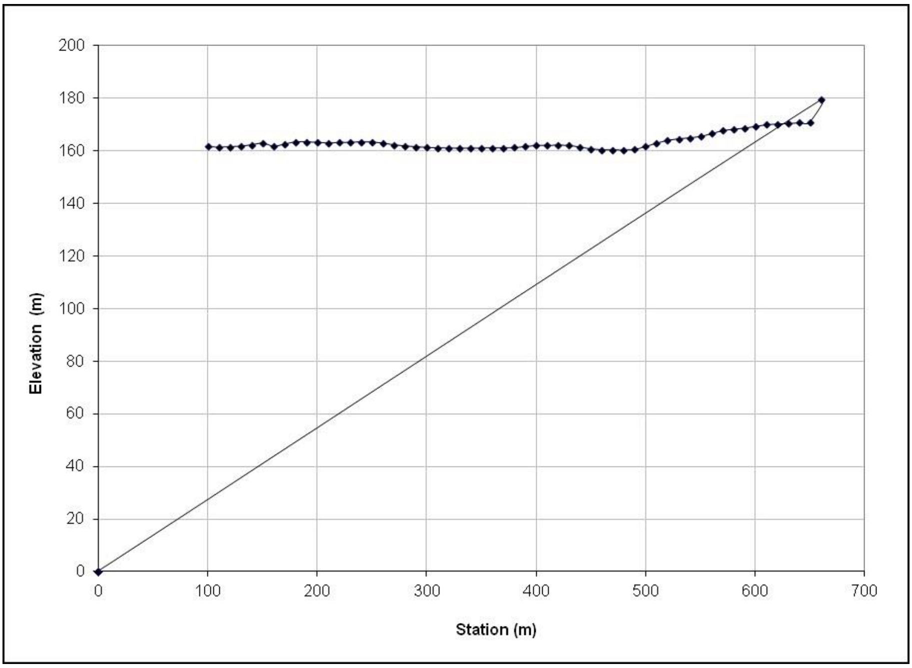

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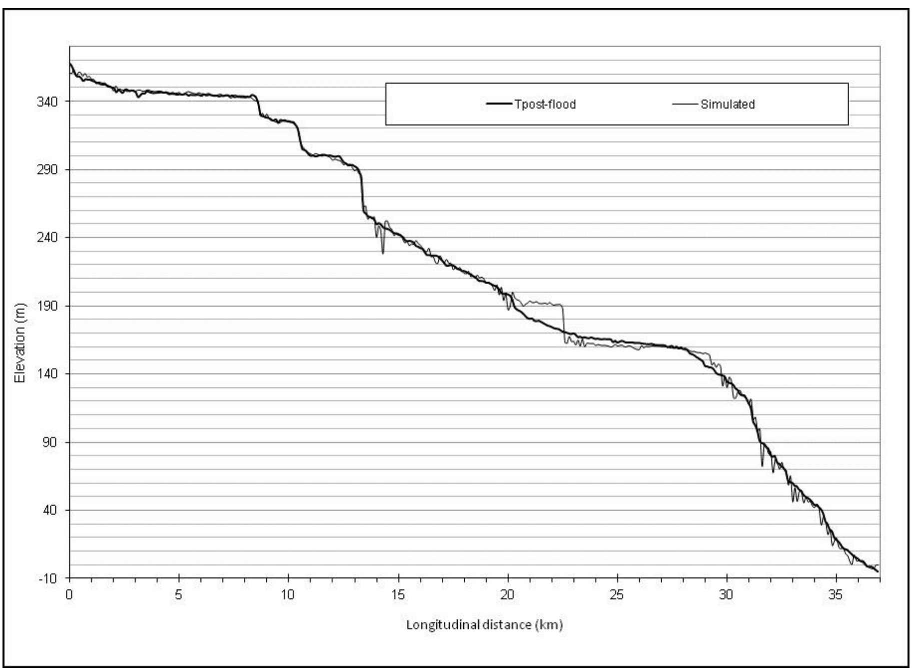

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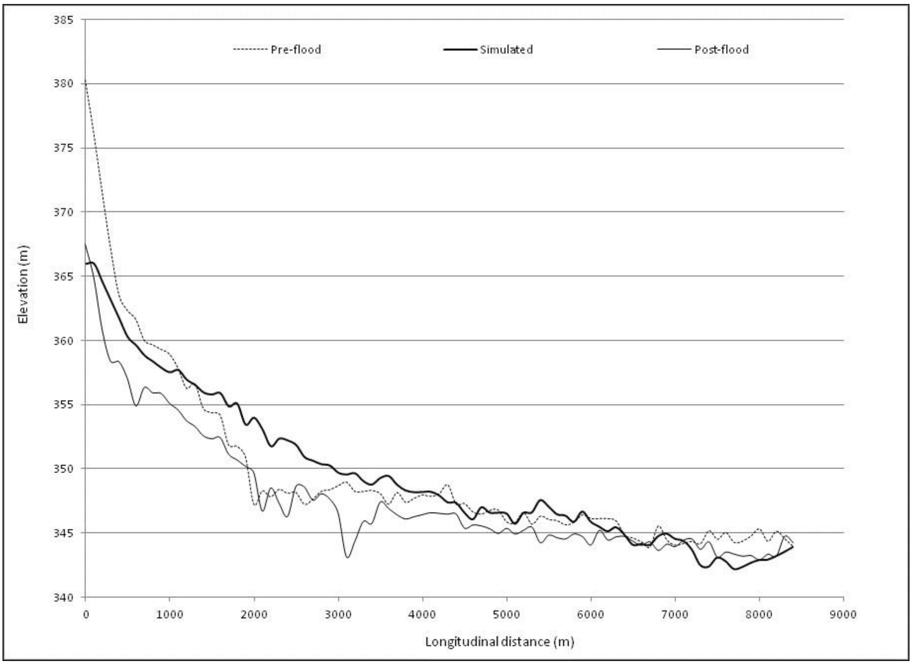
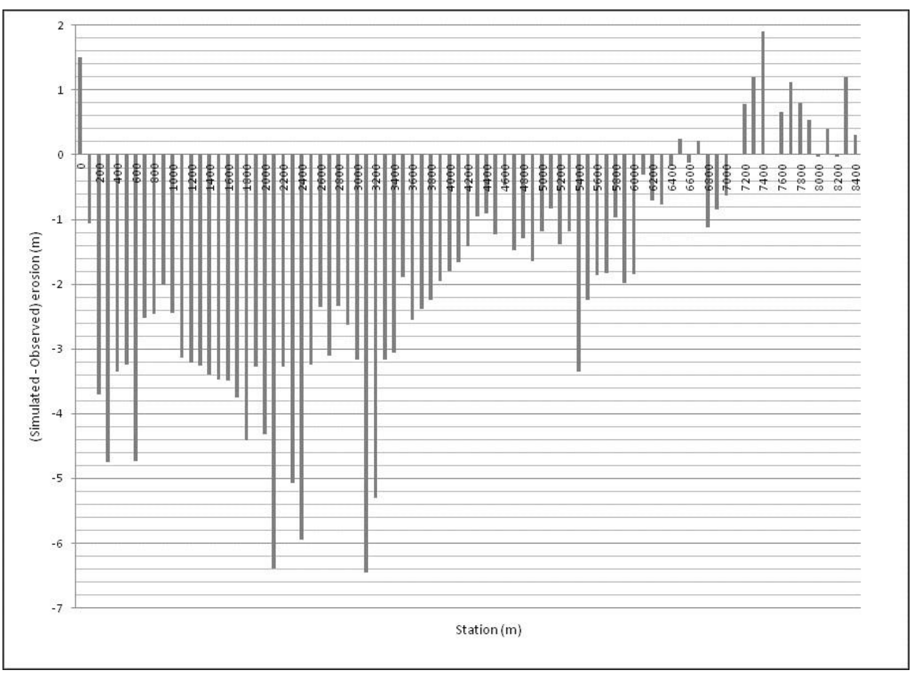


Figure 8



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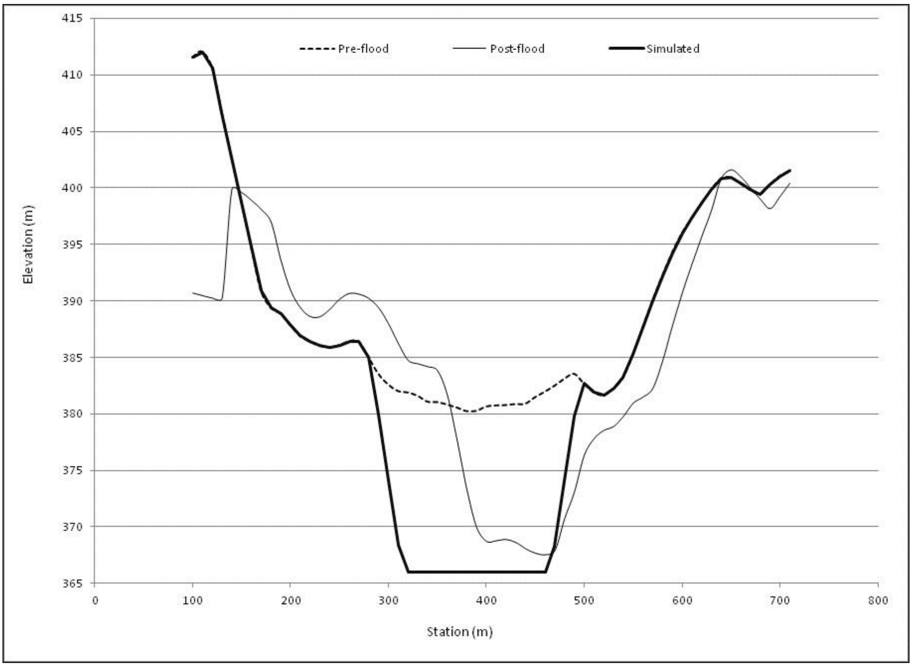
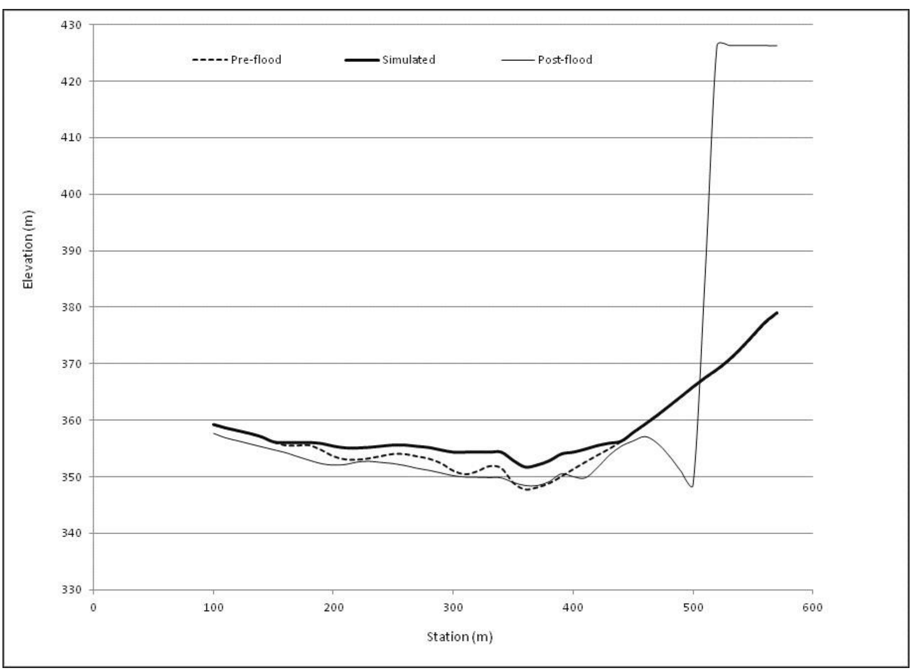


Figure 10



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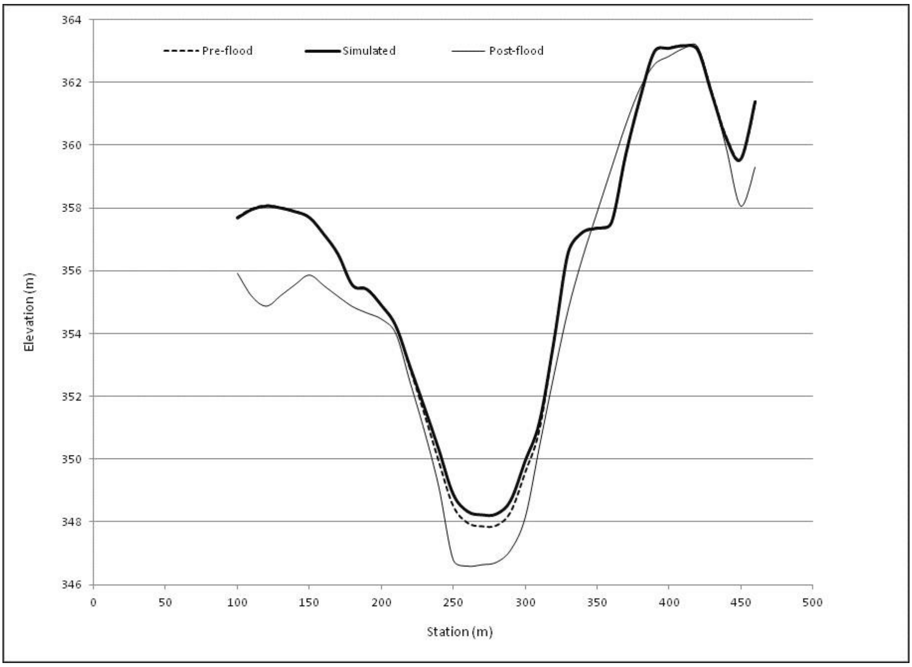

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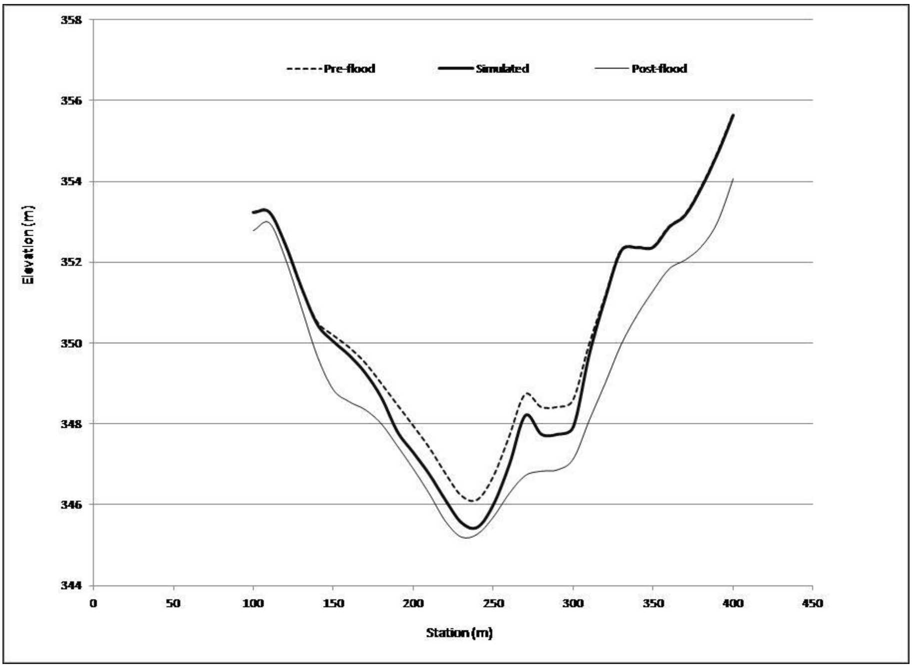

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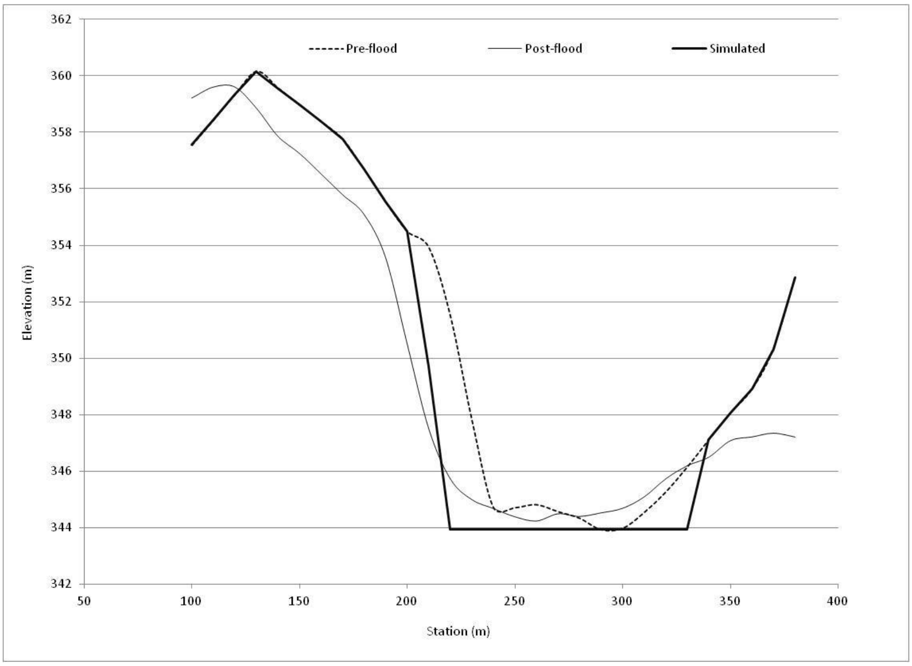
Pre-flood
Post-flood
Simulated
Elevation (m)
Station (m)
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Figure14