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Technical Note

Estimating Flooding at River Spree Floodplain Using HEC-RAS Simulation

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Abstract: River renaturation can be an effective management method for restoring the floodplain's natural capacity and minimizing the effects during high flow periods. A 1D-2D HEC-RAS model, in which the flood plain was considered as 2D and the main channel as 1D, was used to simulate flooding in the restored reach of the Spree River, Germany. When computing in this model, finite volume and finite difference approximations using the Preissmann approach are used for the 1D and 2D models, respectively. To comprehend the sensitivity of the parameters and model, several scenarios were simulated using different time steps and grid sizes. Additionally, dykes, dredging, and changes to the vegetation pattern have been used to simulate flood mitigation measures. The model predicted that flooding would occur mostly in the downstream portion of the channel in the majority of the scenarios without mitigation measures, whereas with mitigation measures, flooding in the floodplain would be greatly reduced. By preserving the natural balance on the channel's floodplain, the restored area needs to be kept in good condition. Therefore, mitigating measures that balance the area's economic and environmental aspects must be considered in light of the potential for floods.

Keywords: 2D floodplain modeling; HEC-RAS; River Renaturation; finite difference approximation

1. Introduction

Naturally, rivers show dynamic behavior that results in alteration of its morphology over time. However, this is a slow process that gives the river time to adjust to its new status while maintaining its capability. On the other hand, things are different when there is artificial manipulation of river and its surrounding areas [1-2]. One of such example is the Spree River in Germany. Over the years, the river was changed for the navigation purpose [3]. The river was straightened, and dikes were constructed along the river stretch. This led to a decrease in the flood retention areas and as a result the river could not cope naturally with the high-water conditions. Flood is a condition when the water reaches a high level in the river and overtops the banks deviating from its natural course and causing inundation in the floodplains. One of the main reasons of flooding is when the river cannot route the incoming water due to low conveyance capacity [4-7]. It is one of the great natural disasters causing the destruction of anything on its way. This has been evident from history when the flood in various parts of the world caused great destruction of life and property leading to about two-thirds of destruction in terms of number and economic loss[8-9]. These are generally a natural phenomena but the impacts and effects can be exacerbated by human interventions.

A Floodplain is an area of low-lying ground adjacent to a stream or river which stretches from the bank of its channel to the base of enclosing valley walls, and which experiences flooding during the period of high discharge [6–13]. Floodplains are formed as the rivers erode their own banks. As the river flows, it washes material downstream of the bank, and when a flood occurs, this material or sediment largely composed of a layer of silt, sand, and mud, is suspended in water, and added to the floodplain [14-17]. Floodplains constitutes a valuable part of the environment as they filter, store, and release floodwaters, recharge aquifers, store a variety of sediments, and also provide a habitat for a diversity of wildlife [18-22]. Floodplain soils absorb water during the wet season, then slowly release moisture to plants and into the streams. This lessen the impact of peak runoff and keeps plants growing and streams flowing longer in to the dry season. Also, the streambank vegetation helps to cool the surface water temperature, and create important habitat for fish, waterfowl, and other wildlife species. River renaturation can be helpful to some extent in the flood reduction in the floodplain. A study carried out in Floha river in the border of Germany and Czech Republic showed that the afforestation in the floodplain reduced the peak flow by 4% than when applied on barren floodplain [23-25]. Though this study did not show a significant impact of renaturation on the flood reduction and may not be a major tool for flood defense, these method contributes on management of flood.

The impacts of flood and the significance of floodplains to maintain the naturality of rivers made it necessary to carry out studies to understand the behavior of river systems for its better management. The concept of river models started during 1970s and later on hydraulic models for rivers, channels and pipe systems emerged during the 1980s for flow prediction, finding the travel time and water level variations in rivers, channels and canal systems. In simple terms, modeling is a process of creating a simulation of reality by different computational process in order to understand the complex phenomena of nature. These days modeling has been an important aspect in every field of research, water resources being one of them. The governing equations is generally same for most of the models but the approach will vary depending on the research topic. The purpose of the study is to simulation of 2-D flooded area (clear water) for the entire reach (about 11 km), sensitivity analysis on time step and grid dimensions and management strategies to reduce the flood risk. This study provide opportunity to apply the HEC-RAS code to simulate flooding events after the main restoration measures and to gain a greater understanding of the theoretical basis and practical application of two-dimensional floodplain modeling. The objectives of this project are accomplished by simulation of two dimensional model for different flooding scenario in the entire reach along with implementation of some flood reduction strategies.

2. Literature Review

2.1. Hydraulic Modeling

The dynamics of river has been assessed using various techniques over the years. Hydraulic model has been developed as a means of simulating flooding events to understand their potential effects and come up with a feasible solution. Conventionally, 1D models were used as a means of modeling the flood events. This approach provides a reasonable results for the flow within the channel even though it is one dimensional and assumes uniform velocity and consistent water level across the cross section [26]. It should also be taken into account that the lateral movement of flooding in the river with complex topography is not addressed through this approach. On the other hand, 2D models are structured in a way where the lateral flow over the floodplains can also be modeled even though the computational process might be more complex. The irregular topography in the rivers leads to a mixed flow regime which leads to complex computation due to wider range of boundary and initial conditions to be considered [27-29]. Any model is a function of the underlying governing equations which are solved using numerical approximations. The first stage of any model is the preparation of the base such as schematics of the river (geometry) which is basically created by interconnecting nodes and allocating the upstream and downstream boundaries for the river section under study. The computation of parameters are done in these nodes. It should be noted that not all the nodes correspond with the available cross section measurements and interpolations are carried out in nodes where the data for cross sections are not available. Among the various hydraulic modelling tools, HEC-RAS is one of the widely used tools and it has been explained in the section below.

2.2. Modeling in HEC-RAS

Hydraulic Engineering Center's River Analysis System (HEC-RAS) is a software developed by the US Army Corps of Engineers [30-32]. This software provides a wide range of applications in the area of water resource management such as steady and unsteady flow simulations, sediment transport as well as water quality analysis. Initially the unsteady flow was only capable to 1D analysis, but the developers installed a new feature in the system for the 2D flow analysis in Rivers. The overview of the components of HEC-RAS has been described in the following section.

The geometry in 1D and 2D model is created in a different manner. In 1D, the geometry is basically described by the connectivity between river reach cross section data and the hydraulic structures. The division between main channel and the floodplain is done by using different roughness coefficient for the cross sections. In case of 2D model, the main channel has a 1D geometry whereas the floodplain has geometry as a computational mesh created by interconnecting cells with no more than 8 faces. The mesh is connected to the 1D channel and the boundary condition by connecting the cell points to the cell 1D structure. The flow between the faces is calculated during the computation and a single water depth for each cell is calculated.

HEC-RAS uses the St. Venant Shallow Water Equations as basis for the analysis of the flow in the rivers. Both 1D and 2D unsteady flow works on the basis of conservation of mass (Continuity Equation) and momentum (Momentum Equation). The computations are carried out through Preissmann Scheme using Finite Difference Method [33, 34]. The governing equations for each of the 1D and 2D flow has been described in the following sections.

The continuity equation for 1D flow is written as:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} + q = 0 \tag{1}$$

where, Q is the flow rate, A is the cross-sectional area and q is the lateral inflow.

The momentum equation for the 1D flow is given as:

$$\frac{\partial v}{\partial t} + g\frac{\partial}{\partial x}\left(\frac{v^2}{2g} + h\right) = g\left(S_0 - S_f\right) \tag{2}$$

where, v is the velocity, g is the gravitational acceleration, h is the water depth, S_0 is the bed slope and S_f is the friction slope.

The continuity equation for 2D flow is written as:

$$\frac{\partial H}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} + q = 0 \tag{3}$$

where H is the water surface elevation, h is the water depth, u and v are the depth averaged velocities in the x- and y-direction, and q is the source term

The momentum equation for the 2D flow is given as:

- In x-direction:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial H}{\partial x} + \nu_t\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - c_f u + fv \tag{4}$$

- In y-direction:

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial H}{\partial y} + \nu_t\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - c_f v + fu \tag{5}$$

where H is the water surface elevation, h is the water depth, u and v are the depth averaged velocities in the x- and y-direction, ν_t is the eddy viscosity coefficient, c_f is the friction coefficient, f is the Coriolis parameter. In the above equations, the first term denotes the local acceleration and the second and third term denotes the convective acceleration, and the remaining terms denotes the forces due to gravity, eddy viscosity, bed friction and Coriolis force respectively [35].

The friction coefficient can be determined by using the Manning's formula which is expressed as:

$$c_f = \frac{n^2 g|u|}{R^{\frac{4}{3}}} \tag{6}$$

Where n is Manning's n, g is the acceleration due to gravity, u the velocity in the x-direction and R the hydraulic radius. Combination of a hybrid discretization scheme with finite differences and finite volumes is used in HEC-RAS to take advantage of orthogonality in grids. Using a Newton-like solution technique. The discrete solution for the hydraulic equations is computed. A finite difference scheme expresses a derivative as the difference of two quantities. This technique has already been tacitly used in the equation mentioned below, to discretize the volume derivative in time as the difference of the volumes at times n and n+1 and divided by the time-step Δt.

$$\frac{\partial y}{\partial x} = \frac{\Omega(H^{n+1}) - \Omega(H^n)}{\Delta t} \tag{7}$$

Finite differences in space work identically. Given two adjacent cells j1 and j2 with water surface elevation H1 and H2 respectively, the directional derivative in the direction n′ determined by the cell centers is approximated by the equation mentioned below. (HEC-RAS). Δn′ is the distance between the cell centers.

$$\nabla H.n' = \frac{\partial H}{\partial n'} \approx \frac{H_2 - H_1}{\Delta n'} \tag{8}$$

Two methods of finite volume methods are used. The first is cell vertex and second is cell-centered. The cell vertex method uses a secondary mesh made up of a cell for every vertex. The HEC-RAS generate a new cell for every vertex by joining the centroids of the grid cell. The finite volume formulation is applied on these newly generated cells. The advantage of the cell vertex method is that the application of boundary condition becomes easy because the cell centroids lie on the boundaries.

2.2. Flood mitigation measures

The attempts of man to protect himself from flooding are as old as the history of civilization. Flood control measures may be divided into the engineering measures (e.g. the construction of reservoirs, dikes, diversion of flood flows, and improvement of river channel) or administrative measures (flood forecasting, flood plain zoning, and flood insurance) [36]. Storing flood water in the upstream part of a drainage basin is the most direct way to reduce the flood hazard in the downstream part of the basin. There are three places where water can be stored: in the ground, in small reservoirs on creeks and minor streams and in large reservoirs on the major stream channels of the river system.

The oldest, most common, and often most economical means of flooding protection is by constructing a system of dikes. Dikes should be kept at a good distance away from river channels. The very need for dikes indicates that we are probably dealing with an alluvial river flowing in a flood plain. Such rivers have a natural habit of continuously eroding their banks. The great hazard involved in a diking system is that it provides full protection up to a certain flood stage and no protection at all for higher stages. A long period of absence of extreme flood stages will create a feeling of security for inhabitants of dike-protected areas, leaving them unprepared for an eventual failure of the dike [31].

The most direct and effective way to cope with a flood situation is to take water away from the river channel. A primitive way of accomplishing this is to breach a dike on purpose, in an area where the resultant damage is relatively small, in order to save the dikes that protect another area where the damage would be relatively large. Some requirements are that the area into which the floodwaters are diverted is free of habitation. A diversion channel will be most effective in lowering water levels, if the diverted water can be taken away from the river, without returning it farther downstream. Dredging is the operation of removing material from one part of the water environment and relocating it to another [37-38]. The overall goal of most dredging activities is to reduce the extent of flooding and perform as a flood management tool. It is sometimes effective because nature always fills the riverbed with sediments. For this reason, for long-term solution, sometimes dredging is not a good concept. By increasing the channel roughness, flood can be mitigated. However, if the channel roughness is increased, some inferior ecological effects might be experienced.

3. Data and Methods

3.1. Study Area

The Spree River originates in the Lausatian Mountains in the border of Czech and Germany. It flows over a stretch of 380 km before meeting the Havel River in Berlin [39]. The study area includes approximately 11 km restored river reach of Spree River which is used to simulate flooding scenario using one and two dimensional hydrodynamic model. The study site is located approximately 10 km north (downstream) of Cottbus, near coal mining activities (Figure 1). The catchment area is about 62 km^2. The longitudinal gradient of the River reach is around 0.07%. The River has a mean discharge of 7.5 m³/s and a bankfull discharge of 35 m³/s [40-41].

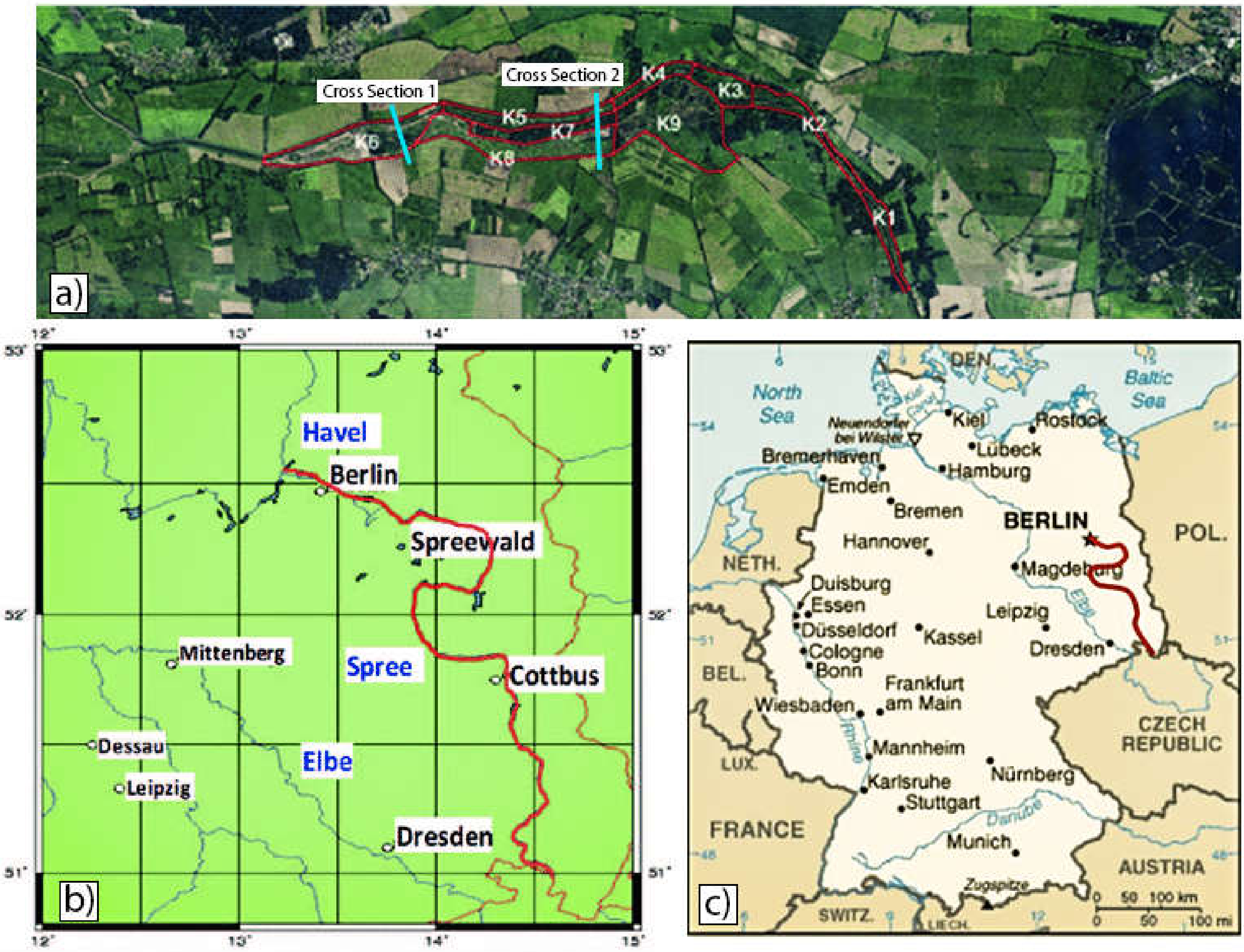

Figure 1. Satellite image of the area of study.

3.2. Renaturation Project

There had been a lot of manipulation in the Spree River over the years. The river was straightened, regulated and diked. On top of that agricultural lands were created by clearing out the forests along the river. This led to the deterioration of the natural structure of the area causing the fall in regenerative capacity as well as the ecological efficiency. In the previous times, the Spree River consisted of a widely branched river system with floodplain extending up to 5km which was changed due to the involvement of human to change the landscape for their benefit. Therefore, in order to reestablish the efficient natural environment in the river, various works was carried out over the period of 2006 to 2014.

3.3. 1D Unsteady Model

A unsteady simulation for the basic model is created with simulation window to be starting from 1st September to 31 October. Different time step was considered such as 1 s, 5 s, 10 s, 15 s etc. minute time step. Initial conditions was chosen as initial flow 14 m³/s at reach no. 58. There are four types of external boundary conditions that may be linked directly to the 2D Flow e.g., flow hydrograph, stage hydrograph, normal depth and rating curve. The Normal Depth and Rating Curve boundary conditions can only be used at locations where flow will leave the 2D Flow Area. The flow and stage hydrograph

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boundary conditions can be used for putting flow into or taking flow out of a 2D Flow Area. For a Flow Hydrograph, positive flow values will send flow into a 2D Flow Area, and negative flow values will take flow out of a 2D area. For the Stage Hydrograph, stages higher than the ground/water surface in a 2D Flow Area will send flow in, and stages lower than the water surface in the 2D Flow Area will send flow out. If a cell is dry and the stage boundary condition is lower than the 2D Flow Area cell minimum elevation, then no flow will transfer [35]. In this model (Figure 2), a flow hydrograph considered at upstream and normal depth considered at downstream as boundary condition. Friction slope of 0.0003 was considered to be in normal depth section as boundary condition at downstream cross section.

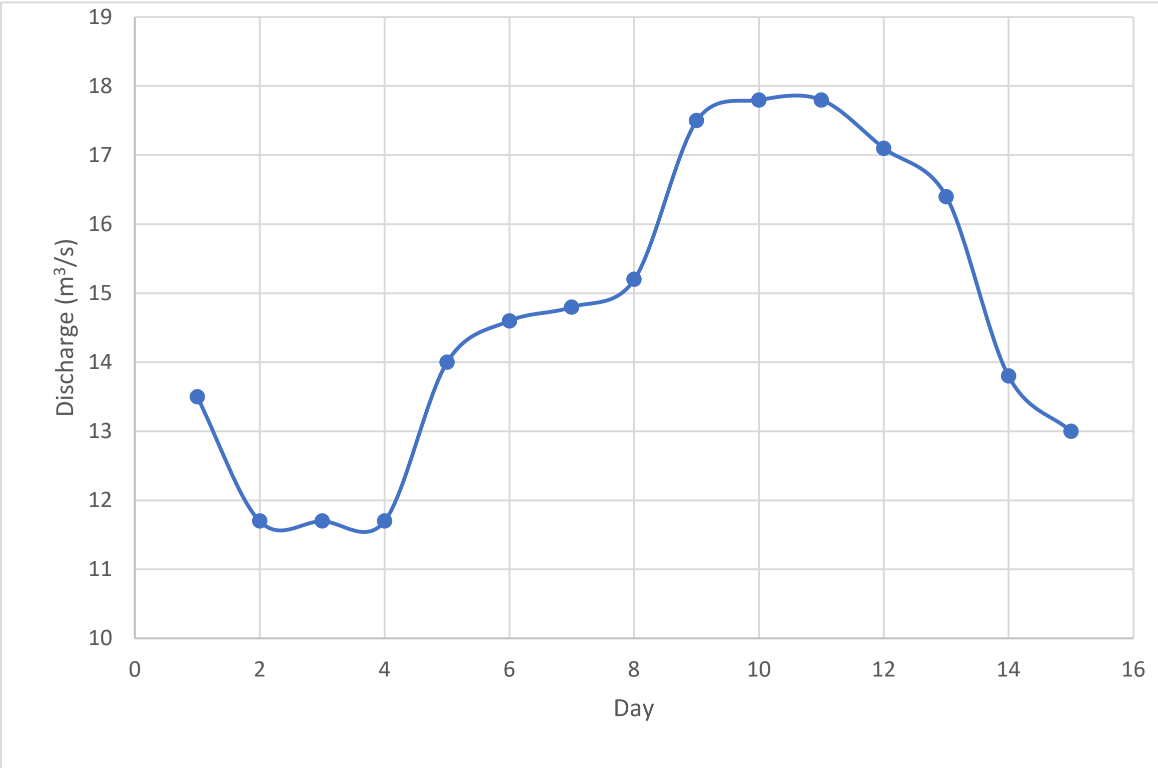

Figure 2. Flow hydrograph at upstream section shows time range of the maximum flow during the observed flood in September 2014.

3.3.1. Implementation of 2D floodplain model:

HEC-RAS 5.0 can perform simulation with 2D floodplain with desired mesh size. This chapter provides a detailed description for creating a 1D and 2D floodplain model using HEC-RAS for Spree river and the floodplain. The terrain data does not often include the actual channel bathymetry underneath the water surface. RAS Mapper now can modify the terrain data to include channel bathymetry by using the individual HEC-RAS cross-sections geometry and the cross section interpolation feature. The result from this step is to generate the channel terrain layer. The channel terrain layer is created by taking the channel bathymetry data from the cross sections and using the interpolation feature to interpolate an elevation for each grid cell between any two-cross sections.

3.3.2. 2D Flow Area Mesh

Main conception of 2D floodplain modeling is usage of a computational mesh. HEC-RAS uses an amalgamation of a finite-difference and a finite volume method to compute water elevation at the center of each computational cell for specific time step. 2D modeling features in HEC-RAS allow user to generate computational mesh. In the Geometric Data Editor, the modeler can specify the limits of the computational mesh that envelopes the channel itself plus any adjacent floodplain areas.

Spatial details describing the polygon can be defined with 2D Flow Area Editor button. Spatial details include the size of the individual 2D flow cells as well as Manning's roughness values for each cell. Manning's roughness values can be defined for specified land use using GIS techniques. After the spatial details of the computational mesh, then detailed information describing the computational grid including hydraulic property table can be generated. There are tolerance input boxes that allow the user to have some control of the 2D grid. Finally, boundary conditions at the upstream and downstream ends using must be defined [41-43].

3.3.3. Connecting a 2D Flow Area to a 1D River Reach with a Lateral Structure:

The 2D Flow Area elements can be connected to 1D elements in several ways: directly to the downstream end or the upstream end of a river reach; laterally to 1D river reaches using a Lateral (s); and/or directly to another 2D area or storage area using the SA/2D Area Connection. The process for connecting the 2D Flow Area to other hydraulic elements is accomplished in the HEC-RAS Geometric editor. 2D Flow Areas can be used to model areas behind levees or overbank flow by connecting a 1D river reach to the 2D area using a Lateral Structure. In general, Lateral Structure weir coefficients should be lower than typical values used for inline weirs. Additionally, when a lateral structure (i.e., weir equation) is being used to transfer flow from the river (1D region) to the floodplain (2D Flow Area), then the weir coefficients that are used need to be very low, or too much flow will be transferred. Below is a table (Table 1) of rough guidelines for Lateral weir coefficients under different conditions [44-47].

Table 1. Lateral weir coefficient.

What is being modeled with the Lateral Structure	Description	Range of Weir Coefficients
Levee/Roadway—3ft or higher above natural ground	Broad crested weir shape, flow over Levee/road acts like weir flow	1.5 to 2.6 (2.0 default) SI Units: 0.83 to 1.43
Levee/Roadway—1 to 3 ft elevated above ground	Broad Crested weir shape, flow over levee/road acts like weir flow, but becomes submerged easily.	1.0 to 2.0 SI Units: 0.55 to 1.1
Natural high ground barrier—1 to 3 ft high	Does not really act like a weir, but water must flow over high ground to get into 2D area.	0.5 to 1.0 SI Units: 0.28 to 0.55
Non elevated overbank terrain. Lat Structure not elevated above ground	Overland flow escaping the main river.	0.2 to 0.5 SI Units: 0.06 to 0.28

4. Results and Discussion

4.1. Sensitivity Analysis

Appropriate grid dimension and computational time step are very important to assess flooding in the 2D areas. The hydraulic modeling systems are powerful systems to choose spatial and time variables to the desired degree of accuracy (HEC-RAS manual) [44-47]. In this study, different computational time steps and grid sizes were analyzed to assess the flooding situation in the project area (Figure 3). The total project area is divided into six sub-floodplains (sub-reach) and a set of eight cells are selected to represent the response in the water depth due to the variation in time steps and grid size.

Figure 3 displays the project area with several cells for comparing flood depth at various time steps. Quantification of flood depth in HEC-RAS is substantially sensitive to the computational time step which is a crucial parameter in numerical discretization of the computational domain and computational efficiency. Eight computational cells are chosen to show the sensitivity of varying computational time steps in the Table 2.

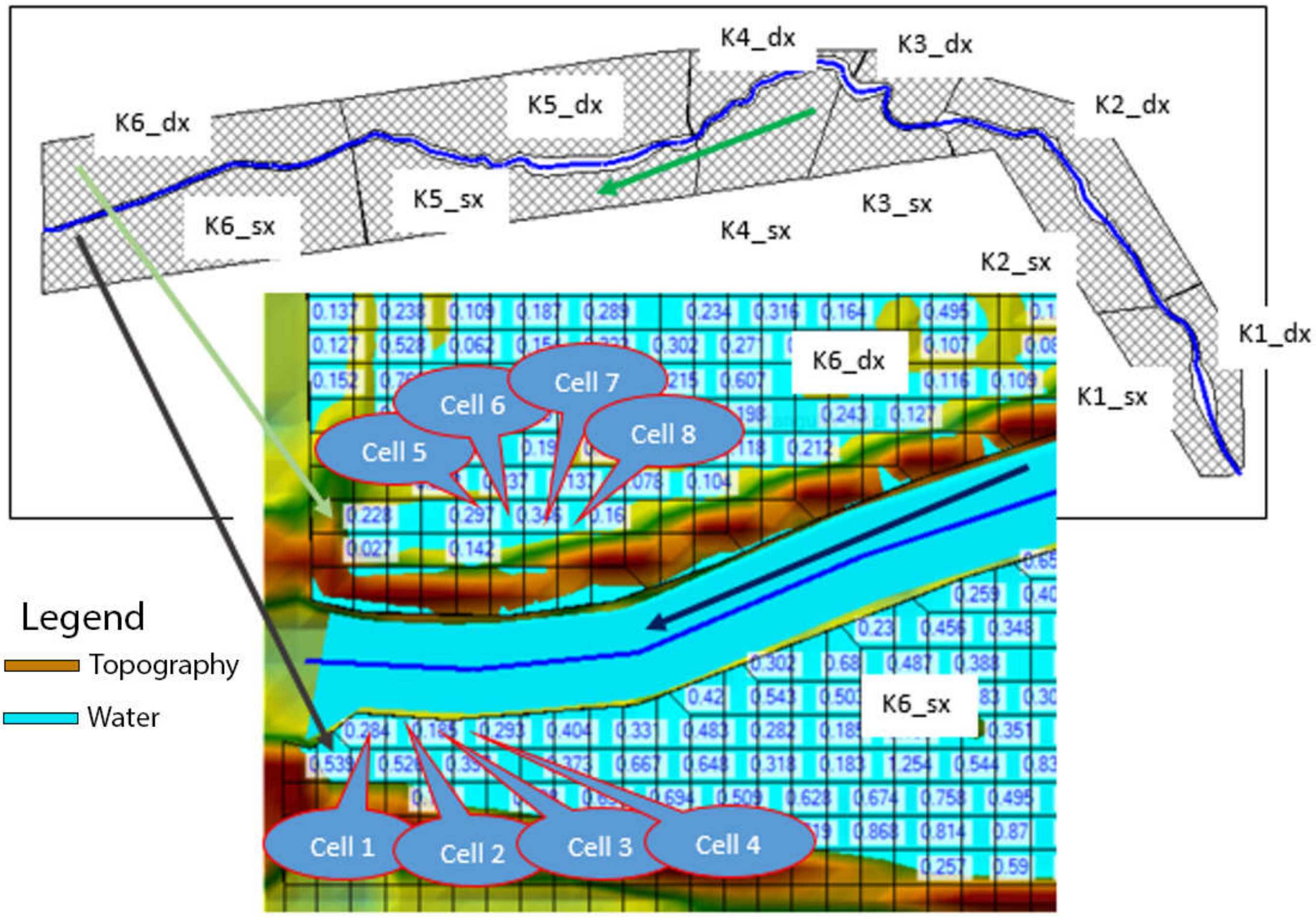

Figure 3. Project area showing different cells for flood depth comparison in different time step.

4.2. Computational Time Step

For the sub-reach K6, flood was calculated in some specific area for different time step, following table (Table 2) shows comparison of flood depth. Table shows the change in the flood depth at the set of selected cells (Figure 3) with the change in computational time step. Figure 4 and 5 shows the response in flood depth with increasing time step. For all cells, the variation takes a parabolic shape where a certain maximum flood depth has been reached (at time step 6s). The range of variation of flood depth is found to be 0.99 to 1.37 m. Corresponding time step of highest flood depth i.e., 6s can be considered in design purpose to be on the safe side. Computational times step is directly linked to the Courant number for stability and accuracy of unsteady model. Time steps are chosen confirming the courant number to be less than unity for numerical stability.

Table 2. Maximum flood depth value in different cells for certain time steps in sub-reach K6.

Time Step (s)	**Cell1**	**Cell2**	**Cell3**	**Cell4**	**Cell5**	**Cell6**	**Cell7**	**Cell8**
	Flood Depth (m)							
1	1.36	1.10	1.00	1.20	0.37	0.30	0.26	0.20
5	1.43	1.17	1.06	1.27	0.19	0.12	0.1	0.07
6	1.44	1.18	1.07	1.28	0.14	0.08	0.06	0.05
10	1.44	1.18	1.07	1.28	0.14	0.08	0.06	0.05
15	1.38	1.12	1.01	1.22	0.47	0.38	0.34	0.28

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Figures 4 and 5 illustrate the relationship between time step and flood depth at the cell in the floodplain. Both figure shows the impact of computational time step over the flood depth at the computational cells.

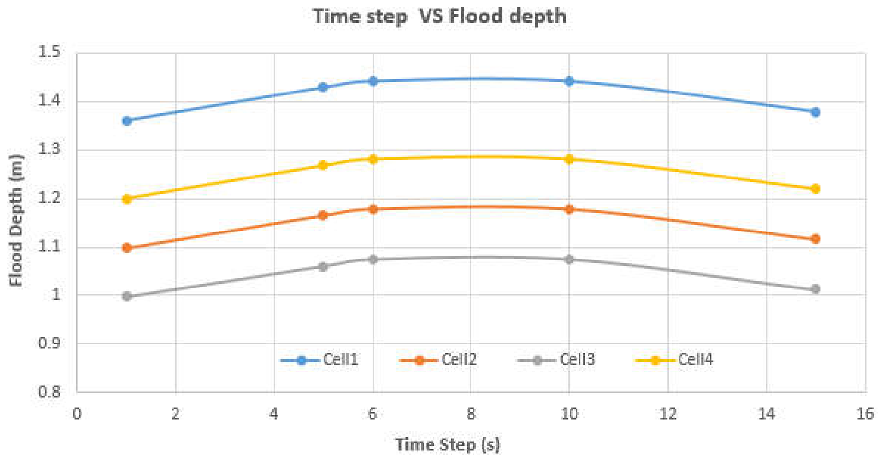

Figure 4. Graph shows relation between time step and flood depth at 4 (Cell 1-4) indicated cell in the floodplain.

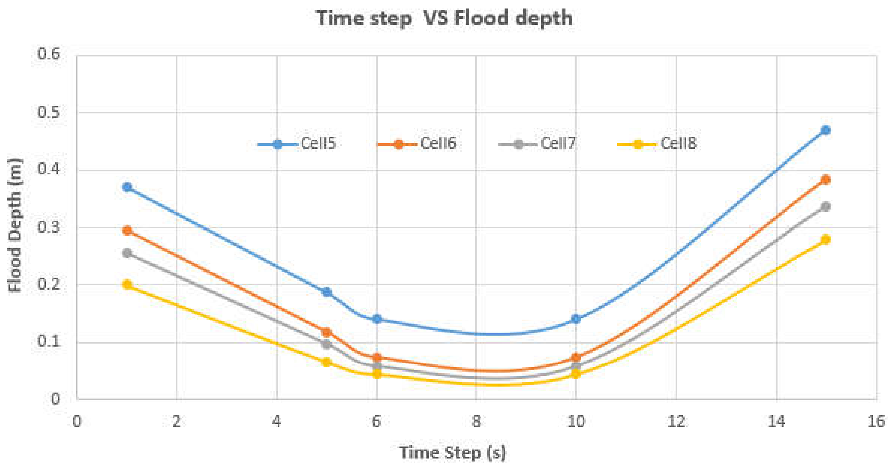

Figure 5. Change of maximum flood depth value (Cell 5-8) for different time steps in sub-reach K6.

For the sub-reach K6, flood was calculated in some specific area for different cross-sections, following table (Table 3) shows comparison of flood depth.

Table 3. Maximum flood depth value in different cells for certain cross-sections in sub-reach K6.

Cross-Sections	Cell1	Cell2	Cell3	Cell4	Cell5	Cell6	Cell7	Cell8
	Flood Depth (m)							
10	1.49	1.23	1.12	1.33	0.21	0.25	0.28	0.24
20	1.39	1.12	1.02	1.23	0.48	0.40	0.35	0.29
50	1.39	1.11	1.02	1.23	0.79	0.72	0.06	0.68

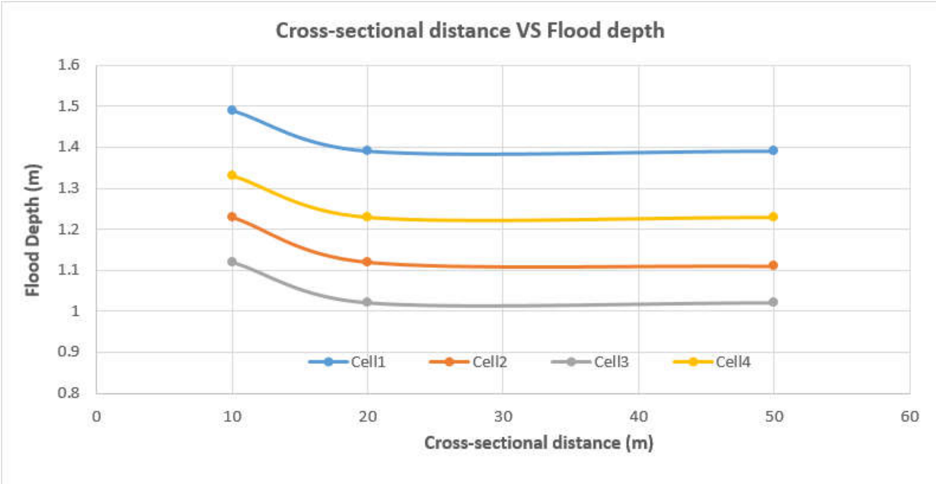

Figure 6. Change of maximum flood depth value (Cell 1-4) for different cross-sectional distances in sub-reach K6.

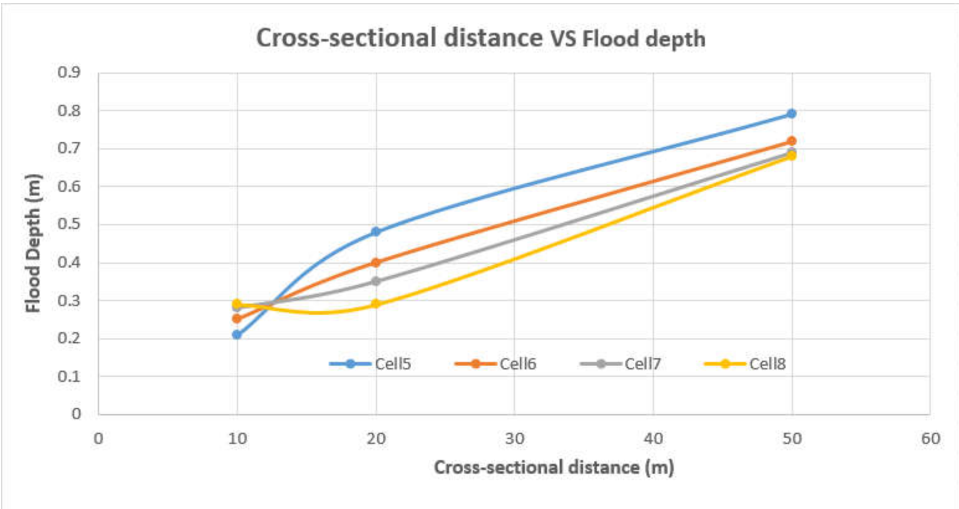

Figure 7. Change of maximum flood depth value (Cell 5-8) for different cross-sectional distances in sub-reach K6.

For the sub-reach K6, flood was calculated in some specific area for different Manning's n value, following table (Table 4) shows comparison of flood depth.

Table 4. Maximum flood depth value in different cells for certain cross-sections in sub-reach K6 (varying Manning's n value).

<table>
<tr><th rowspan="2">Manning's n</th><th>Cell1</th><th>Cell2</th><th>Cell3</th><th>Cell4</th><th>Cell5</th><th>Cell6</th><th>Cell7</th><th>Cell8</th></tr>
<tr><th colspan="8">Flood Depth (m)</th></tr>
<tr><td>0.030</td><td>1.02</td><td>0.76</td><td>0.65</td><td>0.85</td><td colspan="4">0</td></tr>
<tr><td>0.035</td><td>1.45</td><td>1.19</td><td>1.09</td><td>1.29</td><td>0.44</td><td>0.36</td><td>0.31</td><td>0.25</td></tr>
<tr><td>0.040</td><td>1.50</td><td>1.24</td><td>1.13</td><td>1.34</td><td>1.32</td><td>1.25</td><td>1.21</td><td>1.15</td></tr>
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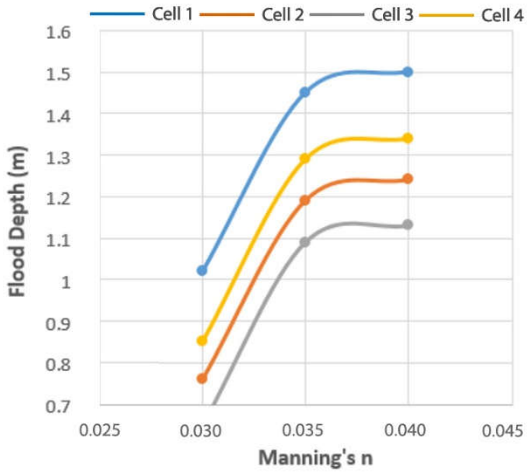


Figure 8. Change of maximum flood depth (Cell 1-4) value for different Manning's n in sub-reach K6.

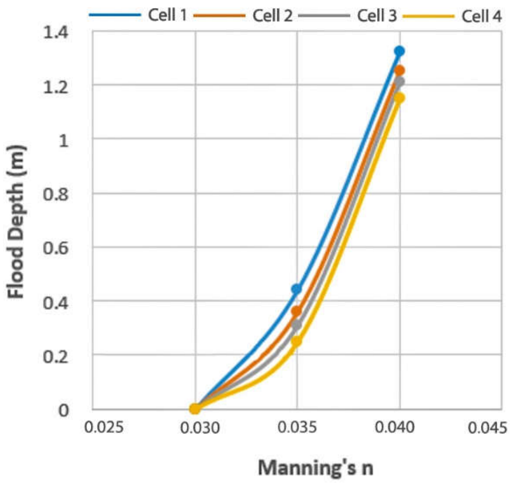


Figure 9. Change of maximum flood depth (Cell 5-8) value for different Manning's n in sub-reach K6.

4.3. Flood Management Strategy

Dredging and dike construction were carried out in different flood prone locations along the Spree River to create a greater depth of water and to regulate water levels respectively with the main objective to prevent flood. At certain locations, riverbed was dredged approximately 0.3m to 0.7m and dikes were constructed on the riverbank with a height of nearly 1m to 3m. Table 5 represents the detail of dredging and dike construction.

Table 5. Detail of dredging and dike construction along the river Spree.

River Station	Reach Length (m)	Cross Section Number	Dredging (0.3m-0.7 m)	Dike (1m-3m)
1-3.4615	1456.772	1,2,3	0.7	3
7.0182-9	600	7,8,9	0.7	3
10.333-11.250	40	10,11	0.7	3
14.286-15.367	271.774	14,15	0.65	3
16.667-18	67.05	16,17,18	0.65	2.5
23.854-25.2	141.149	24	0.6	2.5
26-26.396	215.706	26	0.35	2
35.818-36.143	37.589	36	0.35	2
37.415-39	279.575	38	0.35	2
42-42.086	35.179	42	0.3	1
47.705-49.667	322.777	48,49	0.3	1
50.25-51.4	155.6	50	0.3	1

- Case 1: Dredging (Table 6,7)

Table 6. Comparison of water stage between base scenario and after dredging scenario for different cross-sections. The locations of the cross-sections can be found in the Figure 1.

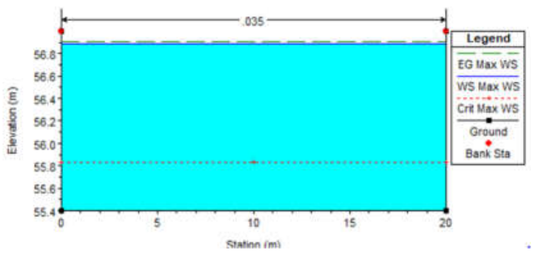
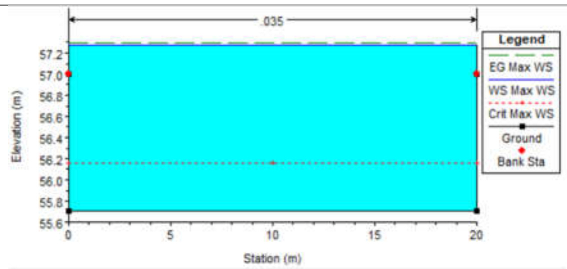
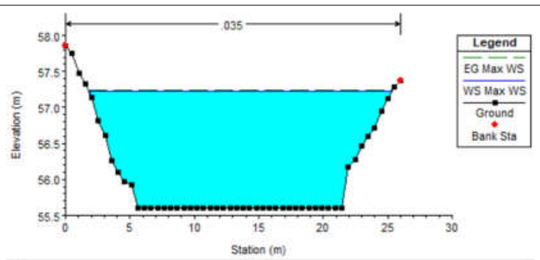
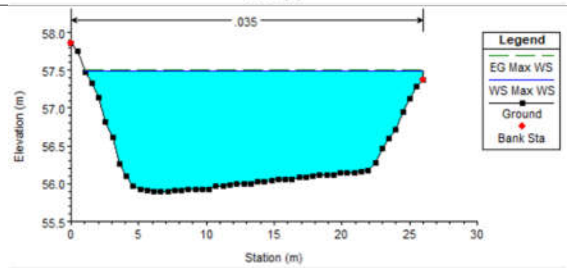
<table>
<tr><th>Cross-section no.</th><th>Scenario 1 (after Dredging)</th><th>Base Scenario</th></tr>
<tr><td>1</td><td>
</td><td>
</td></tr>
<tr><td>3</td><td>
</td><td>
</td></tr>
</table>

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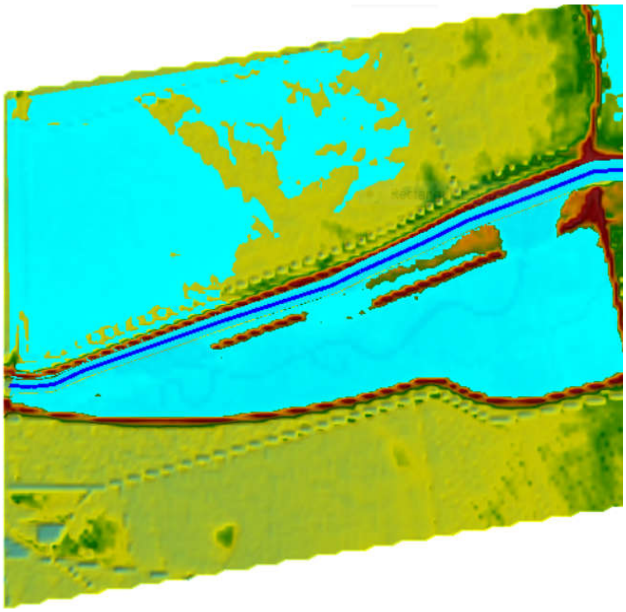
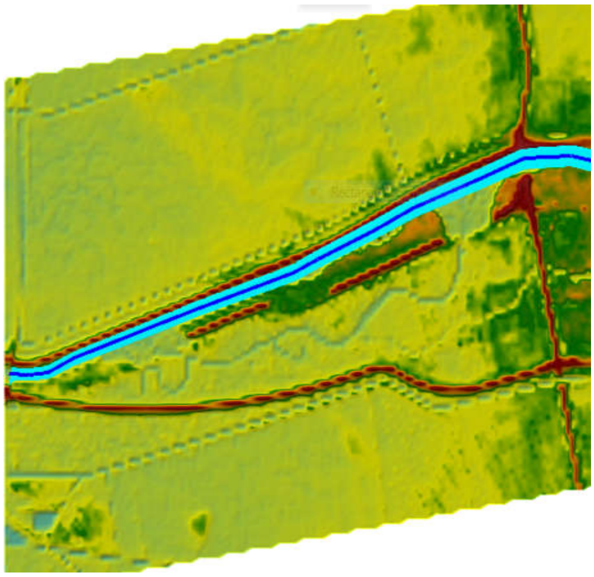
Table 7. Comparison of floodplain inundation between base scenario and after dredging scenario for sub-reach K6.

<table>
<tr><th>Base Scenario</th><th>Scenario 1 (after Dredging)</th></tr>
<tr><td></td><td></td></tr>
</table>

- Case 2: Dike construction (Table 8,9)

Table 8. Comparison of water stage between base scenario and after dike construction scenario for different cross-sections.

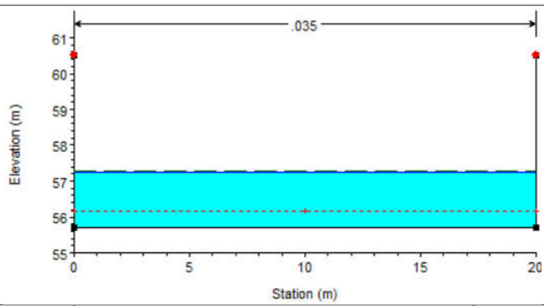
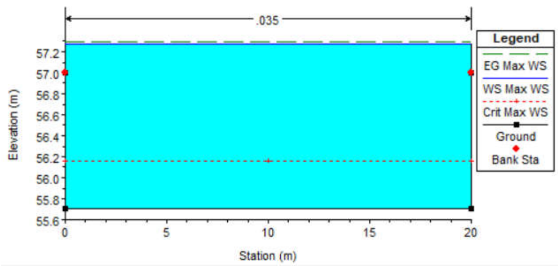
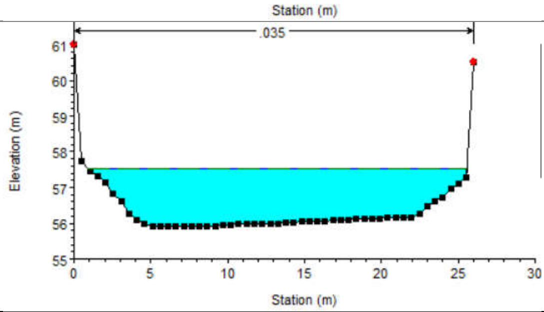
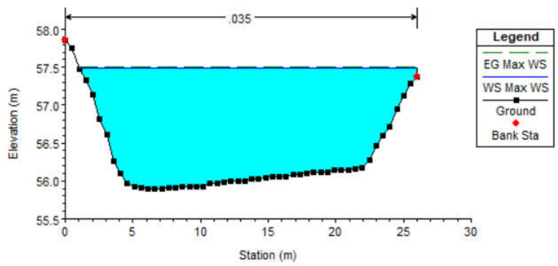
<table>
<tr><th>Cross-section no.</th><th>Scenario 2 (after Dike construction)</th><th>Base Scenario</th></tr>
<tr><td>1</td><td>
</td><td>
</td></tr>
<tr><td>3</td><td>
</td><td>
</td></tr>
</table>

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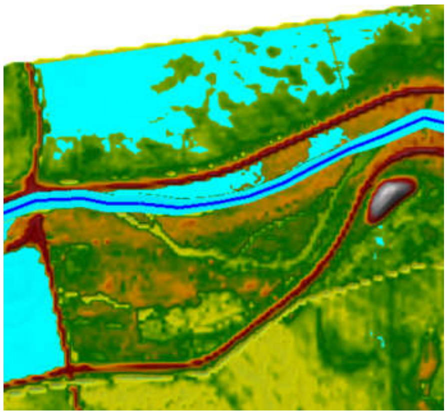
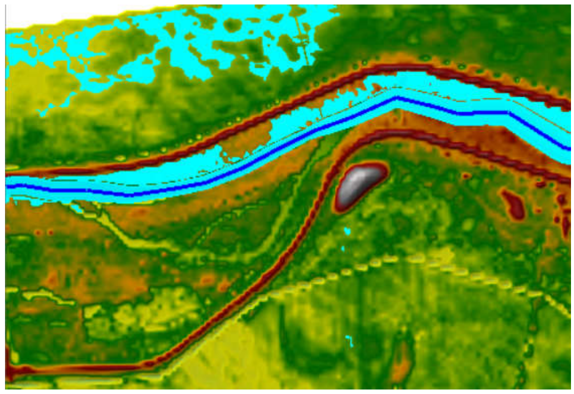
Table 9. Comparison of floodplain inundation between base scenario and after dike construction scenario for sub-reach K5.

Base Scenario	Scenario 2 (after Dike construction)
	

5. Conclusions

The model was simulated for different time steps, grid size, and roughness coefficient and it was observed that the model was sensitive to these parameters. When the time step was changed keeping the same Manning's value and cross-sectional distance, the overtopping of flow was prominent in the right bank of the river. This flood inundation increased with the increasing time steps. A curved pattern was observed which suggested that even though the model was stable for different time steps, more accuracy could be observed in the 6s to 10 s range. This suggest that the model shows a sensitive behavior to time step. On the other hand, when different interpolated distance between cross section was taken into account, there was an insignificant change in the flood inundation pattern.

Also, the model showed a sensitive behavior to the roughness coefficient. The extent of flooding was different for different roughness coefficient which implies that the factors that increases the roughness in the floodplain is of vital importance in preventing flooding. Higher Manning's n (more roughness) led to more flooding than lower Manning's n (less roughness) which clearly suggests the importance of vegetation on the banks of the river to prevent flooding.

This renaturation project was one of the largest river renovations in the state of Brandenburg. The extent of the renaturation was over a length of 11 km and an area of 400 ha. Different mitigation measures adopted in the model provided a change in the inundation pattern. As the results shows above, all the measures like change of vegetation patter (Manning's n), dredging and dyke inclusion in the model reduced the flood inundation significantly. This suggests that the use of such measures could be important to protect the surrounding areas which holds economical value due to its touristic appeal. However, it should also be considered that these flood prevention strategy is not the perfect way to keep the riverine area natural which is the essence of any renaturation projects. This can be achieved by creating an environment where the flora and fauna can survive and flourish. As seen in many different places, the ecological balance in the area can play a vital role in the stability of river and its floodplain. In some cases however, the presence of residential area could be more important than maintaining the ecological balance. Therefore, the measures should be taken considering the trade-off between the environmental impact due to human intervention and the natural losses.

Even though a fairly good result has been obtained from this model, there are still some areas which could be potentially be included in the further study. This model provided a good result to visualize the flood area. However, the model created a coupling of 1D and 2D. One of the approach could be using a 2D model for the entire study area,

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both the channel and the floodplain. This way, the visualization could be clearer. Since, 2D analysis which uses 1D-2D coupling is a relatively new element in the HEC-RAS software, there is a room for further improvement in the approach.

In addition, this model has been carried out for fluvial flooding but not for pluvial flooding as the aspect of rainfall has not been included. A more realistic results could be obtained if the storm water could be incorporated in the model. A model that couples storm water modeling and 1D-2D coupled model could help to get a more realistic outcome. When the underlying equations are taken into account, this model has not covered both the equations for 2D flow. The effect of fully dynamic equation for the river flow could create a different results than the diffusive wave model. The results of both the equations can be simulated and compared which could create a basis for application in another similar area. Even with the restored land, there has been some flooding in the area. Adopting structural measures to mitigate it could neglect the integrity of renaturation. Therefore, further investigations and study could be carried out to analyze other new renaturation techniques and the structural flood mitigation measures and compare them to find the best solution which is feasible both environmentally and economically.

The parameters in the model showed a sensitive behavior to changes as indicated by different results for different scenarios in the preceding chapter. Initially, the model was unstable due to presence of lateral structures. Some of which had elevation lower than the connecting cell elevation of the 2D floodplain area. This created flow error in the model causing instability which suggests that the alignment of the lateral structure plays an important role in the model stability. There are several ways to couple the 1D model 2D floodplain such as connecting a 2D Flow Area to a 1D River Reach with a Lateral Structure, directly connecting an upstream river reach to a downstream/upstream 2D Flow. Among them lateral structure method is more frequently used. However, connecting 1D river with 2D floodplain with lateral structure is sometimes cumbersome due to some inconsistency between terrain and lateral structures elevation. On the other hand, to predict the real extent of flooding, terrain data is needed beyond the original floodplain area. However, only a portion of floodplain is considered in the geometry file. Design engineers and contractors alike entail to furnish projects that basically alleviate the impact of flooding. With other responsibilities and concerns, such as market situation, budget allotment and even climate change effect, it is important to stay one step ahead. Putting a scheme in place, that is built with efficacious and reliability will support to outline a concept for mitigation of flooding when remaining adaptable with environmental and regulatory requirements at the same time.

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