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AN ALGORITHMIC APPROACH TO ITERATIVE FLOODWAY MODELING USING HEC-RAS AND GIS

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ABSTRACT: Hydrologic Engineering Center's River Analysis System (HEC-RAS) software is commonly used to perform hydraulic analysis for floodplain delineation studies. In addition to floodplains, the hydraulic analysis also includes modeling a floodway. Floodway modeling is an iterative process where the 1% annual chance flood discharge is restricted within a floodway without exceeding a 0.3m increase in water surface elevation. An algorithm has been developed to automate floodway modeling using HEC-RAS. The algorithm was tested on Plum Creek in Montgomery County, Virginia. The algorithm's runtime was 4.4 minutes and all but one of the cross-sections was found to have acceptable surcharges while maintaining sub-critical flow in the model. The floodway was mapped using GIS and HECGeoRAS tools. The algorithm was also tested on 5 other hydraulic study reaches. The algorithm achieved significant savings in modeling time providing a good initial floodway that would require minor fine-tuning before being finalized.

***Keywords**: HEC-RAS, GIS, Flood Modeling, Flood Management, Floodplain.*

1. INTRODUCTION

Floodplain management is "*the operation of an overall program of corrective and preventive measures for reducing flood damage, including, but not limited to, emergency preparedness plans, flood control works and floodplain management regulations*" (CFR, Vol. 1 Sec. 59.1). Floodplain management studies typically involve hydrologic and hydraulic modeling of flooding streams to estimate the amount and extent of flooding that may occur in the event of a rainfall. Hydrologic models estimate the flows into a study reach from the contributing watershed which forms the input for hydraulic models to generate floodplain extents.

A floodplain is any area near the main channel which is susceptible to flooding due to excessive runoff. Floodplain extents are dependent on the terrain and the flows corresponding to the various recurrence intervals for floods. The 100 year and 500 year floods are significant events that are usually considered for modeling and planning purposes (Eslamian, 1998). In the past, researchers have mapped floodplains using flood frequency analysis (Bradley *et al.*, 1996), remote sensing data (Bates *et al.*, 1997; Wang *et al.*, 2002), raster-based one dimensional modeling (Bates and De Roo, 2000) and two-dimensional finite element modeling (Bates and Anderson, 1993).

Floodplain delineations are carried out throughout the United States as part of the National Flood Insurance Program (NFIP) administered by the Federal Emergency Management Agency

(FEMA). As early as 1950, a Water Resources Policy Commission identified floodplain zoning as an important part of flood management (L. R. Johnston Associates, 1992). A Unified National Program for Managing Flood Losses was first submitted for review in Congress in 1966. This was followed by two key pieces of legislation, the National Flood Insurance Act (1968) and National Environmental Protection Act (1969), which propelled the scientific and environmental development in floodplain management.

The NFIP started in 1968 and has evolved into a collaborative effort by the federal, state and local governments along with the insurance companies to regulate flood insurance. The NFIP involves identifying special flood hazard areas and flood risk, mitigating and managing the flood risk, and spreading awareness about flood risk and mandating flood insurance policies (Burby, 2001). In addition to floodplains, FEMA also mandates a floodway concept for flood insurance purposes.

A floodway consists of the main channel of flow and its adjoining areas that are maintained to allow base flood discharges without increasing the water surface elevation beyond a stipulated height. The base flood is the 100 year flood (1% annual chance flood) that has a one-per cent probability of occurrence or exceedance in any given year. The “stipulated height” is termed as surcharge, which is the increase in the water surface elevation from the base flood elevation due to constricted flow through a floodway. The process of delineating floodplains and floodways emphasizes the strong spatial component of the hydrology and hydraulics of water flow along a reach.

Geographical Information Systems (GIS) increasingly are being used for spatial and temporal data handling in flood analysis (Townsend and Walsh, 1996; Dutta *et al.*, 2000; Al-Sabhan *et al.*, 2003). Maidment and Djokic (2000) have discussed specific interfaces and algorithms integrated in a GIS to account for the spatial influence in hydrologic and hydraulic modeling. Previous studies (Tate *et al.*, 2002; Whiteaker *et al.*, 2006) have also established the use of GIS for floodplain mapping.

Advancements in GIS data models to include hydrologic and hydraulic data (Whiteaker *et al.*, 2006) for floodplain mapping has not been matched by floodway modeling efforts. This is due to the iterative nature of a floodway modeling routine. Floodway modeling involves fitting an area around the main channel to carry a given volume of conveyance without exceeding a stipulated flood elevation. The best fit involves repeated modeling trials by a modeler to contain the base flood discharge.

This paper describes an attempt to link floodway modeling and GIS by developing an algorithm that automates floodway modeling. The algorithm aims at producing a floodway which would require some manual fine-tuning to be consistent with the development agenda of the local community. The results from the model would be coupled within a GIS environment. Sui and Maggio (1999) discussed various levels of coupling GIS with hydrologic models and the issues involved with them.

2. MODELING BACKGROUND

One of the primary goals of the NFIP is to identify flood hazard areas where special flood insurance policies apply. This involves hydrologic and hydraulic modeling in a watershed or along a stream reach. Some examples of hydrologic principles that are used for estimating flows include the Natural Resources Conservation Service's (NRCS) curve number method, Muskingum flow routing, and the United States Geological Survey (USGS) regression equations. Singh and Woolhiser (2002) provide a more comprehensive list of the various hydrologic principles and methods that are used by water resources engineers.

FEMA has established a list of numerical hydrologic and hydraulic models that can be used for NFIP studies. Some of the major hydraulic modeling software packages and their capabilities are listed in Table 1.

Table 1
FEMA Approved List of Numerical Hydraulic Modeling Software

Hydraulic Model	*Floodway Option*	*GIS Export*	*Public Domain*
HEC-RAS	Yes	Yes	Yes
HEC-2	Yes	No	Yes
Water Surface PROfiles (WSPRO)	Yes	No	Yes
Water Surface Pressure Gradient (WSPG)	No	No	No
StormCAD, Pond Pack	No	No	No
XP-SWMM	Yes	Yes	No
Full Equation (FEQ), Full Equation Utilities (FEQUTL)	No	No	Yes
FLDWAV	No	No	Yes
FLO-2D	Under review		No
MIKE FLOOD	No	No	No

Hydrologic Engineering Center's River Analysis System (HEC-RAS) software was selected for this research based on the following criteria:

1. HEC-RAS provides five stable steady state methods to model a floodway.
2. It is capable of exporting model output into GIS for further spatial analysis.
3. HEC-RAS is available for free on public domain and has been widely used in hydraulic studies for many years.
4. It provides a user friendly graphics user interface for modelers.

The United States Army Corps of Engineers (USACE) pioneered the development of hydraulic modeling programs with their HEC suite of tools. USACE developed and released HEC2 in 1968 which served as the most widely used hydraulic program. Deficiencies in the HEC2 program like the outdated bridge and culvert computation routines and fixed format input and output led to the development of HEC-RAS in 1995. Since then, it has served as a comprehensive hydraulic model in the United States.

HEC-RAS uses one dimensional gradually varied flow equations to solve for water surface elevations at each river station along a reach. The program uses the standard step method (Chow, 1959; Haestad *et al.*, 2003) in an iterative fashion to compute the water surface elevation.

Figure 1, shows a typical profile across two cross-sections and the hydraulic variables used for estimating water surface elevations. The water surface elevation computations are used to identify the floodplain boundary limits.

The equation that is used in the standard step method is:

$$WSEL_2 = WSEL_1 + \frac{\alpha_1 V_1^2}{2g} - \frac{\alpha_2 V_2^2}{2g} + LS_f + C_{c,e}\left(\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right|\right) \quad (1)$$

Where,

$WSEL_{1,2}$ = water surface elevation above datum in the channel at the cross-sections (m)

α_1, α_2 = velocity weighting coefficients

V_1, V_2 = velocities at the cross-sections (m/s^2)

g = acceleration due to gravity (m/s^2)

L = length of flow path between the cross-sections (m)

S_f = average energy slope between the cross-sections (m/m)

C_e = Coefficient of expansion

C_c = Coefficient of contraction

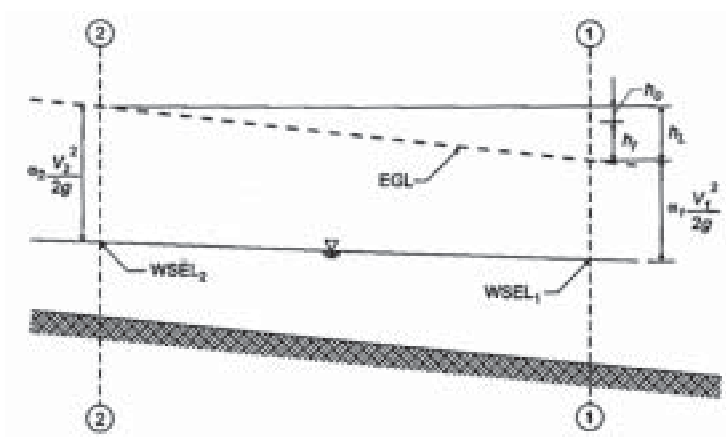

Figure 1: Computation Variables for HEC-RAS Standard Step Method (Reproduced from *Floodplain Modeling Using HEC-RAS*, First Edition, copyright 2007 by the Bentley Institute Press)

The software assumes a water surface elevation and computes the velocity head and conveyance based on energy and Manning's equations. Based on these values, the water surface elevation is computed using equation 1. If the assumed estimate is close to the computed value, the software moves to the next cross-section.

For flood insurance purposes, a floodway model in HEC-RAS requires a minimum of two water surface profiles-the base profile and the floodway profile. The base profile contains water surface elevations for the base flood event (1% annual chance flood) and the floodway profile contains water surface elevations for the floodway.

When modeling a floodway, HEC-RAS follows an encroachment methods analysis (Haestad *et al.*, 2003). The software constricts the flow between two encroachments, one on each side of the main channel. The encroachments are placed in such a way that the conveyance is contained within the two encroachments without exceeding the surcharge. In other words, the goal is to keep the encroached (floodway) profile water surface elevations within a pre-determined surcharge value, usually 0.3m. Conveyance is computed using the Manning's equation as:

$$K = \frac{1}{n} A R^{2/3} \tag{2}$$

where K denotes the conveyance in m^3/s, n denotes the Manning's roughness, A denotes the cross-sectional area in m^2 and R represents the hydraulic radius of the cross-section in *m*.

There are five different methods to perform steady-state floodway modeling in HEC-RAS (USACE, 2002). They are:

Method 1: Specify left and right encroachment stations

Method 2: Specify fixed floodway top width

Method 3: Specify per cent conveyance reduction

Method 4: Specify target surcharge with equal conveyance reduction

Method 5: Specify target surcharge and maximum energy increase

The common modeling approach is to perform a Method 4 floodway analysis and then finalize the floodway using a Method 1 analysis.

In Method 4, the modeler specifies a target surcharge value for the encroached profile. HEC-RAS calculates the conveyance difference between the encroached and base flood elevations and an equal conveyance reduction is performed. The program positions the encroachment stations based on the surcharge value and the equal conveyance reduction. Ideally, the resultant increase in water surface elevation should be less than the specified target surcharge at each cross-section. However, it is common to have excessive surcharges or negative surcharges at few cross-sections (especially near the structures). Figure 2(a) depicts the concept behind Method 4. The modeler repeats the process by changing the target surcharge elevation until most of the cross-sections are within the allowable surcharge limit. Another approach is to create multiple floodway profiles and model each profile with different target surcharges.

Method 1 involves specifying the left and right encroachment stations as shown in Figure 2(b). The modeler specifies the stationing along the cross-section of interest. Since this method involves manual positioning of the encroachments on either side of the main channel, an equal conveyance condition does not exist. During the floodway finalization process, there might be a need to further adjust the floodway for hydraulic consistency. A hydraulically consistent floodway may be one where there are no abnormal jumps in the velocity from one cross-section to another and the top widths are relatively uniform.

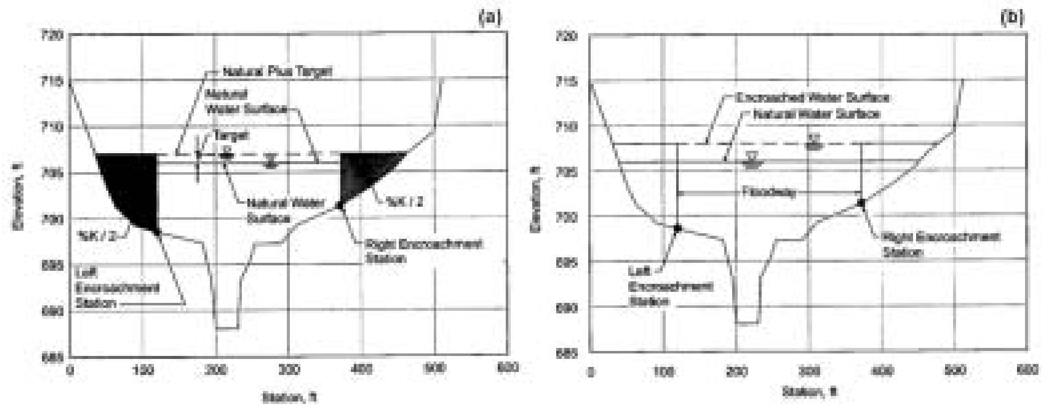

Figure 2: Common Floodway Modeling Approach in HEC-RAS: (a) Method 4 Cross-Section Sketch, (b) Method 1 Cross-Section Sketch (Reproduced from *Floodplain Modeling Using HEC-RAS*, First Edition, copyright 2007 by the Bentley Institute Press)

A typical floodway modeling analysis in HEC-RAS is an iterative process consisting of multiple runs of Method 4 and Method 1 until all the cross-sections along the study reach have an elevation increase less than the allowable surcharge. Thus, there is a need to have an automated procedure in place to perform floodway modeling in HEC-RAS. The automated algorithm described below initiates multiple floodway runs in HEC-RAS without any intervention from the modeler and produces a floodway where most of the cross-sections would satisfy the allowable surcharge requirement. Currently, the algorithm is bundled as a standalone executable file with a user interface, but work is continuing to integrate the software into the ESRI ArcGIS environment.

3. DESCRIPTION OF THE ALGORITHM

The main goal of the algorithm is to provide the modeler with a good floodway model that can be fine-tuned with minimal modeling effort. The algorithm employs the HEC-RAS modeling engine from within a Visual Basic environment to perform the floodway analysis runs. The algorithm is developed following the common modeling approach outlined previously. The algorithm workflow schematic is shown in Figure 3. The algorithm starts with a Method 4 run with an initial target surcharge of 0.15 m (0.5 ft). The user has an option to change this initial surcharge. The floodway at cross-sections with negative surcharges is narrowed by increasing the target surcharge to 0.3 m (1.0 ft) and Method 4 is re-run. The output surcharge information is then imported into a Method 1 input file. In Method 1, the algorithm starts at the most downstream cross-section and moves upstream solving the surcharge to be between -0.003 m and 0.3 m (–0.01 ft and 1.0 ft) at each cross-section. Adjusting encroachment stations at each cross-section is limited by a fixed number of iterations.

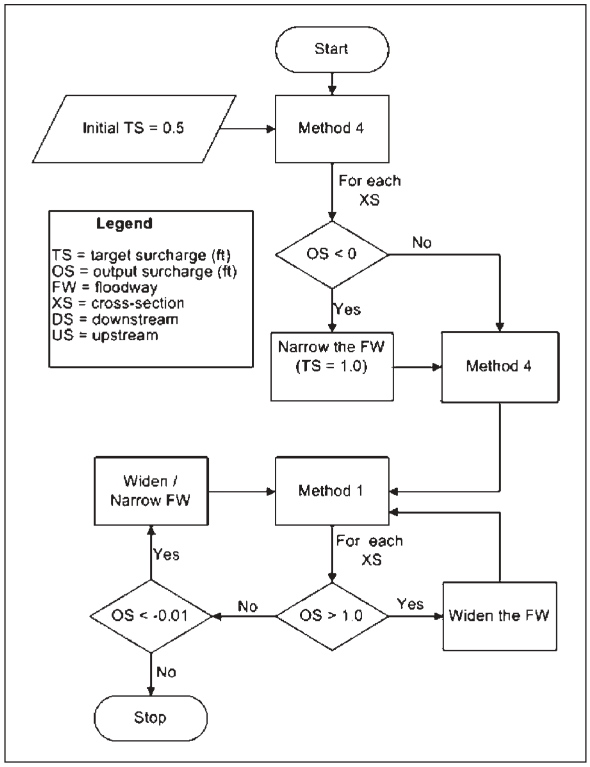

Figure 3: Algorithm Flowchart Schematic

The algorithm takes into consideration various engineering parameters while deciding to narrow or widen the floodway at each cross-section. For example, conveyance of encroached profile may be less than that of the base profile. The algorithm attempts to widen the floodway at that cross-section to allow more conveyance and thereby reducing the surcharge below the acceptable limit. Sometimes, a narrow floodway results in a high velocity head causing negative surcharges. The algorithm widens the floodway at that current cross-section. Thus, the algorithm has been developed to be more intelligent than simply positioning encroachments along a cross-section to model the floodway.

It is common modeling practice to adjust encroachments downstream in order to reduce the surcharge upstream. This algorithm is capable of adjusting encroachments at as many cross-sections downstream as necessary to solve for a cross-section. If a cross-section cannot be solved after traversing to the most downstream cross-section, the algorithm moves to the next cross-section upstream of the defaulting cross-section.

4. USER INTERFACE OPTIONS

The algorithm is supported by an interface which allows the user to set some modeling and computational criteria. The sole input to the program is a HEC-RAS floodway project. The

HEC-RAS project should contain exactly two profiles–the first profile is the 100 year flood profile and the second profile is the floodway profile. The HEC-RAS project should also contain the flow data for both the profiles. The program reads the HEC-RAS project and identifies the various river and reach information in the project. The user can identify cross-sections where the floodway would match the floodplain boundary or the channel boundary.

Some of the key operating parameters that govern the functioning of the algorithm are:

1. Initial target surcharge for the Method 4 run.
2. The maximum number of trials to be performed at each cross-section.
3. Number of cross-sections to traverse downstream for solving a cross-section upstream.
4. Snapping tolerance for encroachments to the floodplain or ineffective area limits

The algorithm was tested on a study creek where hydrologic analysis had previously been completed.

5. STUDY AREA DESCRIPTION AND MODEL SETUP

Plum Creek is a 6.6 km long creek located partially in Montgomery County and partially in Radford City, Virginia. It drains into the New River (Figure 4). The land cover in the surrounding areas of Plum Creek is comprised of densely forested trees (28%), thick brush (24%), open field/pasture (18%), medium shrub (7%) and a few paved roads. Thus, the area is primarily rural and the creek is characterized by narrow channels widening out further downstream.

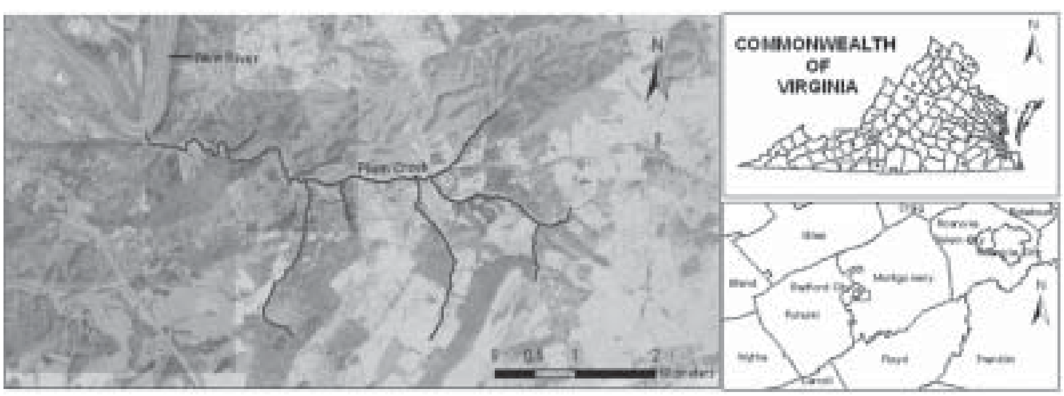

Figure 4: Location Map for Plum Creek

The contributing watershed from Plum Creek and its main tributaries encompass 18.6 square km. Since Plum Creek is not gaged, the hydrologic estimations were based on USGS regression analysis (Bisese, 1995; Mason Jr and Fuste, 2001). The terrain model used for this study was developed from LiDAR data for Montgomery County and Radford City. The hydrologic analysis was performed using Watershed Information System (WISE) software developed by Watershed Concepts.

Hydraulic model setup requires information on the structures along the creek. The structure elevations were surveyed and the hydraulic model was developed in HEC-RAS. The flow information was obtained from the hydrologic analysis. In addition to placing cross-sections upstream and downstream of structures, additional cross-sections were placed based on changes in slopes and flow area. Once the HEC-RAS model was set up completely, the algorithm was used to perform floodway modeling.

6. RESULTS AND DISCUSSIONS

The primary objective in floodway modeling is to maintain the surcharge below 0.3 m at all cross-sections. The Plum Creek hydraulic model had 114 cross-sections. The algorithm runtime was 4.4 minutes. It performed 22 iterations to solve for all the cross-sections from downstream to upstream. Figure 5 shows the surcharges obtained at each cross-section for the entire reach. Each bar represents the magnitude of surcharges obtained at a cross-section. The surcharges at all but one of the cross-section stations are below 0.3 m. The single cross-section that exceeded the 0.3 m surcharge is at a bridge structure. The class library that HEC-RAS provides does not allow access to surcharge information at the structures. So, the algorithm is unable to check for surcharges at the structures. There were three cross-sections with surcharges less than zero. However, the magnitude of surcharges was greater than -0.003 m (–0.01 ft) for those three cross-sections. Thus the surcharge elevation target of 0.3m has been successfully met at more than 95% of the cross-sections for Plum Creek.

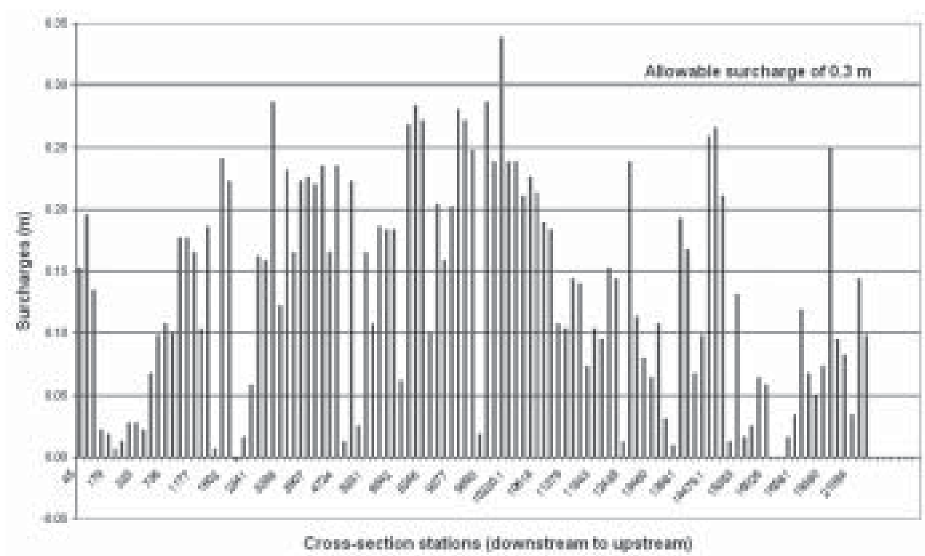

Figure 5: Estimated Surcharges along Plum Creek

Out of 114 cross-sections, 20 cross-sections were found to be at or close to critical depth. It is critically important to keep the water surface elevations above critical depth in order to prevent supercritical flow conditions. The Froude number was less than or equal to one for all the cross-sections (96% cross-sections had Froude number less than one and 4% were equal to one). Thus, this algorithm is highly successful in maintaining sub-critical flow in the model.

HEC-RAS output can be exported as GIS format and mapped in a GIS environment (Figure 6) using HEC-GeoRAS tools. HEC-RAS maps the floodway by joining encroachments along each cross-section by linear line segments. This type of mapping does not consider the sinuosity of the stream centerline. Hence, in order to produce the final floodway polygon, further smoothing is necessary. Another important factor in floodway modeling is the active top width of the floodway. The active top width should be fairly constant or gradually changing along the reach. This algorithm, in its current form, does not check for top width criterion. This will be considered in continuing research to map the floodway within ArcGIS.

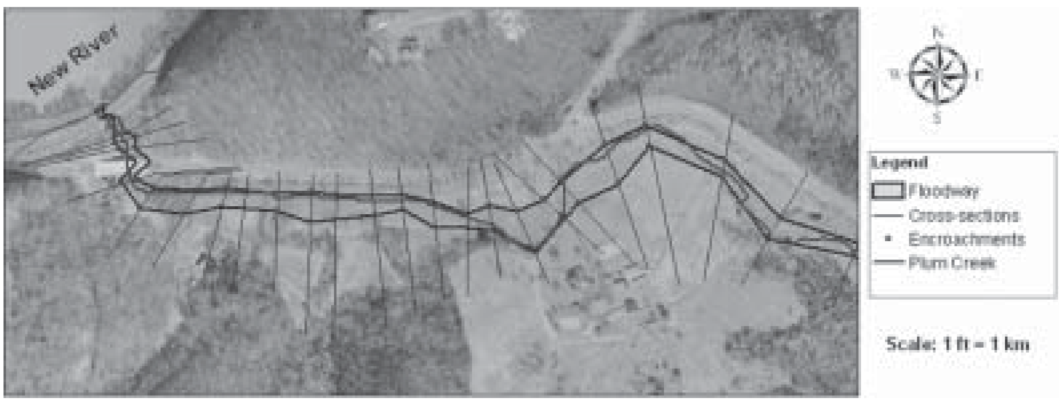

Figure 6: Floodway Mapping as Modeled by HEC-RAS

The algorithm was also tested on five other HEC-RAS floodway models. The efficiency of the algorithm is measured in terms of the number of cross-sections having positive surcharges less than 0.3m. From Table 2, it can be observed that the algorithm is efficient in modeling a majority of cross-sections within the stipulated 0.3m surcharge. The algorithm solved at least 96% of the cross-sections in the models used for testing.

Table 2
Salient Statistics of Algorithm Runs on Various Study Streams

Model	*Length (km)*	*Manual modeling time (mins)*	*Algorithm runtime (mins)*	*Percent time savings (mins)*	*Number of Iterations*	*Number cross sections*	*Percent solved cross sections*
Plum Creek	6.6	180	4.4	97.5	22	114	97.4
Pitner Creek	3.67	30	1.8	94	8	51	96
Noonday Creek	17.82	90	8.4	90.6	38	152	96.7
Yellow River	28.94	110	23.2	78.9	41	190	97.4
Waikapu Creek	8.87	75	3.6	95.2	18	84	97.6
Upper Susquehanna	114.26	300	36.5	87.8	63	307	98

The algorithm runtimes indicate greater time efficiency when compared to the time it takes for manual floodway modeling. On average, the algorithm saved about 90% over manual modeling with HEC-RAS, a significant savings. The longest study reach tested (Upper Susquehanna) reduced modeling time by 88%. However, the length of the reach is not directly correlated to the time savings as the time taken to model a floodway to meet the surcharge requirement depends on the complexity of the hydraulic model, including the structures and the slope of the terrain. The automation of floodway modeling enables modelers to invest time in other areas of building the hydraulic model.

7. LIMITATIONS OF THE ALGORITHM

1. The program cannot automatically create new floodway profiles and import boundary conditions in HEC-RAS. So, it is the modeler's responsibility to provide a HEC-RAS project with a base flood profile and a floodway profile.
2. The program cannot rectify structure modeling issues without user involvement. It is also difficult to access surcharge information for the structures.
3. The program does not attempt to adjust the floodway for a consistent topwidth.

8. SUMMARY AND CONCLUSIONS

The algorithm is a very good utility tool for automating floodway modeling for floodplain mapping studies. The algorithm provides a good starting floodway which can be fine-tuned with much lesser efforts from the modeler to produce the final floodway. The algorithm also uses key hydraulic engineering parameters in the modeling process, thus making the tool hydraulically reliable. The algorithm saves a lot of modeling time for a modeler performing floodway analysis. Since the algorithm uses HEC-RAS software engine for the hydraulics, it also facilitates easy transfer of output into existing GIS data models like HECGeoRAS.

9. FUTURE WORK

Future work would involve creating an interactive component for visualizing and modifying the floodway within the ArcGIS environment. The interactive model is expected to allow the modeler to adjust encroachments on a map and also perform spatial analysis. A floodway topwidth smoothing routine would also be developed.

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