Probable maximum flood inundation modeling: a case study in southern Virginia

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ABSTRACT: A Probable Maximum Flood inundation study was conducted on a 22 km^2 area located within the Whitethorn Creek watershed in south central Virginia, USA. For this analysis, a HEC-HMS hydrologic model was developed for a 107 km^2 study watershed to simulate the rainfall-runoff response resulting from the Probable Maximum Precipitation storm event. This event is representative of the worst-case rainfall event that is theoretically possible in the drainage. Outflow hydrographs from the hydrologic model were routed through a HEC-RAS hydraulic model of three area creeks to determine the extent of the inundation. An inundation map of the study area was generated using ArcGIS and topography from the National Elevation Dataset (1/3 arc-second resolution). Model development was facilitated through the use of HEC-GeoHMS and HEC-GeoRAS to assimilate several geospatial data sources and generate a number of modeling inputs.

1 INTRODUCTION

1.1 *Project overview*

Currently, the largest known undeveloped uranium ore deposit in North America, consisting of an estimated resource of 120 million pounds of uranium, is located in Pittsylvania County in south central Virginia (Santoy Resources 2009). This uranium reserve is large enough to supply the fuel to all nuclear reactors in the United States for two years (U.S. Energy Information Administration 2010). As a result, a number of studies are being conducted to determine the potential implications of developing such a mining operation.

As part of these investigations, a Probable Maximum Flood (PMF) inundation study was carried out on an approximately 22 km^2 area surrounding the uranium reserve. The primary goal of this PMF analysis was to determine the spatial extent of flooding that would occur within the defined study area as a result of the region experiencing the theoretical worst-case scenario precipitation event.

A meteorological model representing the Probable Maximum Precipitation (PMP) was developed for the study watershed. The PMP storm data was simulated in an event-based hydrologic model of the study watershed to obtain PMF response hydrographs. These hydrographs were then routed through a hydraulic model to determine the extent and the elevation of the water surface in the area. Finally, these stage values were utilized, in conjunction with topography and a GIS program, to develop a flood inundation map of the study area. This map will be used for site planning purposes if the mining site is developed to ensure that key structures and operations are not impacted by flood waters during an extreme event.

1.2 *Project site description*

The ore body around which this study was based is located between two rural streams: Whitethorn Creek to the north and one of its tributaries, Mill Creek, to the south. To capture the inundation effects from these streams, in addition to a third smaller stream, Dry Branch, that enters Whitethorn Creek just south of the Mill Creek confluence, the study watershed outlet point was selected as the confluence of Dry Branch and Whitethorn Creek. This point is approximately 4 km upstream of the mouth of Whitethorn Creek and corresponds to an area where the creek floodplains begin to become confined in a narrow valley. Figure 1 depicts the 107 km^2 Whitethorn Creek study watershed delineated upstream of the selected outlet point, as well as the 22 km^2 PMF study area in which the hydraulic modeling and inundation mapping took place. The figure also shows the 10 subbasins that the watershed was divided into for hydrologic modeling purposes.

The land cover of the watershed characterized primarily as deciduous forest and agricultural land (hay/pasture) (Fry et al. 2011) and over 85% of the watershed is considered to be underlain with soil having a moderately low runoff potential (hydrologic

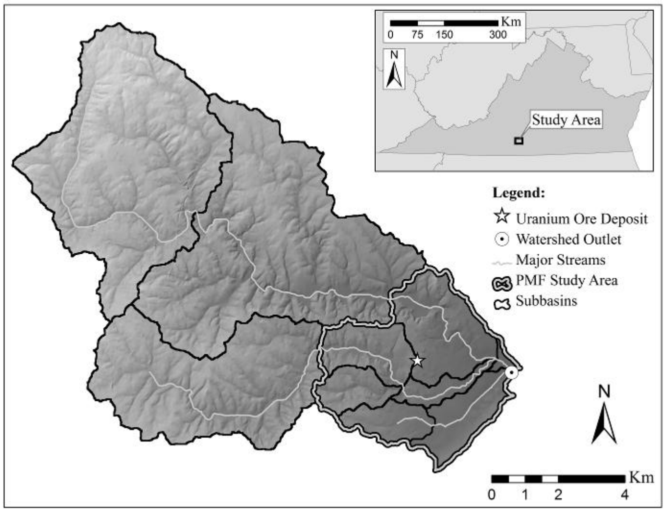

Figure 1. Location map of the Whitethorn Creek study watershed and its major features - Inset map showing project site location in Virginia.

soil group B) (NRCS 2009). Elevations within the study watershed range from 156 to 332 m above mean sea level and the average basin slope is approximately 7.8% (Gesch 2007, Gesch et al. 2002).

2 MODELING

2.1 *Probable Maximum Precipitation*

To develop the PMF inundation map, a PMP analysis was conducted for the study watershed, as the PMP would generate the highest expected runoff volume that would cause the PMF. For this study, the 72-hr PMP storm event was simulated. PMP is defined as "the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year" (Huschke 1959).

The theoretical PMP for any location in the USA east of the 103rd Meridian (with the exception of areas within the Appalachian/Blue Ridge Mountains) can be determined by following the methodologies outlined in Hydrometeorological Reports No. 51 and 52 (HMR 51/52) (Schreiner & Riedel 1978, Hansen et al. 1982). HMR 51/52 provide guidance on how to take point PMP depths that have been estimated for a select set of basin sizes and transform them into an idealistic, elliptical storm pattern with a specific size, orientation, and temporal distribution. These suggestions are based on observed characteristics from a number of historic extreme precipitation events.

Consistent with the recommendations made in HMR52, Figure 2 depicts the selected spatial distribution and storm orientation for the PMP storm over the study watershed. The storm pattern is modeled as an idealized series on concentric ellipses, termed isohyets, each with a major to minor axis shape ratio of 2.5 to 1. HMR 52 suggests standard area sizes for each isohyet, the first five of which are denoted in the figure. This methodology allows for a pattern of up to nineteen isohyets, covering a storm area of up to 155,400 km^2, however, due to the relatively small size of the basin, only the first five standard isohyets were used.

The center isohyet represents the most intense precipitation and the intensity scales down with each subsequent ellipse. The area contained within or between two adjacent isohyets represents a unique, constant rainfall depth at a particular point in time. However, the same area is assigned different depths at different times during the storm, as the intensity of the simulated rainfall changes over the course of the storm event.

The storm is generally positioned and orientated to maximize the precipitation falling within the drainage. This is accomplished by placing the greatest number of whole isohyets completely within the watershed, since the isohyets that enclose smaller area sizes contain proportionately higher rainfall amounts. For the Whitethorn Creek study watershed, an orientation of 310° from north was selected to best cover the drainage (Fig. 2). In this way, the major axis of the storm pattern roughly corresponds to the apparent axial orientation of the watershed.

HMR52 recognizes that in a realistic storm situation, very intense rainfall cannot be sustained for long periods of time. It recommends dividing the 72-hr PMP event into twelve 6-hr periods, each with a different degree of intensity. The report also suggests different temporal distributions for modeling the storm, as the most intense period is not likely to occur at the very beginning or very end of a storm. For this analysis, one of the HMR 52 recommended temporal distributions was adopted. This distribution placed the most intense rainfall at the start of the third day of the storm (ninth 6-hr period), with the precipitation intensity scaling down on either side of it. Table 1 displays the PMP depths associated with each isohyet for each 6-hr period of the 72-hr PMP storm that were calculated for the study watershed.

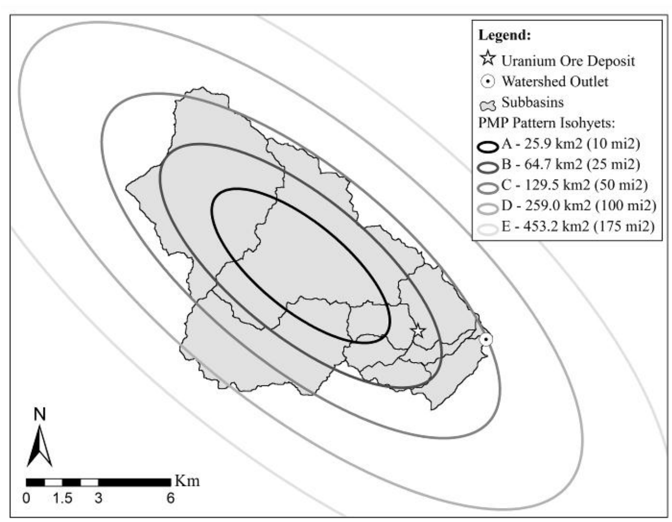

Figure 2. Selected isohyetal distribution for the Whitethorn Creek PMP storm event.

Table 1. Isohyetal PMP depths for each 6-hr period of the 72-hr PMP storm for the Whitethorn Creek study watershed.

Storm Period (hrs after start)	Isohyet / Incremental PMP Depth (cm) A	B	C	D	E
0-6	0.94	0.94	0.94	0.74	0.59
6-12	0.99	0.99	0.99	0.77	0.62
12-18	1.14	1.14	1.14	0.90	0.72
18-24	1.43	1.43	1.43	1.12	0.90
24-30	2.54	2.54	2.54	1.99	1.60
30-36	2.54	2.54	2.54	1.99	1.60
36-42	3.03	3.03	3.03	2.38	1.91
42-48	6.48	6.36	6.28	5.00	4.02
48-54	65.8	61.5	57.1	41.0	33.5
54-60	12.5	11.9	11.4	8.99	7.39
60-66	4.11	4.11	4.11	3.22	2.59
66-72	2.05	2.05	2.05	1.61	1.29

Once the incremental isohyetal PMP depths were determined, the meteorologic model of the PMP was built. For the Whitethorn analysis, a meteorologic model consisting of ten individual precipitation time-series gages was developed. Each gage corresponded to one of the ten subbasins of the watershed and contained its own 72-hr incremental PMP hyetograph. In this, rainfall was considered to be uniformly distributed, both spatially and temporally, within each subbasin.

To distribute the incremental isohyetal PMP depths, an area-weighted averaging approach was employed, based on the area of each isohyet that was contained within each subbasin. By summing up the products of each depth and the area to which it was applied, and then by dividing the sum by the total area of the subbasin, a subbasin-average PMP depth was obtained for each 6-hr storm period.

This technique of generating separate precipitation time-series, based on proximity to the storm center, enabled the simulation of different rainfall inputs for different areas of the watershed. In this way, the PMP was modeled with greater resolution than if a single watershed-averaged approach had been taken. This theoretically would improve the quality of the modeling results, as it allows for a more precise hyetograph to be simulated over a smaller area, with unique estimates of the location's hydrologic conditions.

2.2 *Hydrologic modeling*

The Whitethorn Creek study watershed hydrologic model was built using the US Army Corps of Engineers Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) and Geospatial Hydrologic Modeling Extension (HEC-GeoHMS). These publically-available software packages are recognized as industry standards for hydrologic modeling purposes. In addition, Environmental Systems Research Institute's (ESRI) ArcGIS software was used in conjunction with these programs to combine and assimilate much of the geospatial data necessary to build the hydrologic model.

2.2.1 *Event hydrologic modeling*

For this study, an event-based hydrologic modeling approach was adopted due to the need to determine how the watershed would react to the PMP storm. Event hydrologic modeling aims to accurately represent the precipitation-runoff processes in a drainage for specific rainfall events. This necessitates the characterization of finer-scale hydrologic processes, requiring the basin to be broken up into smaller, individual subbasins and stream reaches. The overall watershed response to extreme events is compartmentalized, allowing for separate analyses to be carried out at finer resolutions across the watershed. These individual subbasin responses can then be agglomerated again at different points along the watershed flow network to obtain a large-scale response at key locations, such as at stream confluences or at the watershed outlet (Scharffenberg & Fleming 2010).

Dividing a watershed enables different parts of the basin to be analyzed with different parameters. This allows for a more accurate representation of the variable conditions and natural heterogeneity that exist within large watersheds. By modeling a drainage as a series of small, interconnected subbasins, that are homogenous in and of themselves, the hydrologic processes that are being simulated for each can be tailored specifically to the region that they represent. This is especially important when studying watersheds with varying characteristics, such as land cover, soil type, imperviousness, etc. If the basin was modeled as a single watershed, with only one set of parameters assigned to it, certain generalizations would be required, introducing error that could be minimized by using a finer resolution (Chu & Steinman 2009, Chaubey et al. 1999). The ten subbasins in the Whitethorn Creek study watershed enabled the model to better account for this spatial and topographical variability.

2.2.2 *Model description - HEC-HMS*

One of the most frequently utilized and most widely accepted modeling programs for hydrologic modeling is HEC-HMS (Razi et al. 2010). This one-dimensional hydrologic model is designed to simulate the precipitation-runoff processes of dendritic watershed systems. These dendritic systems are one of the most common types of drainage systems found in nature and generally consist of a main stream or river channel that branches out into a number of smaller contributing tributaries. These systems arise from patterns in the terrain, with the flow networks usually forming in the valleys created by the landscape (Scharffenberg & Fleming 2010, Garcia et al. 2008).

HEC-HMS, like other rainfall-runoff models, simulates the precipitation-runoff response of a watershed or network of sub watersheds to a given amount and distribution of precipitation over a defined period of time. The model converts precipitation excess to overland flow and channel runoff using user defined loss, transform, and routing methods (Knebl et al. 2005).

HEC-HMS requires three basic input components: a basin model, a meteorologic model, and a control specifications model. The basin model is composed of individual hydrologic elements (subbasins, reaches, junctions, reservoirs, etc.) as well as information about their connectivity and contains all of the physical characteristics of these features. The meteorological model is the input file that contains the precipitation/storm information (with respect to both space and time) for the events that are to be modeled. The control specifications model contains the temporal information for the simulation run (modeling time-step, simulation start and end dates, etc.) (Olivera 2001).

Provided with a basin model, a meteorological model, and a control specifications model, HEC-HMS can create a simulation run and output discharge hydrographs at various points in the system. Each of these hydrographs contains time-series information so that a user can track how a flood-wave propagates through a watershed during an extreme event (Knebl et al. 2005, Garcia et al. 2008).

2.2.3 *HEC-GeoHMS*

In an effort to streamline the data assimilation and model input development process, HEC developed HEC-GeoHMS, which acts as an intermediary program between the GIS platform (ArcGIS) and HEC-HMS. This program is a geospatial hydrology toolkit that interfaces between the two source programs to make the data transition easier and more efficient. HEC-GeoHMS, acting as an extension in ArcGIS, enables a user to visualize the basin model's spatial information and automates many of the processes involved in parameter selection that would normally need to be calculated by hand. This toolkit allows a modeler to perform spatial analysis, delineate subbasins and stream networks, and construct and export most of the input data and files required for a HEC-HMS simulation (Chu & Steinman 2009, Fleming & Doan 2010).

HEC-GeoHMS utilizes the ArcHydro Tools 9 toolkit (included in the software package) and the Spatial Analyst extension for ArcGIS to generate a number of hydrologic modeling inputs that the program can then combine and convert to a single .hms file that can be read and tested in HEC-HMS. By analyzing digital terrain data, HEC-GeoHMS is capable of transforming the drainage paths and watershed boundaries into a hydrologic data structure schematic that represents the drainage network (Fleming & Doan 2010).

2.2.4 *Whitethorn hydrologic modeling methodology*

For the Whitethorn Creek hydrologic model, data from a number of publicly-available sources were collected and utilized to develop the required modeling inputs. One of the most important of these datasets was the topography data, which was used to obtain a number of parameters, in addition to being used to delineate the watershed, subbasins, and flow network. The elevation data was acquired in the form of a Digital Elevation Model (DEM) from the US Geological Survey's National Elevation Dataset (NED). The NED is a continuously updated grid of elevation values across the United States that is available for download at varying spatial resolutions (Gesch 2007, Gesch et al. 2002). For the Whitethorn Creek study area, a DEM grid resolution of 1/3-arc-second (approximately 10m) was selected for the terrain analyses, as this was the finest resolution available.

Other key datasets included a land use dataset from the National Land Cover Database 2006 (NLCD 2006) (30m grid resolution) and a hydrologic soil group soil dataset from the Soil Survey Geographic Database (SSURGO). Following the methodology developed by the USDA Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS), these two datasets were used in HEC-GeoHMS to develop a runoff curve number (CN) grid for the watershed.

The CN is an empirical parameter that provides an indication of storm runoff potential over an area, based on land use, soil type, and hydrologic condition (Knebl et al. 2005, Chaubey et al. 1999). This value is a fundamental input into the HEC-HMS loss method that was selected for the Whitethorn analysis: the SCS Curve Number Loss Method. The loss method aims to conceptually represent how infiltration, surface runoff, and subsurface processes interact within each sub-basin element (Scharffenberg & Fleming 2010). The SCS Curve Number Loss Method was chosen because it has been widely used for estimating rainfall-generated surface runoff in small watersheds with event-based hydrologic models (Chu and Steinman, 2009).

With the CN grid, a subbasin-averaged approach, similar to one taken for the PMP, was utilized to assign a single weighted CN to each of the subbasins. In addition to the CN, the SCS Curve Number Loss Method requires an initial abstraction (I_a) value for each subbasin. This parameter represents the total rainfall lost before runoff initiates, including losses from interception, initial infiltration, surface depression storage, and evapotranspiration (USDA NRCS 1986). The I_a for each subbasin was estimated following the SCS methodology as:

$$I_a = 0.2\left(\frac{2540}{CN} - 25.4\right) \quad (1)$$

where I_a = initial abstraction (cm); CN = subbasin-averaged Curve Number.

After the loss method has been selected, the transform method and routing method must be specified. The transform method dictates the actual surface runoff calculations that are performed for each subbasin and the routing controls how flow is modeled in the reach network connecting the subbasins (Scharffenberg & Fleming 2010). For this study, the SCS Unit Hydrograph Transform Method and the Muskingum Routing Method were selected to simulate the remaining hydrologic processes.

The SCS Unit Hydrograph Method was developed from observed data collected in small agricultural watersheds, making it a relevant option for this study. This transform method utilizes a standard dimensionless hydrograph approach, scaled by a basin lag time, to convert a hyetograph into a runoff hydrograph. The subbasin lag times were approximated as 60% of the time of concentration for each subbasin, at the recommendation of the HEC-HMS manual (Scharffenberg & Fleming 2010).

The Muskingum Routing Method is a reach routing algorithm that accounts for both mass translation of flow and for peak flow attenuation, and has been widely used for event-based modeling (McCuen 1998, Olivera 2001). This method assumes that the water surface in a reach is linear, but non-level, and in doing so, makes it possible to represent increased storage capacity during the rising side of a flood wave and decreased storage capacity during the receding flood wave. To approximate peak flow attenuation, Muskingum incorporates reach travel time (K) and a weighting factor (X) representing the influence of inflow and outflow in the reach. The Muskingum K can be estimated for each reach with knowledge of the reach length and flow velocity. The Muskingum X ranges from 0.0 (maximum attenuation) to 0.5 (no attenuation) with an intermediate value of 0.2 commonly used for natural streams. In addition to the K and X factors, the number of sub-reaches that each reach is broken up into must be specified. This is done to maintain numerical stability during simulation. HEC suggests that this number should be approximately equivalent to the reach length divided by the product of the wave celerity and the simulation time step (Scharffenberg & Fleming 2010, McCuen 1998).

For the Whitethorn study, the Muskingum K for each reach was estimated using Manning's Equation, with best estimates of channel characteristics. For the Muskingum X, the commonly used value for natural streams of 0.2 was selected, representing mild attenuation capacity.

After all of the basin model parameters were determined, the PMP meteorologic model was simulated over the watershed, using an arbitrarily assigned control specifications model. This simulation produced outflow hydrographs corresponding to the PMF at each node in the hydrologic model. These then served as the flow inputs into the hydraulic model.

2.3 *Hydraulic modeling*

Analogous to the hydrologic modeling, the US Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS) and the Geospatial Hydraulic Model Extension (HEC-GeoRAS) were used to represent and model the network of streams present within the area of interest. As with HEC-HMS and HEC-GeoHMS, these publically-available software packages are widely accepted as industry standards for hydraulic modeling purposes.

2.3.1 *Model description – HEC-RAS*

HEC-RAS is designed to perform one-dimensional hydraulic computations for a full network of channels (Brunner 2010). HEC-RAS is capable of performing steady and unsteady flow simulations, sediment transport computations, and water quality analysis. The objective of HEC-RAS is to compute water surface elevations from either a specified flow rate (steady flow simulation) or from a discharge hydrograph (unsteady flow simulation). It requires two basic inputs for flow analyses: geometric data and flow data. The geometric data file includes all the information related to cross-sectional station and elevation data, reach lengths, bank stations, energy-loss coefficients, stream junctions, and the geometry of hydraulic structures. The flow data requires defining boundary conditions, initial conditions (unsteady), and either peak discharges or discharge hydrographs depending on the simulation type (steady or unsteady, respectively).

Even though HEC-RAS has limitations as a one-dimensional model, its versatility and simplicity in terms of required input data and simulation speed make it an extensively used model for hydraulic simulations. This, in turn, provides a great deal of confidence in the use of HEC-RAS as a tool for modeling steady and unsteady flow through multiple river reaches.

2.3.2 *HEC-GeoRAS*

HEC-GeoRAS is a group of ArcGIS-compatible tools designed to process geospatial data for using with HEC-RAS. This extension facilitates the pre-processing of the input data, as well as the post-processing of the HEC-RAS simulation results. It can be utilized to extract geometric data from an existing digital terrain model (DTM) and then produce complementary datasets for the HEC-RAS simulation (Ackerman 2009).

The program's pre-processing capabilities include the generation of cross-sectional station-elevation data and the determination of reach lengths, bank stations, and bridge/culvert locations using data provided in ArcGIS. These are all used to create the HEC-RAS geometric data file. The post-processing of the data includes the use of the HEC-RAS simulation results for flood inundation mapping in ArcGIS.

2.3.3 *Whitethorn hydraulic modeling methodology*

One of the most important components of the hydraulic model is the river terrain model used to represent the streams of interest. Its complexity is associated with the kind of model being used (1-D, 2-D, or 3-D). The type of model determines the amount and detail of input data required to successfully model a watercourse. Since HEC-RAS is a one-dimensional model, it only requires a series of cross-sections to adequately represent the river channel geometry and its surrounding topography, while two and three-dimensional models require that the river system be represented as an integrated continuous surface (Merwade et al. 2008).

For the Whitethorn hydraulic model, a methodology similar to the one presented by Tate et al. (2002) was used to build the river terrain model. This methodology involved merging channel bathymetry data in HEC-RAS with floodplain geometry from the DEM in ArcGIS, extracted with HEC-GeoRAS. This was done for the four main reaches on the Whitethorn hydraulic model: two main streams – Whitethorn Creek and Mill Creek – and two small tributaries – Dry Branch and an Unnamed Tributary to Mill Creek. Table 2 contains the reach lengths for each of these streams, as modeled in the HEC-RAS.

The channel bathymetry of the streams at each bridge crossing was provided by the Virginia Department of Transportation (VDOT) and it was surmised from field observations that the streams exhibited a uniform channel geometry. As a result, the HEC-RAS interpolation routine was employed to generate the remainder of the bathymetric channel cross-sections between the bridge points. For all of the cross-sections, the floodplain geometry was extracted from the NED (~10m grid resolution), avoiding the need to interpolate floodplain geometry where actual data was available. This resulted in a river terrain model that incorporated the best data available for both the channel and its floodplain. A total of 163 cross-sections were generated for the hydraulic model, including two bridge crossings and two culvert crossings.

Another important part of the hydraulic model is the channel and floodplain roughness, represented by the Manning's n coefficient. For the channel, a first estimate of the Manning's n value was assigned based on images in the literature consistent with field observations of the study sites (Barnes 1967). These values were adjusted through a calibration procedure using regression equations for bankfull channel geometry for non-urban streams in Virginia (Lotspeich 2009). Equations for bankfull cross-sectional area and estimated bankfull discharge were used to validate the current geometry and determine the final Manning's n values for the channel. For the floodplains, the Manning's n values were calculated using an area-weighted approach based on suggested roughness coefficients presented by Kalyanapu et al. (2009) for each land use classification within the NLCD. Table 3 shows the Manning's n values used for the Whitethorn Creek hydraulic model for both the channel and the floodplains.

It should be noted that Manning's n values using this approach for the floodplains are larger than the ones typically reported in the literature. Since no real data or regression equations are available for the calibration of this parameter, the value of the Manning's n used represents a conservative estimation based on available data (NLCD 2006). Additionally, a sensitivity analysis of this constraint was carried out to ensure that the final results were not

Table 2. Simulated reach lengths included in the Whitethorn hydraulic model.

Reach name	Reach length
	km
Whitethorn Creek	
Upper Reach	4.97
Middle Reach	0.61
Lower Reach	0.08
Mill Creek	
Upper Reach	3.31
Lower Reach	3.71
Dry Branch	5.62
Unnamed Tributary	2.60

Table 3. Selected Manning's n values for the Whitethorn hydraulic model.

Reach name	Manning's n value	
	Channel	Floodplains
Whitethorn Creek		
Upper Reach	0.020 – 0.040	0.3245
Middle Reach	0.025 – 0.030	0.3365
Lower Reach	0.030	0.3484
Mill Creek		
Upper Reach	0.012 – 0.020	0.3352
Lower Reach	0.035 – 0.060	0.3255
Dry Branch	0.012 – 0.025	0.3323
Unnamed Tributary*		0.3387

* The unnamed tributary was included in the model with the purpose of evaluating the backwater effects from a bridge crossing located on Mill Creek onto the floodplains. Therefore no channel was generated.

contingent on variations of this parameter.

Standard procedures were used to perform the steady and unsteady flow simulations in HEC-RAS. Initially, steady flow simulations were carried out to calibrate the Manning's *n* values for the channel. Once this calibration was accomplished, unsteady flow simulations were performed to route the PMF hydrographs generated by the hydrologic model through the river system. Bankfull conditions were considered as initial conditions. The hydrographs produced by the hydraulic model at select points within the river network were compared to the hydrographs generated by the hydrologic model to evaluate the effects on the peak magnitude and time.

3 RESULTS

Using HEC-GeoRAS, the results obtained from the HEC-RAS simulations were exported into ArcGIS and a PMF flood inundation map was generated (Fig. 3).

The maximum inundation occurred in the vicinity of the confluence between Whitethorn Creek, Mill Creek, and Dry Branch, where the terrain is flatter than the area located upstream. For the simulation, backwater effects were evaluated on the river sections located near the confluence and hydraulic structures, such as bridges and culverts. As expected for such an extreme event, the capacity of the bridges and culverts within the river network is insufficient to accommodate the passage of the PMF. Table 4 presents the PMF inundation results for the cross-sections where the water depth, corresponding discharge, flow area, and top width, are greatest (Fig. 3), representing the worst-case scenario for each river reach.

In order to better understand the magnitude of the obtained results, the PMF flood inundation map was compared against the Federal Emergency Management Agency (FEMA 2009) 100-year flood inundation map (Fig. 4).

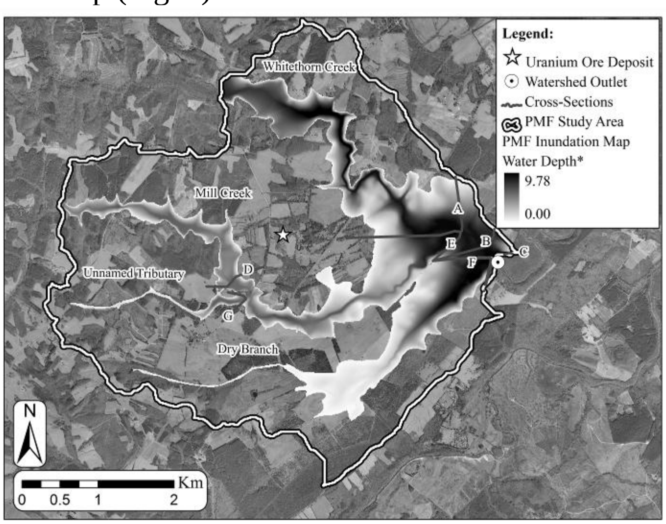

Figure 3. PMF inundation map showing cross-sections representing the "worst-case" conditions (see Table 4)

* Elevations measured from bankfull elevation.

Table 4. PMF results for cross-sections where the water depth, corresponding discharge, flow area, and top width, are greatest.

Reach name	PMF results			
	Depth** m	Q m^3/s	Flow Area m^2	Top width m
Whitethorn Creek				
Upper Reach-A	9.86	1212	9493	1851
Middle Reach-B	9.64	1556	10,483	2290
Lower Reach-C	10.01	1635	1944	385
Mill Creek				
Upper Reach-D	6.59	118	1452	378
Lower Reach-E	9.94	365	9569	1688
Dry Branch-F	10.54	40.76	5951	1011
Un-named Tributary-G	4.93	59.43	801	268

** Measured from the channel bottom.

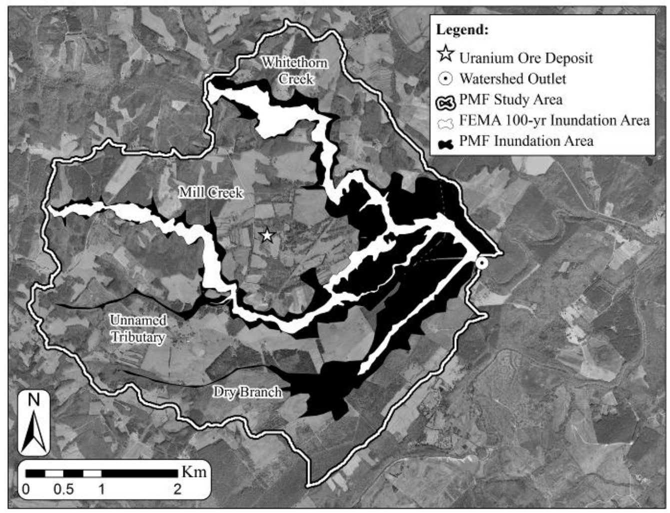

Figure 4. Flood inundated area comparison of the PMF against the FEMA 100-yr flood.

4 DISCUSSION

The obtained results clearly indicate the magnitude and catastrophic impact that a PMP event would have if it were to ever occur within the Whitethorn Creek study watershed. Modelling predicted that certain regions of the PMF study area would experience water depths of nearly 10m above bankfull conditions. In addition, the model forecasted that approximately 30% (6.6 km^2) of the 22 km^2 PMF study area would become inundated as a result of the PMP/PMF event.

The comparison with the FEMA 100-yr flood inundation map, which covers approximately 9% (2 km^2) of the study area, better illustrates that the area near the confluences of Whitethorn Creek, Mill Creek, and Dry Branch, is the most critically flooded area. As stated before, this region has a flatter topography than the upland portions of the watershed and is therefore more effected by extreme floods. In contrast, the upper reaches of Whitethorn Creek and Mill Creek are confined by the steep side slopes of their floodplains, significantly reducing the changes in the horizontal inundation extent with increasing flows.

5 CONCLUDING REMARKS

The PMF inundation map generated for the Whitethorn Creek study area predicts the water surface elevation and its extend for the theoretical worst-case rainfall event possible (PMP) within the watershed. Since no actual or observed data is available in this area to validate either models for such an extreme event, the best engineering practices have been employed to generate the most accurate results within the scope of this study.

6 ACKNOWLEDGEMENTS

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