ANALYZING THE EFFECTIVENESS OF USING TWO-DIMENSIONAL HYDRAULIC FLOODPLAIN MODELLING IN THE SIMS BAYOU WATERSHED

A Thesis

by

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ABSTRACT

With the widespread availability of two-dimensional (2D) hydraulic modelling, it is important to understand its potential advantages over currently accepted one-dimensional (1D) hydraulic models to further the disaster resiliency of communities in the future and more accurately predict the FEMA floodplain extents. Hydrologic Engineering Center – River Analysis System (HEC-RAS) 4.1 and 5.0.3 were selected as the 1D and 2D computational models, respectively, to compare their generation of the 100-year floodplain and the 10-year floodplain. A large and small storm were selected as inputs to identify any advantages of using one model or another based upon the size of the storm. The study was conducted in Sims Bayou Watershed of Houston, Texas.

1D HEC-RAS 4.1 models were downloaded for free from the Harris County Flood Control District (HCFCD) while the 2D model was created using the best available data closest to the development of the 1D models and implemented rain-on-grid where precipitation was applied directly to the 2D computational area. Inundation boundary maps, maximum water depth maps, and maximum velocity maps were created for both storms using both modelling methods.

The 2D model yielded inundation areas that covered over 40 square miles more than the 1D model inundated areas for the same storm. When values below one foot were removed from the 2D model's maximum depth, the floodplain became more similar to the 1D inundation map. However, there were several locations outside of the 1D floodplain with over a one foot depth of water in the 2D model, especially for the

larger 100-year storm. Therefore, the 2D model revealed areas not designated in current 1D floodplains where potential flood waters could threaten a community. However, the 2D model lacked the capability of modelling bridges that the 1D model contained; therefore, resulting in higher flow velocities in downstream areas of the watershed in the 2D model. This appeared though to have a minimal effect on the floodplain extents. Using 2D models to observe flood water propagations both during the river channel water collection and eventual channel overflow is important in understanding the disaster resiliency and vulnerability of the communities in the area; however, would be unnecessary for modelling smaller floods as the benefit of the 2D modelling of the floodplain would decrease.

DEDICATION

This Thesis is dedicated to my family who gives me unconditional love and support each and every day.

ACKNOWLEDGEMENTS

I would like to thank my family for raising me into the person I am today and guiding me with values of integrity, respect, and dedication. I would not be where I am today without them. I would like to thank my committee: Dr. Francisco Olivera, Dr. Philip Berke, Dr. Anthony Cahill, and Dr. Jacob Torres who was a special appointment to my committee that provided valuable guidance. My committee challenged me to think in new ways and guided me in my journey. I consider each of them great people, each dedicated to their passion, and serve as examples of integrity. I would like to especially thank Dr. Torres for his voluntary time spent guiding me through the frustrations of hydraulic modelling. I would also like to acknowledge Leslie Munoz, who conducted, explained, and provided her research on Sims Bayou to me.

Texas A&M and the Civil Engineering Department provided me with opportunities, support, and experiences over the years that I will carry with me the rest of my life. I am grateful to have been a part of the Institute for Sustainable Communities where Dr. Berke and Dr. Olivera helped me realize the value in interdisciplinary collaboration and engaging our research with the communities we studied for their betterment.

I am thankful for Dr. Olivera for also helping me realize after a study abroad in 2013 that water resources engineering was where my passion lied. Finally, I thank God for giving me strength, blessing me with an intellectual ability, and instilling me with a humility and humbleness that has carried me far in life thus far.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Francisco Olivera [Co-Chair] and Anthony Cahill of the Department of Civil Engineering, Professor Philip Berke [Co-Chair] of the Department of Landscape Architecture and Urban Planning, and special appointee Dr. Jacob Torres of Lockwood, Andrews, and Newnam, Inc.

The problem description identified in Section 2 was provided by Professor Olivera and Professor Berke. Elevation data acquired in Section 5.1 was provided by Professor Olivera. Methodology for 2D modelling in Section 5.3 and land use parameters in Section 5.3.1 were provided by Dr. Torres. Studies linking this study to interdisciplinary uses in Section 7.2 were inspired by Professor Bereke.

All other work conducted for the thesis (or) dissertation was completed by the student independently.

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NOMENCLATURE

1D	One Dimensional
2D	Two-Dimensional
DEM	Digital Elevation Model
FEMA	Federal Emergency Management Agency
GIS	Geographic Information System
HCFCD	Harris County Flood Control District
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modelling Software
NLCD	National Land Cover Database
NRCS	National Resources Conservation Service
RAS	River Analysis System
USACE	United States Army Corps of Engineers

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1. INTRODUCTION

Each year severe flooding devastates communities and results in loss of life. Therefore, it is imperative to be able to predict the extents of flood events and to identify vulnerable areas within a community in order to update policies and implement measures to lead to more disaster resilient communities. Currently, one-dimensional (1D) hydraulic models created using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) software package set the standard for the 100-year floodplain utilized by the Federal Emergency Management Agency (FEMA). 1D hydraulic models are generally acceptable under the assumption that two-dimensional (2D) flow doesn't occur. Meaning, a 1D model assumes water flowing within a creek or channel and its overbanks flow in the direction of the channel. 2D hydraulic models, on the other hand, do not restrict the water to flow in one direction. In a flat area (mostly <2% slope) like Houston, Texas, the 1D assumption may not hold true and could yield inaccurate inundated areas as a result. With the advent of 2D hydraulic models and their now free availability, it is essential to understand any benefits or advantages 2D modelling may have on floodplain determination, especially in an area such as Houston, one of the currently fastest growing cities in the United States. The currently accepted FEMA floodplain developed utilizing a 1D hydraulic model needed to be compared to the 2D model's results to determine the benefits or limitations of using 2D modelling for floodplain determination and if it could lead to safer, more disaster resilient communities.

Several works were analyzed involving the fundamentals of this study, the use of two-dimensional modelling. Two-dimensional hydraulic modelling was effectively used to model a dam breach in Baldwin Hills, California. The study concluded that the high resolution data input for the 2D model in addition to the finite volume algorithm implemented by 2D models had a significant impact in accurately modelling the dam breach as long as the upstream reservoir parameters were accurately identified; dam breaches naturally involve rapid flow changes and highly 2D flow behavior (Gallegos, Schubert, & Sanders, 2009). This study illustrates some benefits of 2D modelling, but does not apply it to a floodplain analysis.

Another study focused on modelling flooding of the Tiber River compared a 1D, 2D, and coupled 1D-2D model to compute the flood extents and then compare to remote sensed imagery of the flood. This study concluded that the 1D-2D coupled model yielded similar results to the fully 2D model. It is important to note that it was also concluded that the 2D models or 2D portions of the coupled model better represented the lateral floodplain propagation (Morales-Hernandez, Petaccia, Brufau, & Garcia-Navarro, 2016). This study concludes some benefits of using a 2D model but does not compare the modelling technique to the analysis of government accepted floodplains or current modelling standards used by the region.

A study focused on modelling a complex upland floodplain in River Wharfe, United Kingdom, of a 6 km section of a reach also found that the 1D HEC-RAS model used could not match the measured flood's extents without having to incorrectly parameterize the channel to force the results to match, whereas, the 2D model matched the flood extents significantly more without unrealistic parameter changes (Tayefi, Lane, Hardy, & Yu, 2007). This study supports the need for the implementation of a 2D floodplain analysis, especially in an area with several relatable research studies to create a potential, unique future impact that might not otherwise be possible.

One study on urbanization effects on rainfall runoff exists for Sims Bayou of Houston, Texas, conducted by Leslie Munoz. Her study utilized impervious cover to represent urbanization between the years of 1980 and 2000. The study concluded that urbanization between 1980 and 2000 led to a 5% increase in peak flow, resulting in a 12.7% increase in floodplain area for the 100-year storm (Munoz, 2015). This study used 1D steady state HEC-RAS models which are suspected to not be properly representing the flow of the flatland area. The study used a 20-year urbanization analysis period. Additionally, Sims Bayou is unique in that the Institute for Sustainable Communities (ISC) at Texas A&M conducts interdisciplinary research in the area focused on community engagement, social vulnerability, and education within communities of the Sims Bayou watershed; therefore, increasing the potential impact of the results of the study if applicable to future interdisciplinary studies being conducted within the region (TAMU Institute for Sustainable Communities, 2017).

The HCFCD publishes their HMS and 1D RAS models used for determining the 100-year floodplain in Harris County. The 1D HEC-RAS models, using HEC-RAS 4.1, currently serve as the standard for determining the 100-year floodplain for the region (Harris County Flood Control District, 2008). HEC-RAS is also one of the most widely used software packages since it is freely available to the public and easily accessible.

There are multiple software packages capable of 2D modelling. Horritt and Bates compared HEC-RAS 1D, TELEMAC-2D, and LISFLOOD-FP. It was concluded that all models could match a storm they were calibrated to; however, HEC-RAS was the best model in terms of predictive performance and for calibrating with a lack of parameterization data; therefore, supporting the use of the same platform of HEC-RAS to perform the 2D modelling (Horritt & Bates, 2002). Additionally, HEC-RAS 5.0.3, the 2D capable version, is also freely available to the public. HEC-RAS 5.0.3 utilizes a 2D computational mesh with underlying terrain and land use raster data. A finite volume algorithm and diffusion wave equation allow the flow to be modeled two-dimensionally. HEC-RAS 5.0.3 is available at the USACE HEC website (U.S. Army Corps of Engineers, 2016). Utilizing the 2D capability of HEC-RAS 5.0.3 requires much data. A list of detailed input parameters and requirements were found in the HEC-RAS 5.0.3 2D Modelling User's Manual (Brunner & CEIWR-HEC, 2016).

A Digital Elevation Model (DEM) must be input into a 2D model. Sanders conducted a study on DEM's available online and concluded the highest density spatial resolution available is best to use for 2D modelling; however, 10x10 meter resolution DEM's could result in underestimated floodplain extents of up to 25% without properly pre-processing of the DEM local minimums (Sanders, 2007). However, using data such as LIDAR can lead to much redundancy in the DEM and increase computational time significantly (Marks & Bates, 2000). Using high resolution elevation data though is recommended in the HEC-RAS User's Manual (Brunner & CEIWR-HEC, 2016).

A land cover dataset or land use regions must be input into 2D models with each land cover field associated with a manning's roughness coefficient. The land cover dataset available closest to the date of the models within the HCFCD Model and Map Management system was found, which was the 2006 National Land Cover Dataset (NLCD) (U.S. Geological Survey, 2016). However, traditional publications relating manning's roughness coefficient to the NLCD fields cannot necessarily be used. Manning's roughness is not the same for a 1D model land use as it is for a 2D model land use (Engineers Australia Water Engineering, 2012).

2. PROBLEM DESCRIPTION

Floodplain models used to guide policy and development are based upon 1D steady state hydraulic models, which may be missing significant flood properties or inundated areas the latest 2D hydraulic models could find. The latest technological advancements in hydraulic modelling has resulted in the capability of modelling in two dimensions in an unsteady state with excess rainfall able to be applied directly in the hydraulic model instead of using instream hydrographs from a hydrologic model. 1D models are based upon a riverine system; meaning, water starts in a defined channel and overflows into the overbanks. 2D models utilizing rain-on-grid start with precipitation input over the entire defined terrain and routes the water to the channel.

According to the HCFCD, Tropical Storm Allison caused five billion dollars of damages in Harris County. Policies, insurance options, development projects, and the general public are affected by accepted floodplains.

Figure 1: Flooding from Tropical Storm Allison in Sims Bayou Watershed near the cul-de-sac of Simsbrook and Buffalo Speedway (reprinted with permission of the Institute for Sustainable Communities)

As shown in the image above, flood waters are outside of the main channel. Water outside the main channel in an area like Houston without gradually steep elevation changes is capable of creating 2D flows away from the main channels and flooding other areas of a community that would have otherwise been assumed a low risk zone.

It is imperative to understand the differences between 1D and 2D hydraulic modelling as it pertains to floodplain determination. Potential improvements in floodplain modelling techniques can lead to safer, more disaster resilient communities, better public policies, and a greater understanding of affected areas during a flood.

3. STUDY AREA

Within Houston, Texas, the Sims Bayou Watershed was selected as the study area and is shown below in Figure 1 (Harris County Flood Control District, 2017b). Sims Bayou was selected as the study area due to past research projects in the area, the readily available data, and its mildly sloped land. The downstream direction of the main reach goes from the western side to the eastern side of the watershed. Hydraulic and hydrologic models were freely available from download for the region from the HCFCD.

Sims Bayou watershed has an area of 94 square miles and as of 2010 a population of about 285,000 people. The watershed consists of 121 miles of open streams total. However other than its flatlands, Sims Bayou was a worthwhile selection for analyzing because this watershed was used for a past study quantifying urbanization trends in the region and their effects on the runoff, which could be useful for drawing future comparisons in parallel with 2D modelling (Munoz, 2015). In addition, the Institute for Sustainable Communities is active in the region conducting interdisciplinary studies that could potentially have a future impact on this study. The Harris County Flood Control District (HCFCD) states, "The watershed is almost fully developed, with the exception of the middle reaches around SH 288 where there are large undeveloped areas. Development is expected to continue at a fairly steady pace" (Harris County Flood Control District, 2017a). The HCFCD's statement supports that the Sims Bayou watershed has experienced development over the past decades and will continue to further develop into the future; therefore, identifying the need for continually better, versatile methods of planning for flood disaster and a continued pursuit of accurate floodplains from which to make policy decisions.

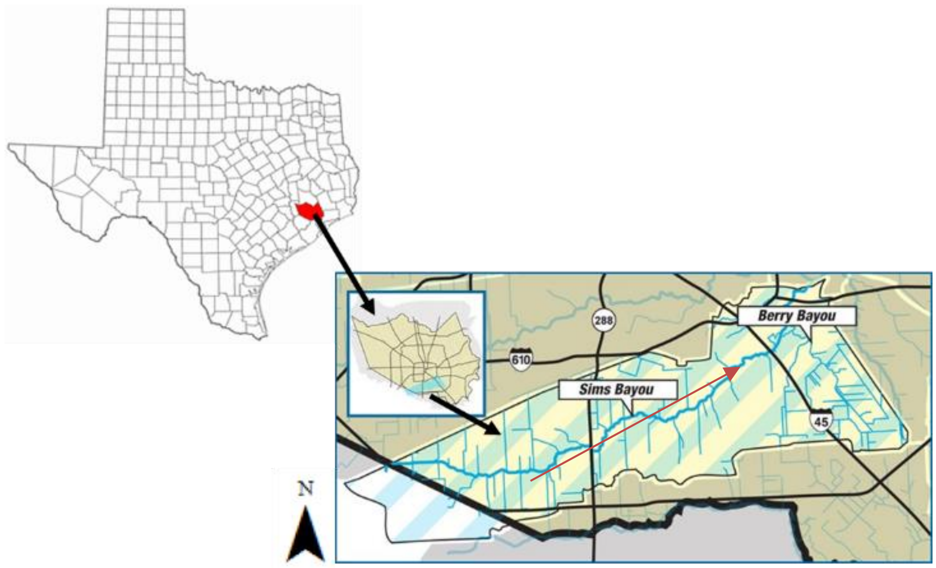

Figure 2: Map of study area - Sims Bayou Watershed, Houston, Texas (reprinted with permssion of Harris County Flood Control District, 2017b)

4. HYDRAULIC MODELLING THEORY

4.1 1D Steady State HEC-RAS Modelling

1D steady state models assume flow is constant with time; meaning water depths will not change with time at a given cross-section. The flow entered in the steady state model is usually the peak flow or portion of the peak flow of the hydrograph from a storm for that reach. Below is the equation utilized for basic steady state calculations (U.S. Army Corps of Engineers, 2010).

Equation 1: Energy equation iteratively solved for basic profile calculations for 1D steady state

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} + h_e$$

Where:

Z_1, Z_2 = elevation of the main channel inverts

Y_1, Y_2 = depth of water at cross sections

V_1, V_2 = average velocities (total discharge/ total flow area)

a_1, a_2 = velocity weighting coefficients

g = gravitational acceleration

h_e = energy head loss

According to the HEC-RAS reference manual, limitations include the assumption of a steady state, gradually varied flow, one-dimensional flow, and less than 10% slopes.

4.2 2D Unsteady State HEC-RAS Modelling

The 2D HEC-RAS model employs unsteady state modelling; meaning, flows change with time. For the model used in this study, the diffusion-wave form of the momentum equation was employed for its stability and computational efficiency. The diffusion-wave equation is found below (U.S. Army Corps of Engineers, 2016):

Equation 2: Diffusion-wave form of the momentum equation

$$\frac{n^2|V|V}{(R(H))^{4/3}} = -\nabla H$$

Where:

V = velocity vector

R = hydraulic radius

∇H = surface elevation gradient

n = Manning's n

Finite volume analysis is used to solve for the water surface at each cell in a 2D computational mesh, interpreting elevation-storage relationships from the terrain, which allows the cells to be partially wet or partially dry. The greatest advantage is the capability of 2D flow, allowing water to flow in different horizontal planar directions. However, one significant limitation is the disability to model bridges in 2D models (Brunner & CEIWR-HEC, 2016).

5. METHODOLOGY

The floodplain models developed by the HCFCD for Sims Bayou were chosen as the basis for comparison of the potential benefit, effectiveness, or difference between using a 2D model and 1D steady state models. HCFCD developed 1D steady state models that are available to the public to compute the 100-year and 500-year floodplains for Sims Bayou. However, for the purposes of this study, the models were used to create a 10-year and 100-year floodplain to illustrate if the model output differences are more or less significant with a smaller or larger flow storm when modeled in 1D versus 2D. A comparable 2D model was developed for this study and used to illustrate significant advantages or differences.

HEC-RAS was chosen as the modelling software to use for a variety of reasons. The most recent version released during the time of this study, HEC-RAS 5.0.3, was capable of executing 1D, coupled 1D/2D, and 2D hydraulic models. The 1D steady state models used by the HCFCD were developed in HEC-RAS. Additionally, HEC-RAS was freely available from the USACE.

The goal of this study was to compare the latest advancements in 2D hydraulic computations with older 1D computational method standards accepted by FEMA and Harris County. 2D hydraulic models utilizing rain-on-grid was the latest advancement at the time of this study. Rain-on-grid is a boundary condition that allowed excess precipitation to be input directly over a terrain in the HEC-RAS model. In order to meet the objective of comparing floodplain outputs from a 1D steady state and 2D unsteady state hydraulic model, the following methodology was developed for the 1D and 2D models and tasked into the steps listed:

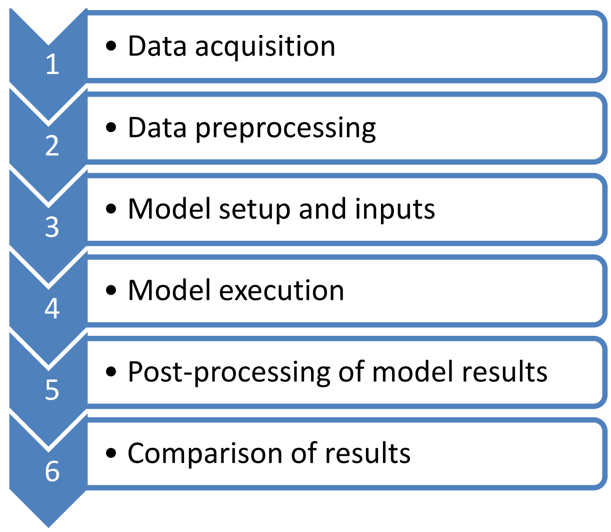

Figure 3: Methodology used for 1D and 2D modelling of Sims Bayou floodplains

5.1 Data Acquisition

In order to execute the hydraulic model runs, several types of datasets were required. These datasets included but were not limited to geometric information, elevation data, land cover data, and hydrologic information. The data specifically used for this study included:

a) Hydrologic Inputs: HEC-HMS models including the 100-year and 10-year design storm hyetographs and calculated hydrographs for Sims Bayou were obtained from the Model and Map Management System from the Harris County Flood Control District (Harris County Flood Control District, 2008).

b) <u>1D Hydraulic Models:</u> 1D steady state HEC-RAS models were obtained from the Model and Map Management System from the Harris County Flood Control District. These models included all required flow information, geometries, land use data, and execution plans used to develop the current FEMA accepted floodplains for Sims Bayou (Harris County Flood Control District, 2008).

c) <u>Digital Elevation Model (DEM):</u> A 3-meter DEM of the Sims Bayou region was downloaded from the NRCS Geospatial Data Gateway. The DEM's used were developed from the National Elevation Dataset. The 3-meter grid was the finest resolution available closest to the year 2007, which was the time of development of the models used to create the FEMA floodplains for the region used in this study. The DEM files were originally acquired and processed by Leslie Munoz and used for a prior study of Sims Bayou. The DEM was projected in the same projection of the data frame using the *Project Raster* tool. The coordinate projection of the data frame was the same projection used by the HCFCD when developing the 1D HEC-RAS models, NAD_1983_StatePlane_Texas_South_Central_FIPS_4204_Feet. The 3-meter DEM tiles were mosaicked together using the *Mosaic to New Raster* tool of ArcMap and converted from metric to customary units. The grid sizes contained slight variations and were resampled using bilinear interpolation into a 15-foot gridded format (National Resources Conservation Services, 2014).

d) <u>Land Use Data:</u> Land use data was obtained through the National Land Cover Database 2006 (NLCD 2006). This data was the closest available land use data to the time the 1D HEC-RAS models were developed (U.S. Geological Survey, 2016).

e) Major Roads: A major road network shapefile for Houston, Texas, which includes Sims Bayou, was obtained from the GIS database of the Houston-Galveston Area Council (H-GAC) (Houston-Galveston Area Council, 2016).

5.2 1D HEC-RAS Modelling

1D HEC-RAS model outputs were developed to compare with the 2D HEC-RAS model outputs. The 1D HEC-RAS models were previously developed and setup by the HCFCD for determining the Sims Bayou floodplain in the year 2007; therefore, the model was simply executed and the results were analyzed. The following procedure was used to execute the 1D hydraulic model and obtain the results.

5.2.1 Model Setup

The 1D HEC-RAS models acquired form the Model and Map Management System were downloaded as fourteen different 1D steady state models. Two models represented the main reach of Sims Bayou while the other twelve represented significant tributaries to the main reach.

Geometric cross sections, manning's values, and bridges/culverts were included in the model when obtained. Calibration was not necessary since these models were already developed and were the models used in developing the FEMA floodplain in the year 2007. Therefore, these models were calibrated already for their intended use to determine the Sims Bayou floodplain, which is the same use of the models for this study.

Steady flow data for each reach was also was acquired with the models from the HCFCD. Flows were input by the HCFCD for the 10, 50, 100, and 500 year storms. Only the 10 and 100 year steady flow data were kept for the purposes of this study. These flows were obtained from a HEC-HMS model output for Sims Bayou developed by the HCFCD that had hyetographs input for the 10, 50, 100, and 500 year design storms. The peak flows from the HEC-HMS output hydrographs and peak flows at flow change locations were input by the HCFCD into the 1D HEC-RAS models as steady state flow profiles. The figure below illustrates a steady flow dataset used for the main reach of Sims Bayou. As previously mentioned, each flow entered for the 4 profiles was obtained by the HCFCD from the HEC-HMS file they developed for Sims Bayou.

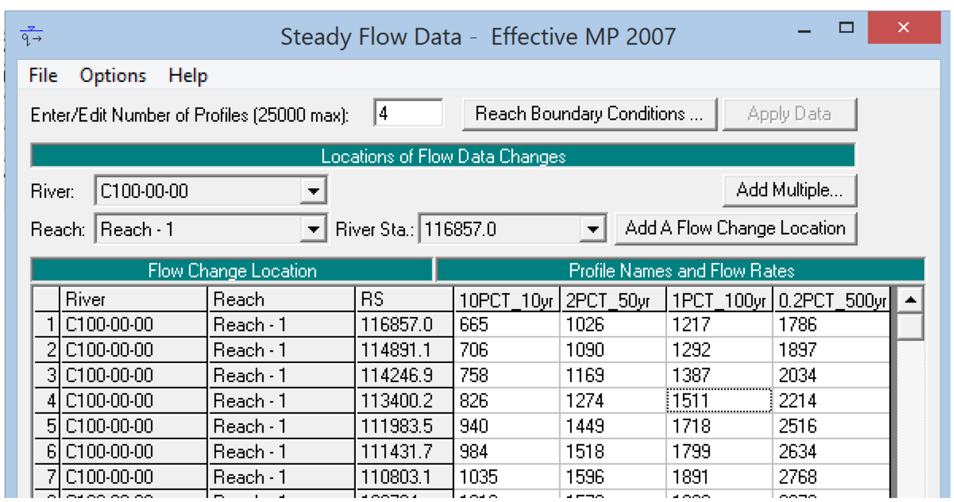

Figure 4: Example of 1D steady flow data file from HEC-RAS for Sims Bayou's main reach C100-00-00

5.2.2 *Model Execution*

The steady flow analysis plan *Effective MP 2007* was ran for each 1D HEC-RAS model. This was the predeveloped analysis plan used by the HCFCD where "MP" stands for "Multiple Profiles." The calculation tolerances and options were unchanged from what the HCFCD chose. A subcritical flow regime was selected, which was the default, since large storms were being modeled in a relatively flat region of Houston (less than 2% slope) as shown in the figure below.

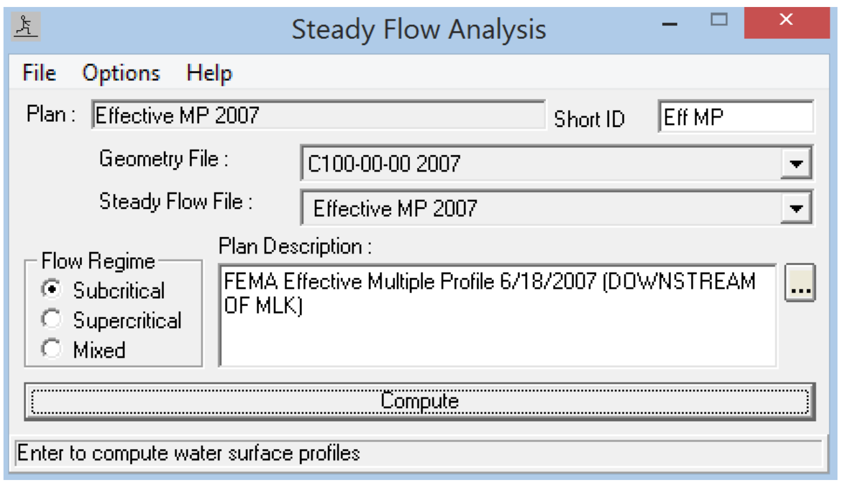

Figure 5: Example of steady flow analysis file setup for C100-00-00 of Sims Bayou

5.2.3 *Model Results and Post-Processing*

Each of the fourteen models produced water surface profiles for the 10 and 100 year design storms. Additionally, average velocities for the overbanks and main channels at each geometric cross section were output for each flow profile of each model. The figure below illustrates the output of the 1D steady state model for the 10 and 100 year storm at a cross section. The water surface elevation and water depth was calculated at every cross section in each model.

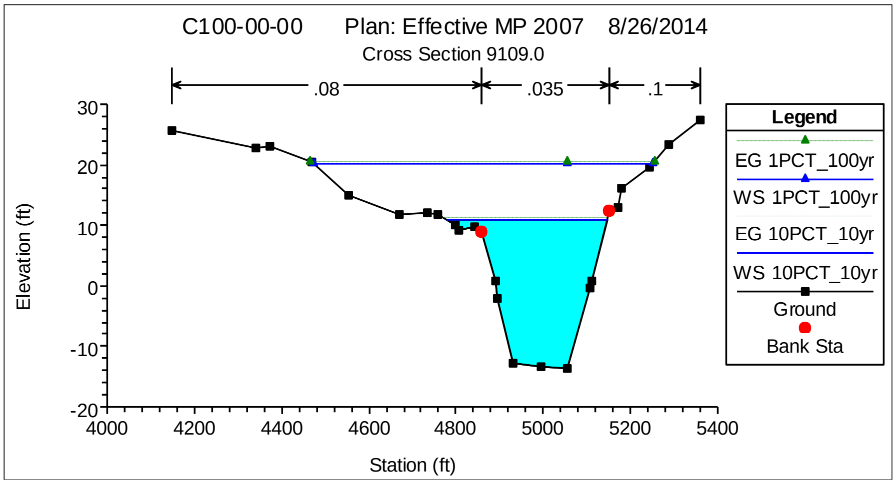

Figure 6: Example of 1D model output for a cross section within Sims Bayou's main reach

The fourteen model outputs were exported to ArcGIS to be converted to a grid format, a format comparable with the 2D model results. To accomplish this task, water extent, water depth, and velocity data for the results of the 10 and 100 year design storm were first exported. In order to generate a water surface map to display the three output types from the models, HEC-GeoRAS was added into ArcMap. The exported HEC-RAS files were first converted to *.xml* files to be in a format recognizable by GeoRAS. The preprocessed DEM was used as the terrain reference. For each of the fourteen 1D models, a GeoRAS project was created by using *RAS Mapping →Layer Setup*. Then the *Import RAS Data*, *Inundation Mapping*, and *Velocity Mapping* GeoRAS commands were used in that order to generate a water extents, water depth, and velocity data map in a gridded format for each of the two storms for each model, resulting in 84 total raster files.

The *Mosaic to New Raster* tool was used to combine the 6 sets of raster files (1 set of 14 files for each of the three output types for each of the two storms). Some files contained overlapping areas; therefore, when mosaicking, the tool was set to use the maximum depth or velocity value of any two overlapping areas. The results were shown briefly summarized in the table below and detailed in the figures below.

Table 1: Brief summary of 1D HEC-RAS maximum preliminary results

	10-year storm	100-year storm
Inundation Extents	4.82 sq mi	15.3 sq mi
Max Water Depth	25.8 ft	33.9 ft
Max Velocity	10.7 ft/s	12.0 ft/s

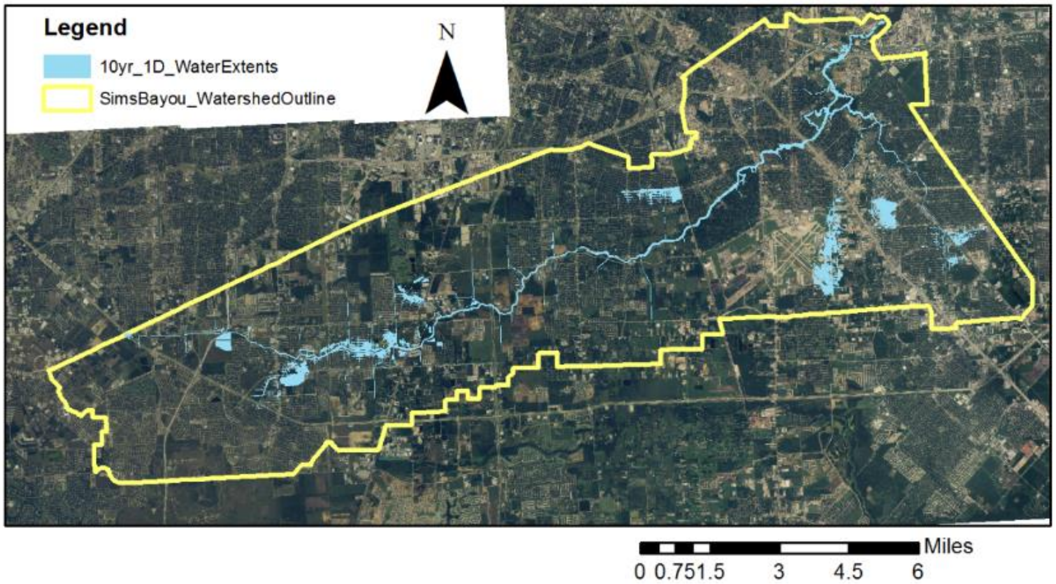

Figure 7: 1D flood water extents for the 10 year storm

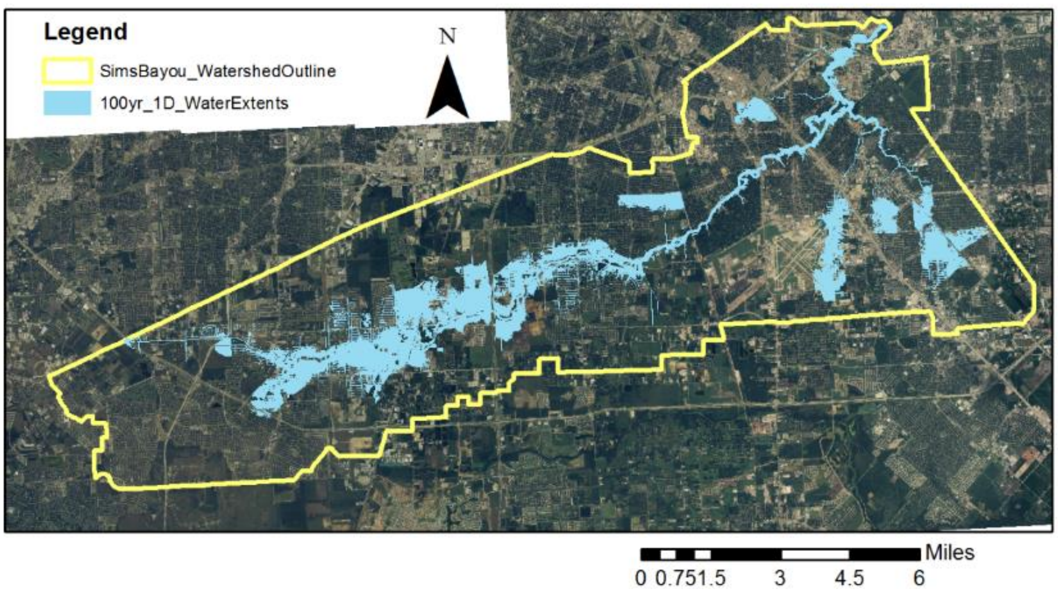

Figure 8: 1D flood water extents for the 100 year storm

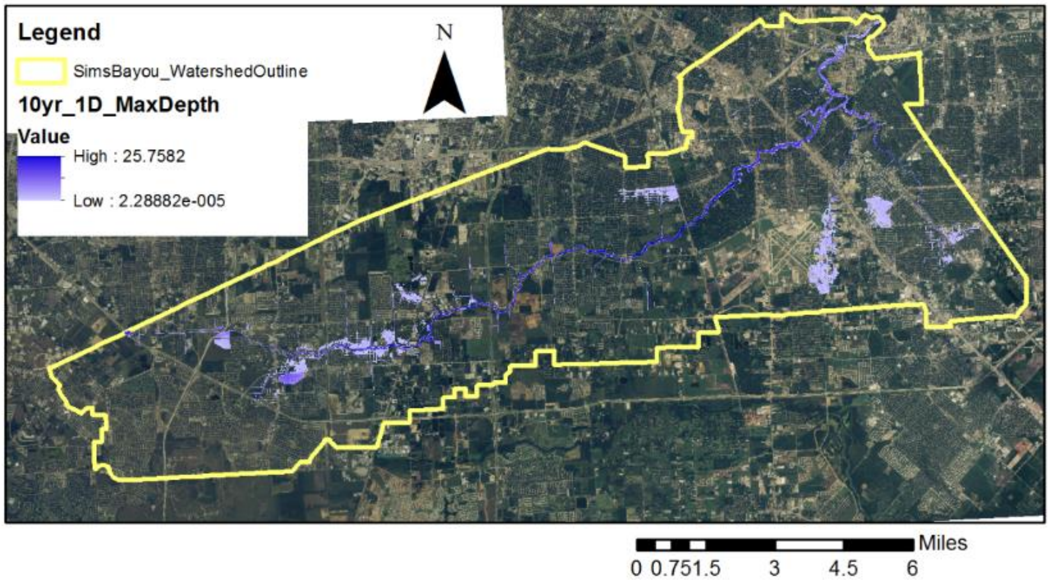

Figure 9: 1D max depth for the 10 year storm

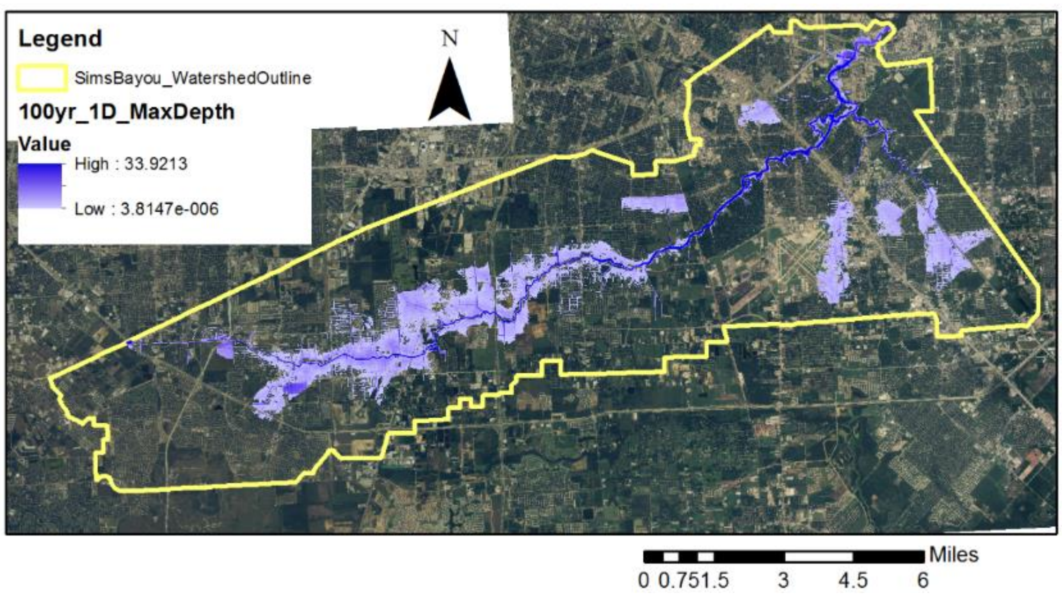

Figure 10: 1D max depth for the 100 year storm

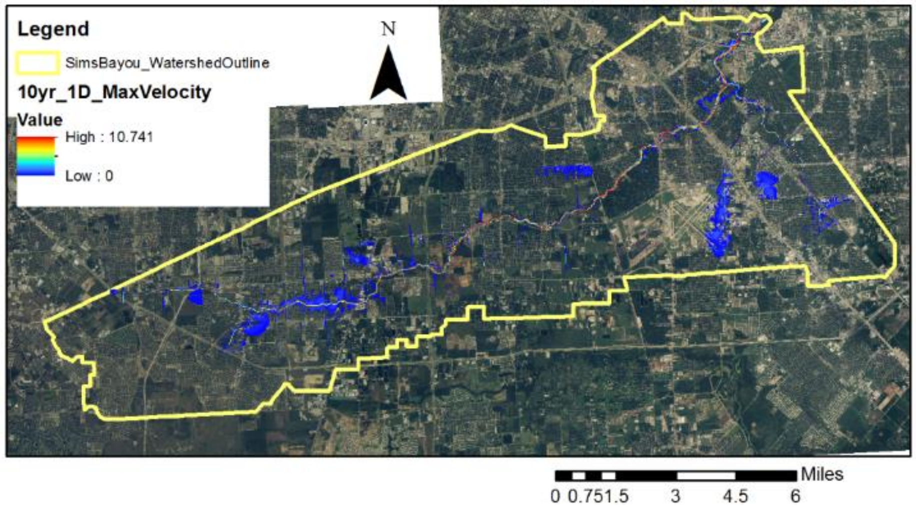

Figure 11: 1D max velocity for the 10 year storm

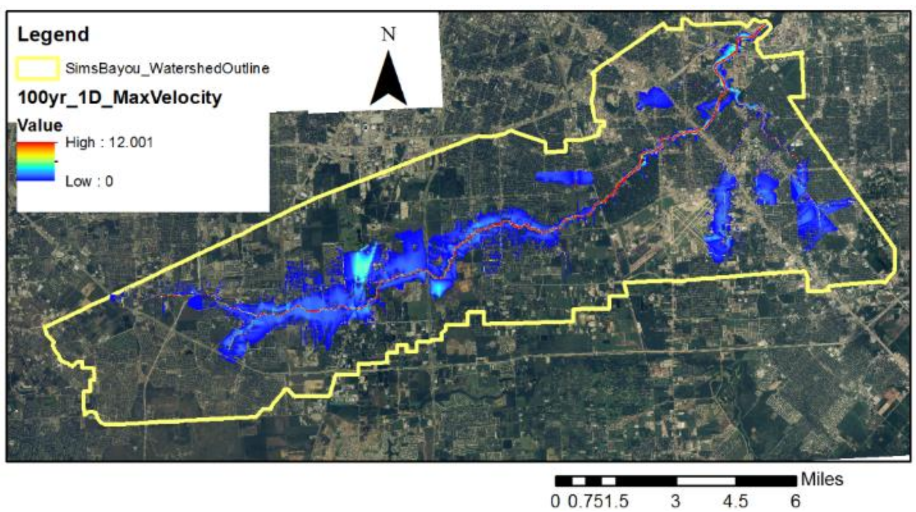

Figure 12: 1D max velocity for the 100 year storm

5.3 2D HEC-RAS Modelling

One 2D model was created for the Sims Bayou watershed. Unlike the 1D HEC-RAS models, the 2D models were run in an unsteady state. The model was ran for the 10 and 100 year design storms. The results of the 2D model were used to compare to the results of the 1D model and illustrate any differences and reasons for those differences. Inundation extents, water depth, and velocity maps were created. The 2D model setup and execution followed the HEC-RAS 5.0 2D Modelling User's Manual (Brunner & CEIWR-HEC, 2016). This method was used to create and compute the desired maps and was outlined below.

5.3.1 Model Setup

The 2D HEC-RAS model required more detailed inputs than the 1D HEC-RAS models. A comparison of the model inputs required for this study were shown in the table below.

Table 2: Comparison of 1D and 2D HEC-RAS model inputs

	1D Model	2D Model
Geometry Type:	Terrain cross sections covering channels and overbanks of Sims Bayou	2D computational mesh on entire terrain of Sims Bayou
Land Use:	Manning's values entered in cross section profiles	Manning's values associated with land cover type
Boundary Condition:	Flow rates	Excess precipitation
Geometry Source Data:	Survey data	DEM

First, the 15-foot DEM of Sims Bayou was input into the model to be used as the terrain. The NLCD 2006 was then input to provide land cover data accurate for the time period of the DEM and 1D HEC-RAS models. Manning's values were associated with each land cover type based on the HCFCD'S draft of Two-Dimensional Modelling Guidelines and not traditionally used manning's values for 1D models for the same land cover because manning's values for use in a 2D modeled area differ (Harris County Flood Control District, 2017c). Since the NLCD 2006 did not have well-defined, high resolution land use type over the main reach of Sims Bayou, an override *2D Area Mann n Region* was inserted over the main channel of the main reach, C100-00-00, of Sims Bayou and given a value of 0.04, consistent with the manning's values used in the main channel for the HEC-RAS 1D model but rounded up to the nearest hundredth.

Next a 2D computational mesh area was input over the terrain. The mesh was drawn over the DEM areas that encompassed the Sims Bayou watershed. The watershed outline area was exported from HEC-HMS and represented the land receiving precipitation within the HEC-HMS model. The mesh was generated with 200-foot by 200-foot computational cells. The cell size was determined from similar, private 2D models created for a different region of Houston and other privately employed studies. HEC-RAS allowed break lines to be entered into the 2D mesh. Break lines caused the 2D mesh to regenerate smaller, higher resolution cells along both sides of the break lines and are used at areas with drastic elevation changes. A major roads network was imported for the Sims Bayou watershed, which was used as a guide for entering the break lines. Break lines were also input along the banks of the main reach, the edges of large ponds, and other roads with relatively high embankments. The figure below shows a screen capture of the geometry file of the 2D model.

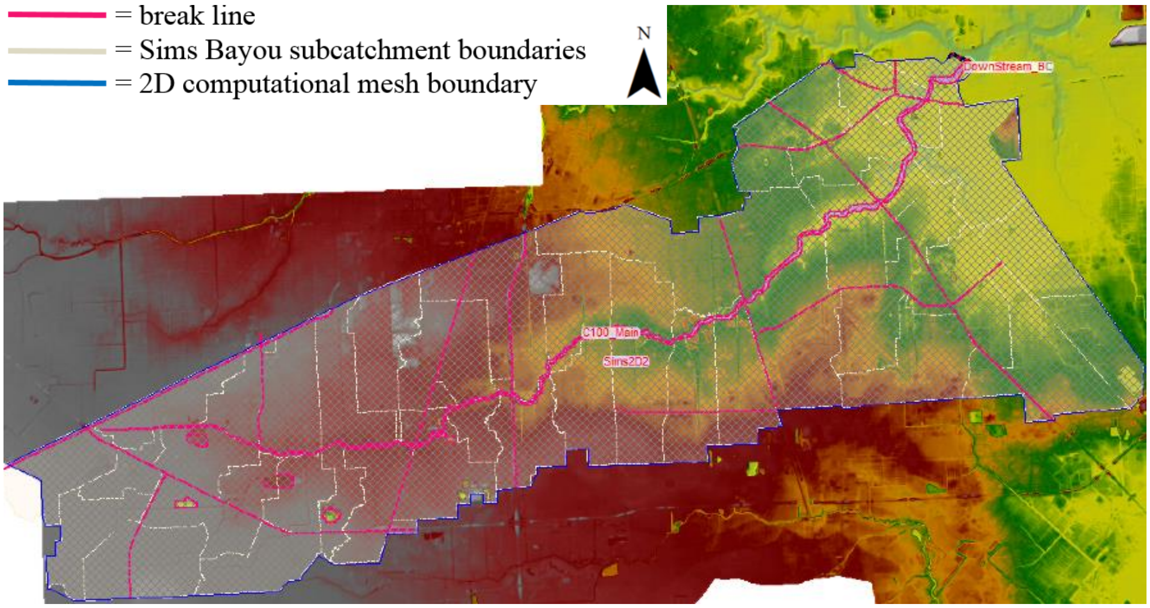

Figure 13: Screen capture of 2D geometry file

Excess precipitation for the 10-year and 100-year storm was taken from a sub-catchment of the Sims Bayou HEC-HMS model and entered as a flow boundary condition. Excess precipitation was used because HEC-RAS does not account for infiltration. HEC-RAS uniformly applied the excess precipitation over the 2D area since the excess precipitation among all the sub-catchments did not vary by more than about 0.03 inches for the 10 and 100 year storm. Finally, a downstream boundary condition was entered as a normal depth of 0.0001, which was consistent with the downstream boundary condition of the main reach of the 1D HEC-RAS model. Since no 2D calibration criteria exists and run times of over 1.5 hours occurred, the model employed the most accurate data available for the time period of the study. No flow gages were available in the overbanks of the model.

5.3.2 Model Execution

For the 2D model to compute using the full length of time of the excess precipitation file, the simulation time was set to match that length of time. Default calculation tolerances were used. The computational time step was set at 1 minute. After the computation was run for the 100 and 10 year storm, this time step was checked to ensure it satisfied the Courant condition (Brunner & CEIWR-HEC, 2016).

Equation 3: Courant condition used to validate computational time step used

$$C = \frac{V\Delta T}{\Delta X} \leq 2.0 \quad (with\ a \max\ C = 5.0)$$

Where:

C = Courant Number

V = Velocity (feet per second)

ΔT = Computational Time Step (seconds)

ΔX = Length of One Grid Face

To be conservative, the Courant equation was checked using the 100-year run since the 100-year storm produced a higher average maximum velocity than the 10-year storm. The mean velocity for the 100-year storm was 0.43 feet per second with a standard deviation of 0.54 feet per second for a right-tailed distribution. For practical reasons, the maximum velocity for use in the equation was taken as 3 standard deviations to the right of the mean or 2.05 feet per second. The highest velocity was about 14 feet per second; however, velocities this high made up an insignificant percentage of the maximum velocity values. 200 feet was used for ΔX, 60 seconds for

ΔT, and 2.05 feet per second for V, which resulted in a Courant number of 0.615 which is less than 2.0; therefore, the condition was satisfied.

5.3.3 Model Results and Post-Processing

After the model computations were finished, the results were viewed in *RAS Mapper*. The inundation boundary, maximum water depth, and maximum water velocity maps were exported to GIS for comparison to the 1D HEC-RAS results. Only 0.07% of a western portion of the watershed was not contained in the terrain and was assumed to have an insignificant impact on the results of this study. A brief summary of the results is shown in the table below followed by detailed figures:

Table 3: Brief summary of 2D HEC RAS maximum preliminary results

	10-year storm	100-year storm
Inundation Extents	45.9 sq mi	61.7 sq mi
Max Water Depth	51.5 ft	60.3 ft
Max Velocity	13.1 ft/s	14.1 ft/s

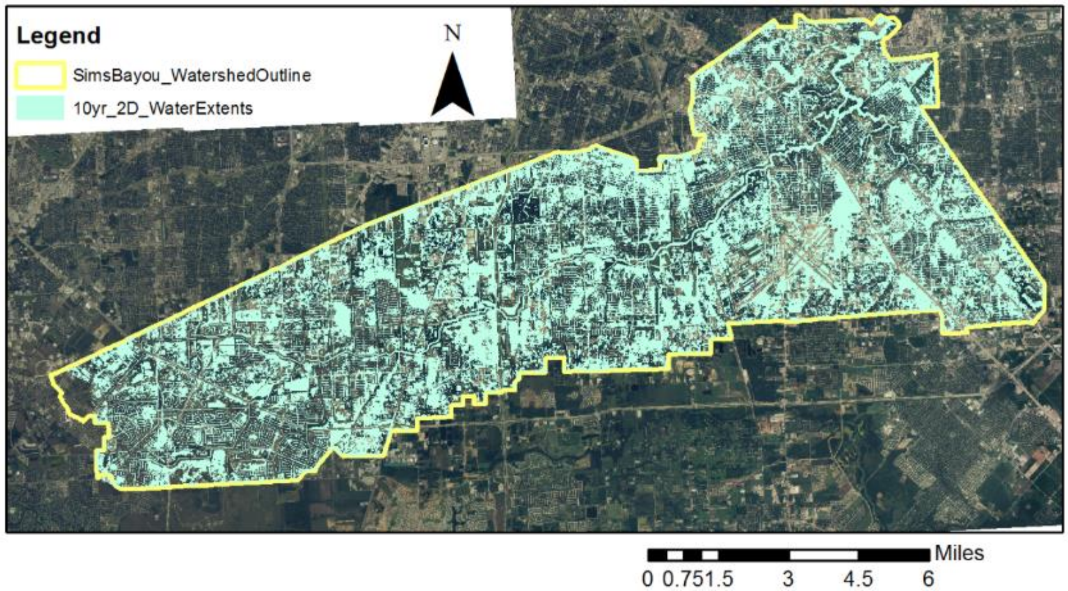

Figure 14: 2D flood water extents for the 10 year storm

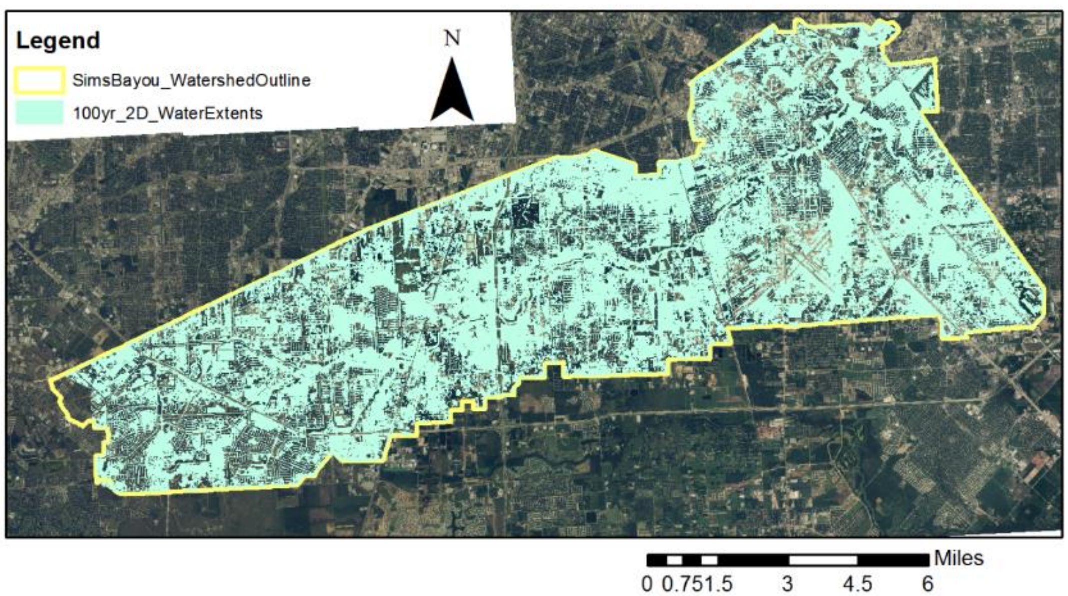

Figure 15: 2D flood water extents for the 100 year storm

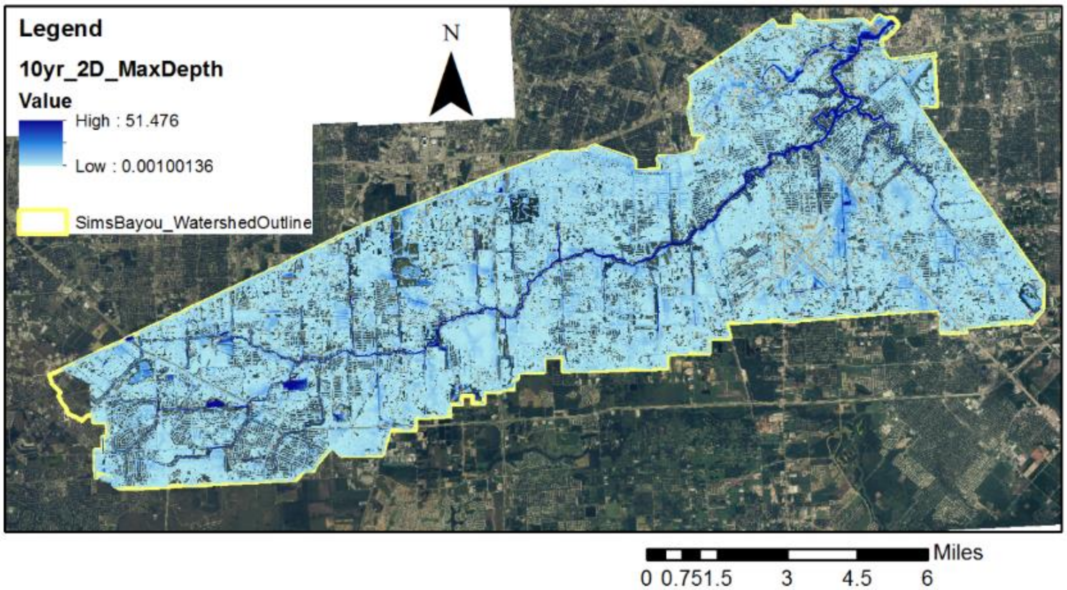

Figure 16: 2D max depth for the 10 year storm

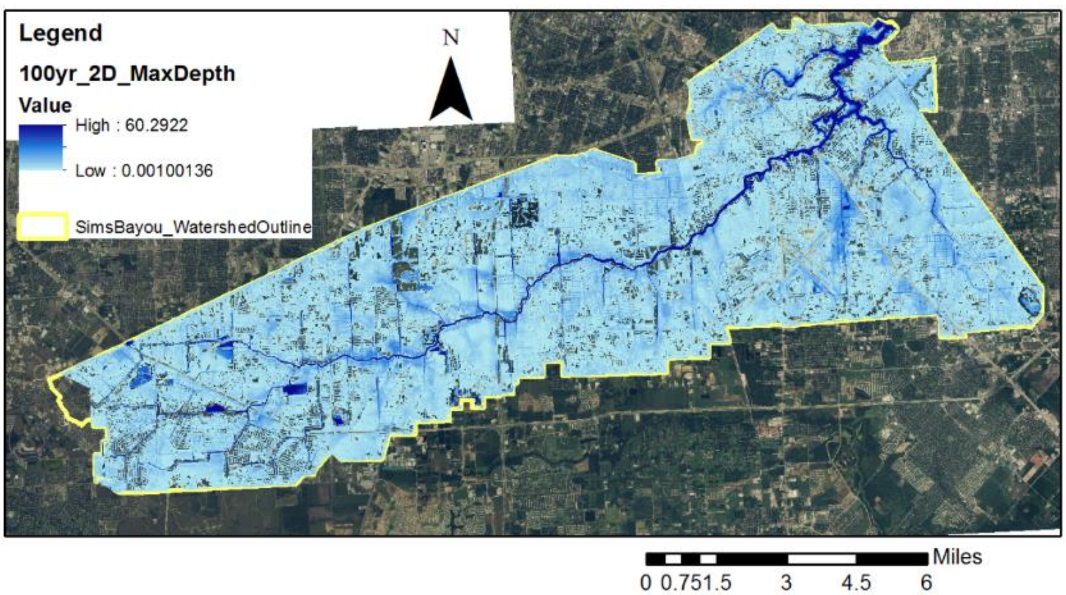

Figure 17: 2D max depth for the 100 year storm

High flow depths of 51 and 60 feet only occurred at one deep detention pond in the southwestern region of the watershed where the DEM contained lower elevations than the 1D model geometry.

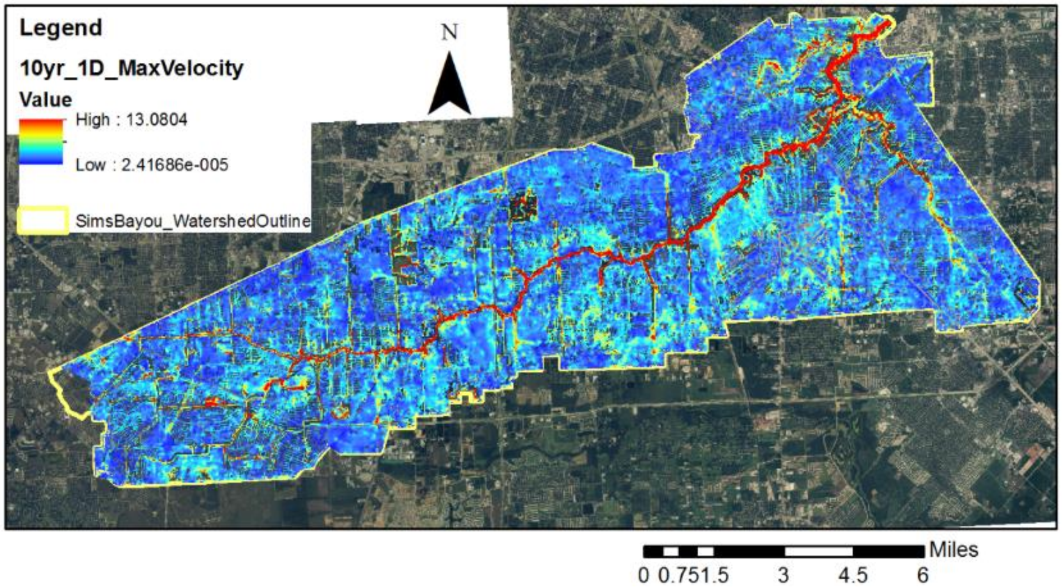

Figure 18: 2D max velocity for the 10 year storm

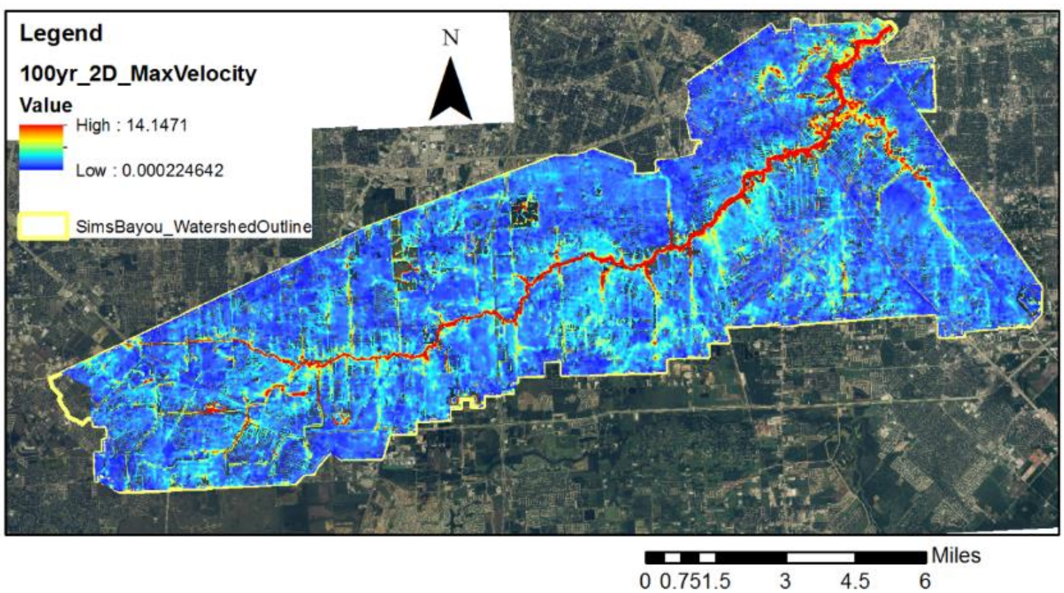

Figure 19: 2D max velocity for the 100 year storm

5.4 Comparison of Results

Velocity maps, inundated area maps, and water depth maps were all compared in ArcGIS. To compare the inundated area or water extents maps, the inundated boundary for the 1D 10-year storm was overlaid on the 2D 10-year storm layer with the same process being used for the 100-year storm maps. The inundated area comparison is shown in the figures below.

Following the inundation boundary comparison is the maximum water depth comparison between the 1D and 2D models. To compare water depth maps, the raster files needed post-processing. All cells with "NoData" values were converted to a value of zero using the *Raster Calculator* of ArcGIS in order to subtract the 1D water depth raster file for a storm from the 2D water depth raster file. The watershed boundary was used as a computational mask so no values outside of the watershed were calculated and incorrectly considered. After subtracting the 1D depths from the 2D depths for the 10 and 100 year storms, all values of zero were then converted back to "NoData" values, so areas where there was no inundation in either the 1D or 2D models would not be mistakenly measured. The difference in maximum water depth between the 1D and 2D models for the 100 and 10 year storms are shown in the figures below.

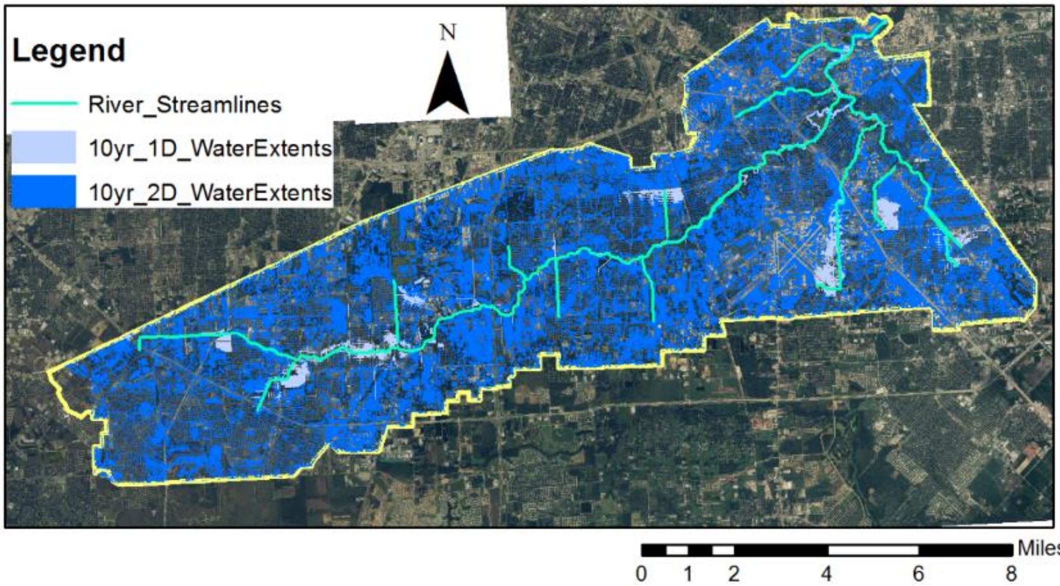

Figure 20: 1D versus 2D inundation boundary for the 10 year flood

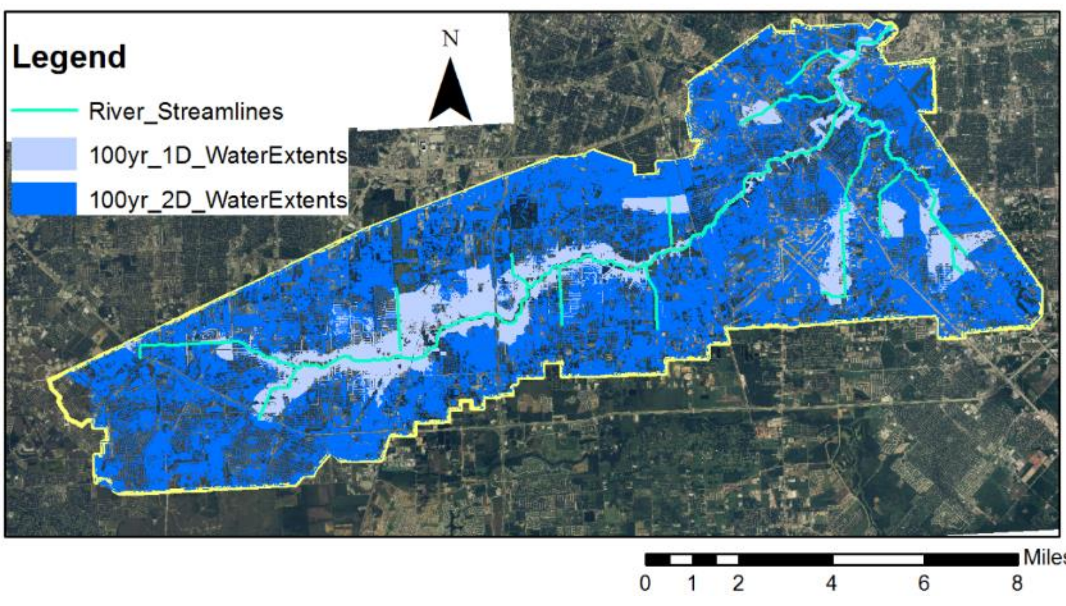

Figure 21: 1D versus 2D inundation boundary for the 100 year flood

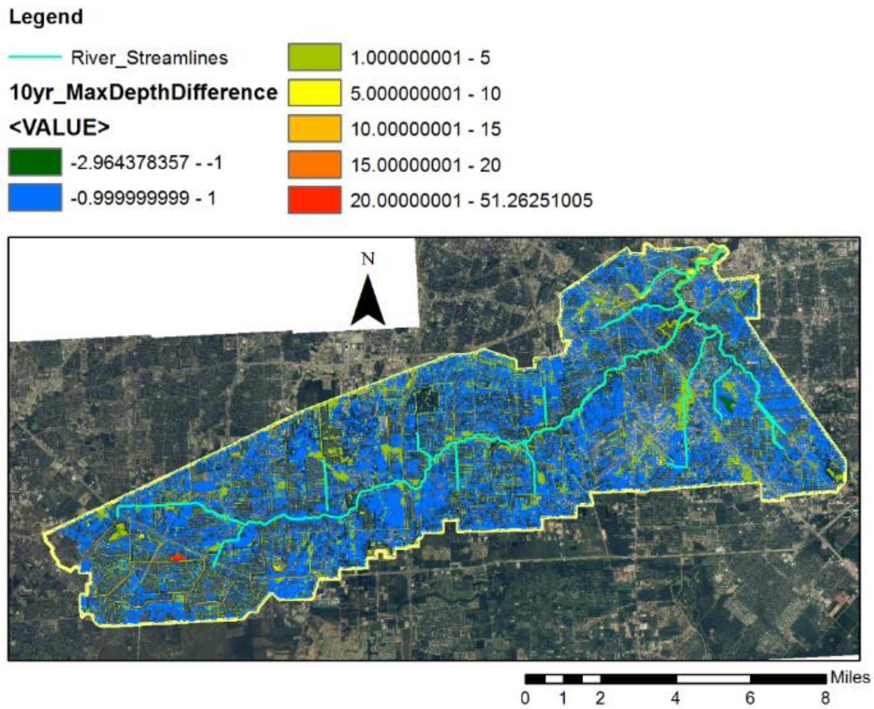

Figure 22: 2D minus 1D maximum water depth for the 10 year storm (feet)

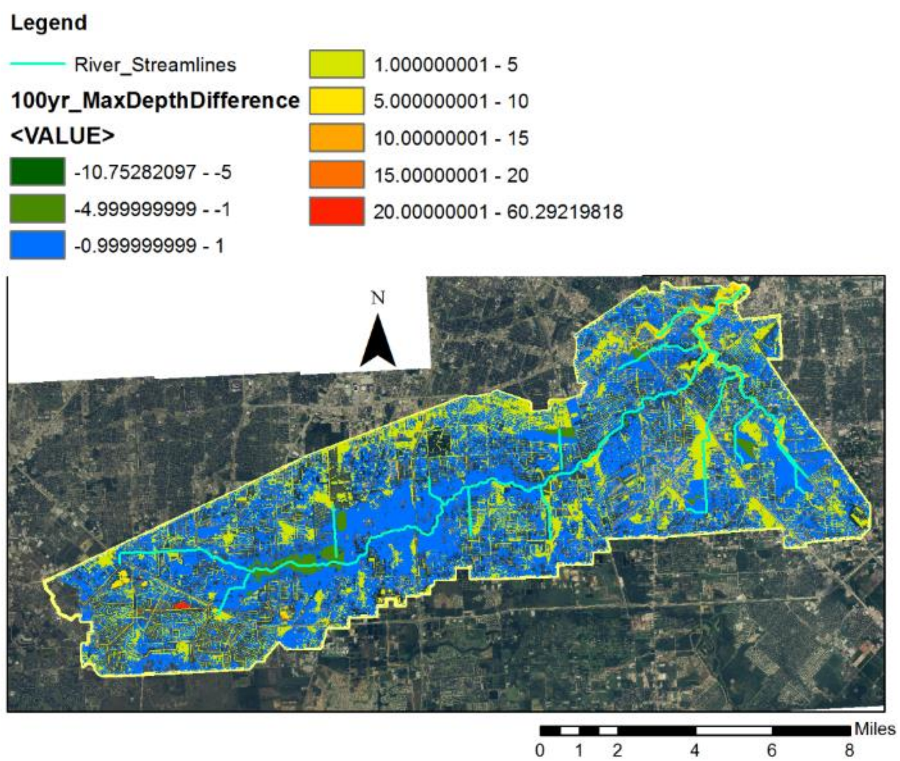

Figure 23: 2D minus 1D maximum water depth for the 100 year storm (feet)

As can be seen in the inundation boundary maps that display the difference water extents for the design storms, the 2D inundation boundary covers a vast majority of the watershed, while 1D inundation boundaries are compacted around the streamlines of the watershed. Since the 2D models employ rain-on-grid, the majority of the watershed was measured as part of the inundation boundary. To eliminate areas with low water depths or sheet flow in the 2D model inundation maps, *Raster Calculator* was used to filter out maximum water depths below 0.5 feet and 1 foot to identify only areas of significant water depth. The comparison is shown in the following 4 figures.

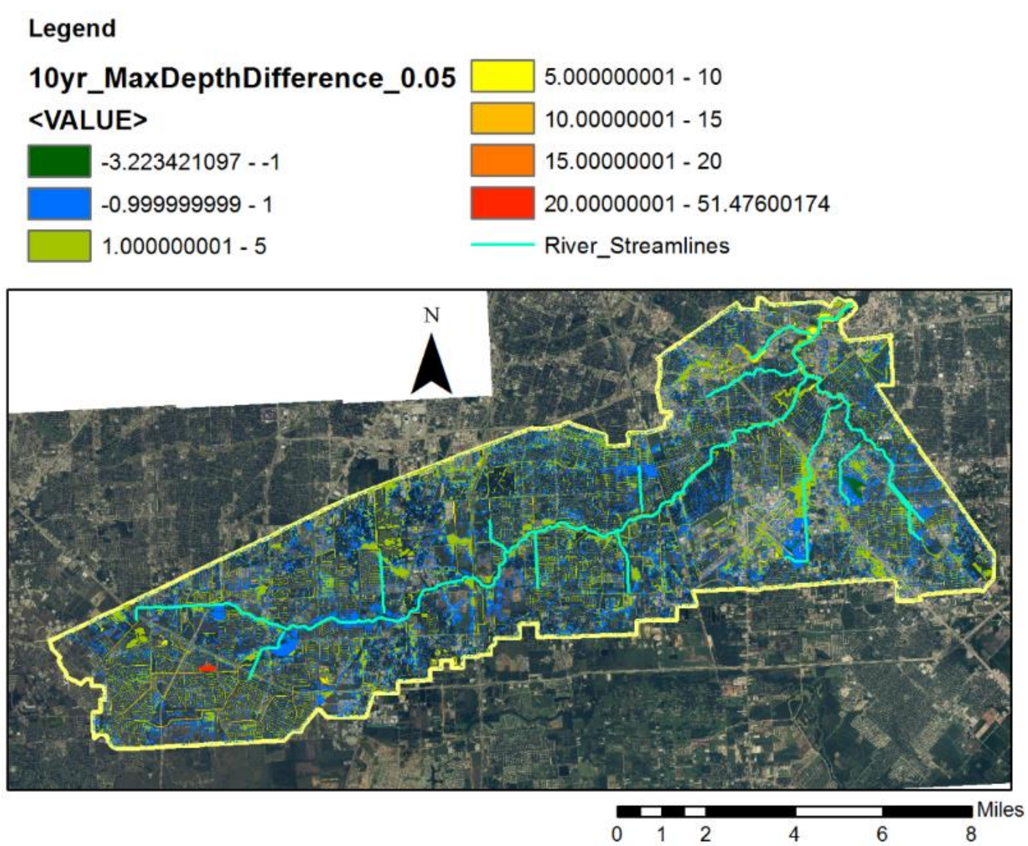

Figure 24: 2D minus 1D maximum depth difference with 0.5 foot threshold depth for the 2D output

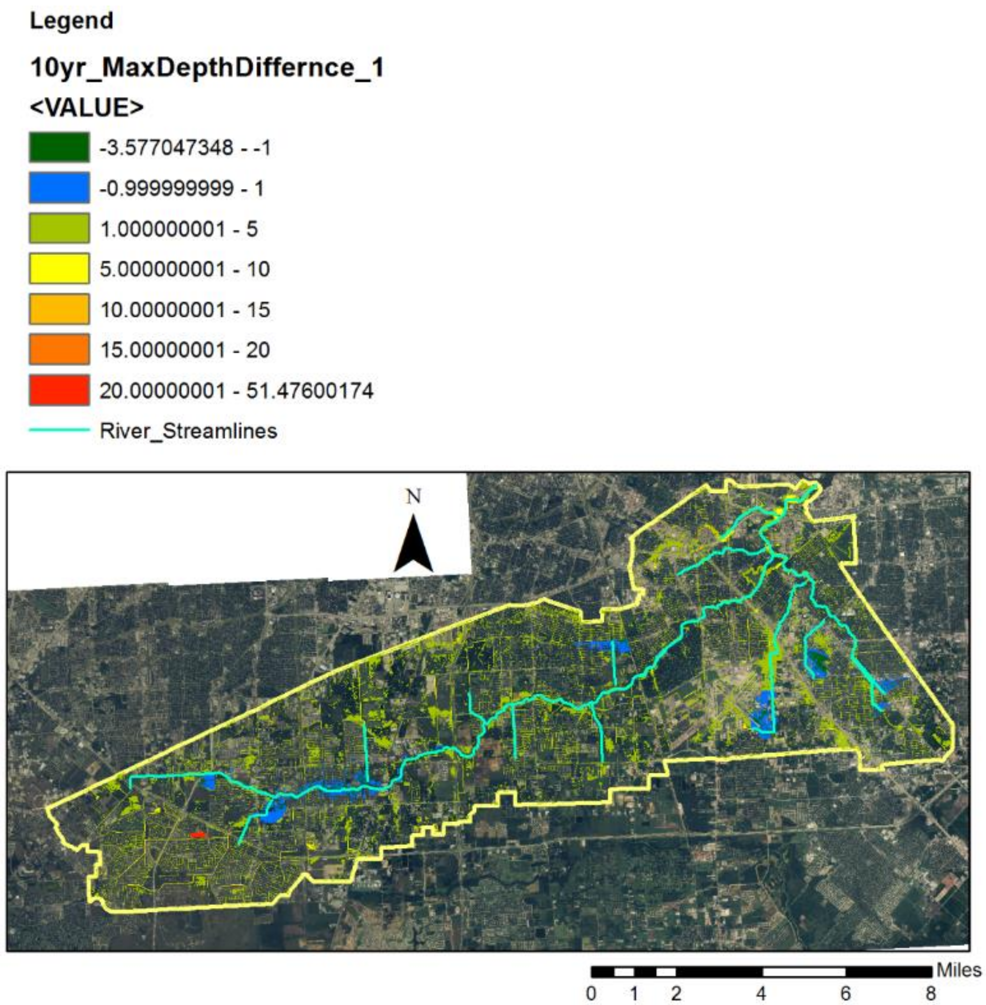

Figure 25: 2D minus 1D maximum depth difference with 1 foot threshold for the 2D output

It was shown in Figures 24 and 25 that the higher the threshold depth value, the closer the 2D flood inundation was to the 1D inundation for the 10-year storm shown in Figure 20. The majority of the reduction in inundation due to the depth threshold value occurred areas well outside of channel banks and overbanks in primarily 2D flow areas. It was also shown that the upstream 2D depths near the channels were primarily within one foot of the 1D depths; however, 2D depths were one to five feet greater typically in the more downstream sections of the model.

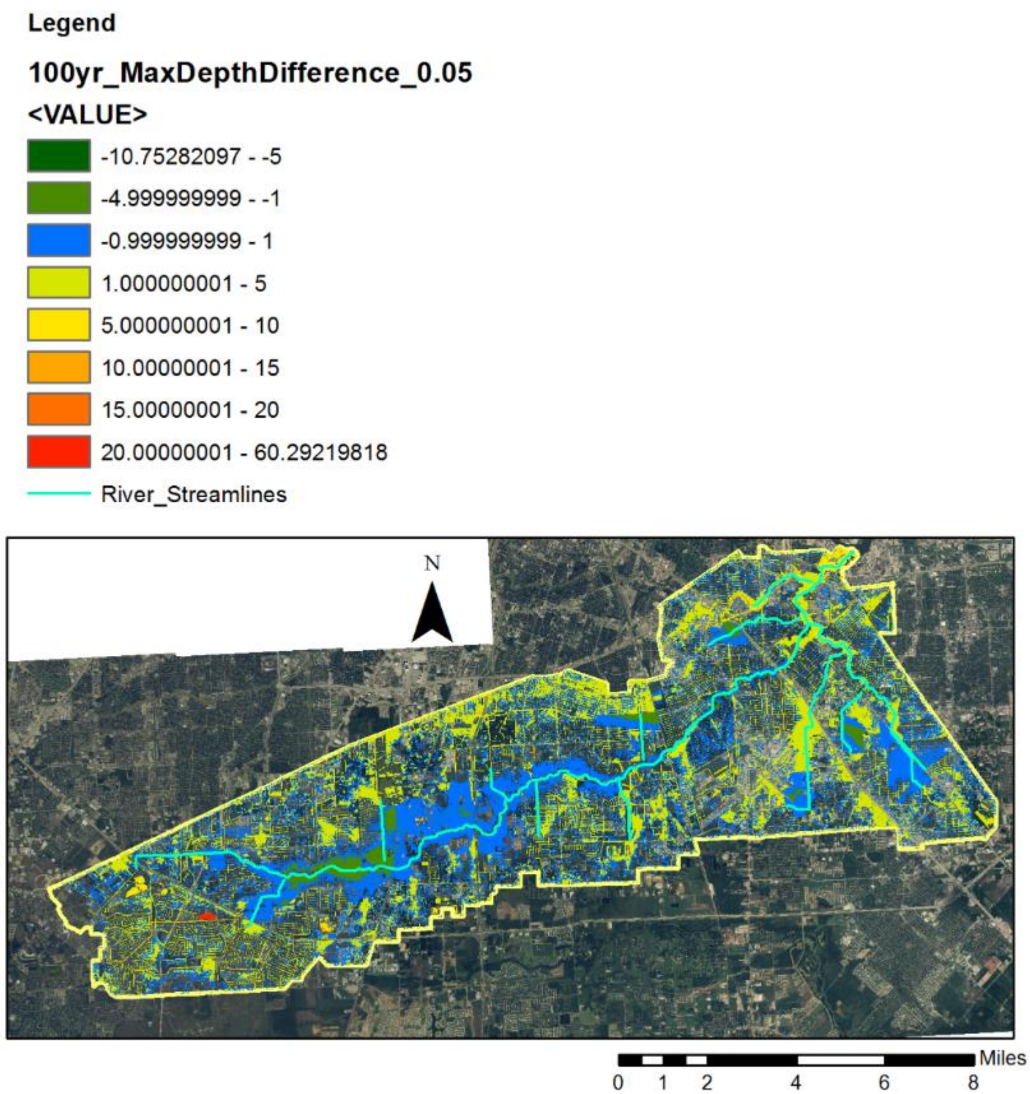

Figure 26: 2D minus 1D maximum water depth for the 100 year storm with 0.5 foot threshold for the 2D output

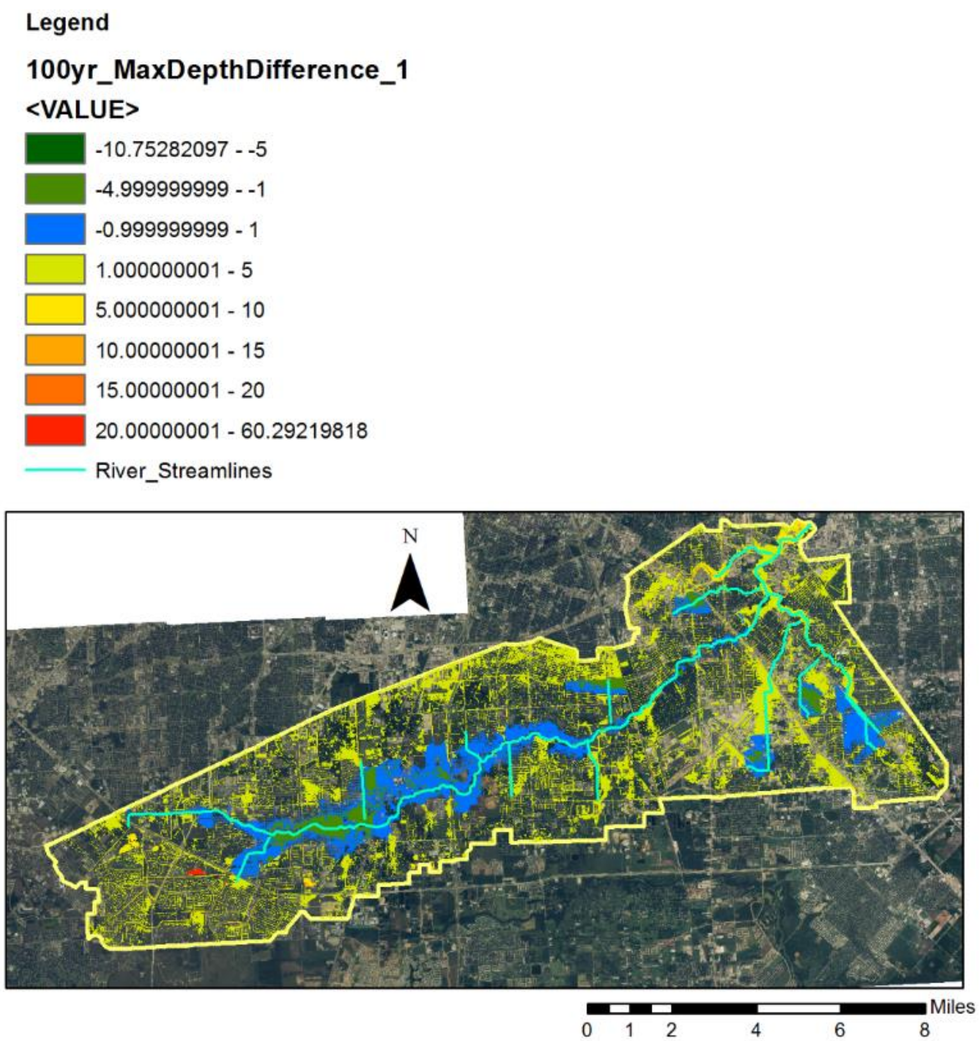

Figure 27: 2D minus 1D maximum water depth for the 100 year storm with 1 foot threshold for the 2D output

Figures 26 and 27 illustrated the same concept as the 10-year storm. As the threshold 2D depth was increased, the inundation boundary became closer to that of the 1D inundation boundary. The depth outputs were more similar upstream than downstream similar to the 10-year storm comparison as well. However, there were much more locations with 2D depths greater than one foot around the watershed when compared to the 10-year storm depths. The difference between the 1D and 2D outputs for the 10 and 100 year storms as it pertains to the maximum velocity were illustrated in the next two maps.

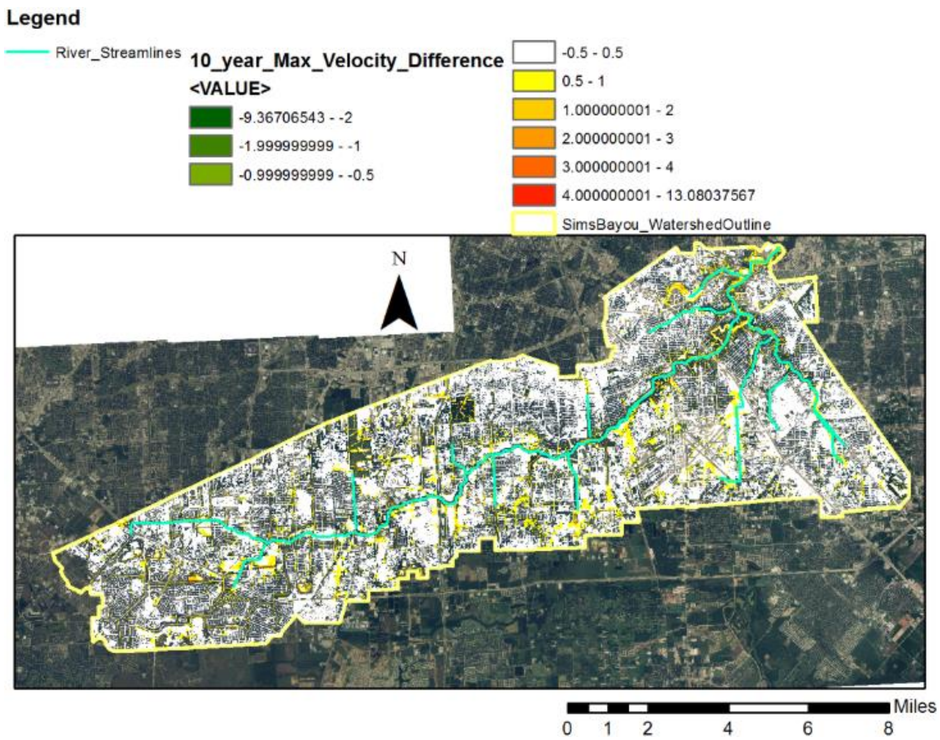

Figure 28: 2D minus 1D maximum velocity for the 10 year storm (ft/s)

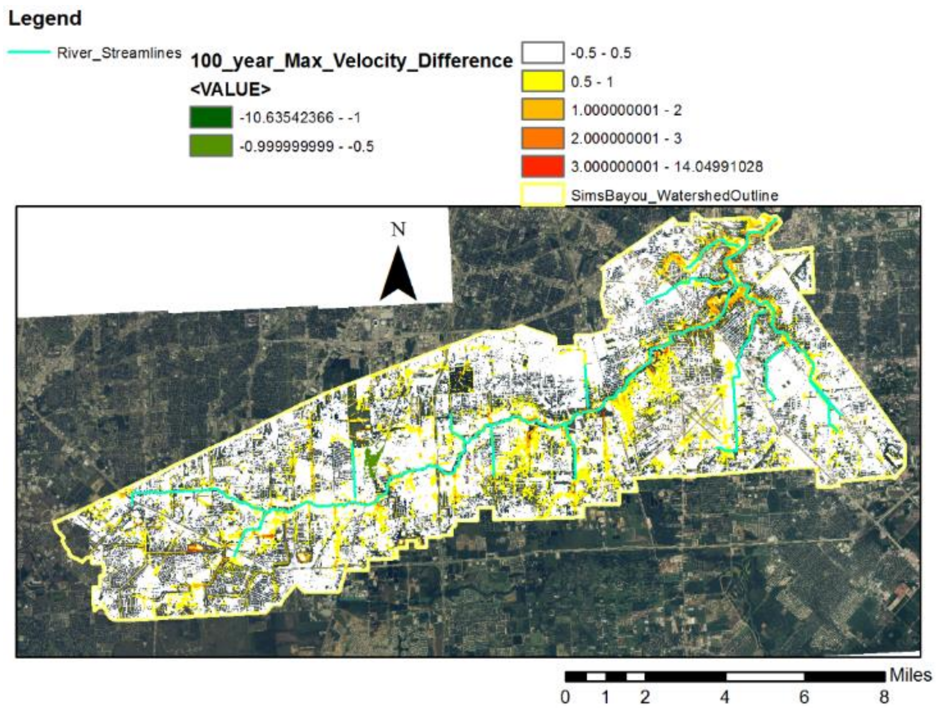

Figure 29: 2D minus 1D maximum velocity for the 100 year storm (ft/s)

Velocity differences between the 1D and 2D models were shown for the 10 and 100 year storm in Figures 28 and 29, respectively. From Figure 28, it was shown that velocity values were within 0.5 feet per second for most of the watershed; however, the 2D flow velocities were greater than the 1D flow velocities by about .5 to 2 feet per second, increasing with the downstream direction of the main channel of the watershed. Velocities of 0.5 to 1 foot per second were common where both precipitation occurred in the 2D model and no flow occurred in the 1D model.

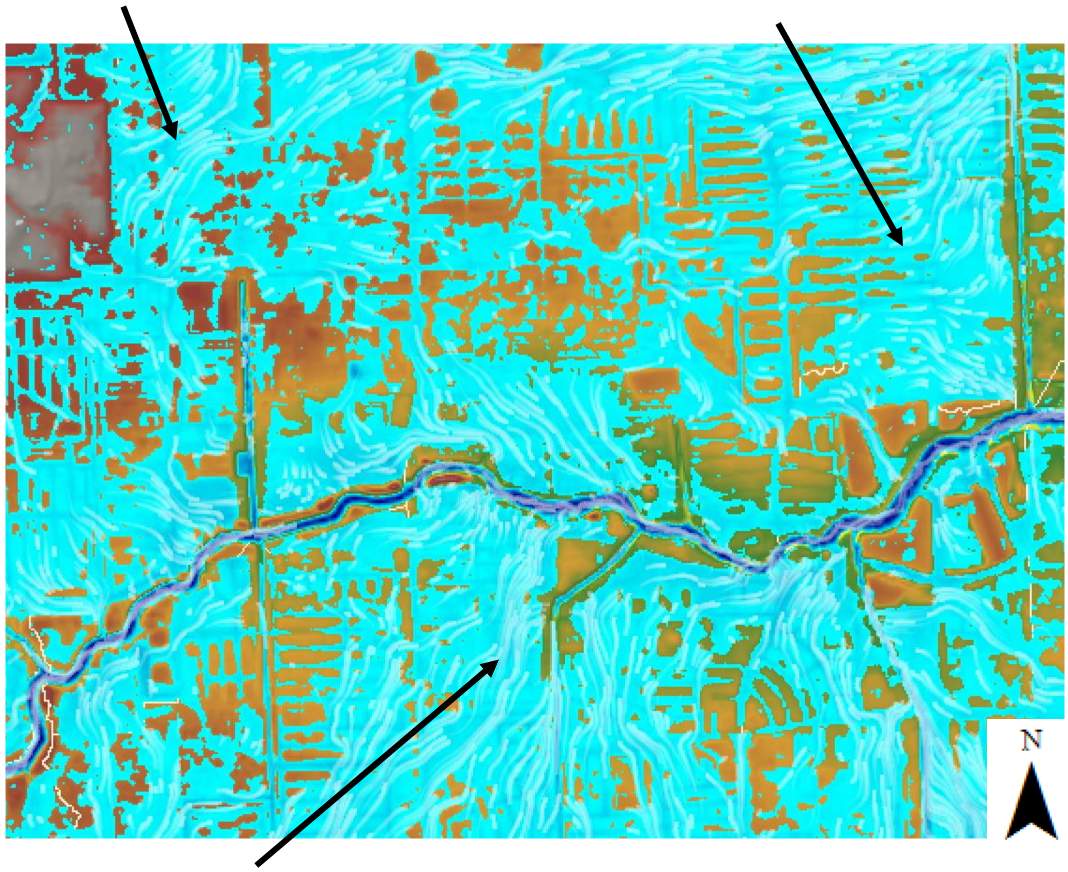

Figure 30: Velocity gradient illustration from 2D HEC-RAS from the center of the Sims Bayou Watershed during the rising limb of the 100-year storm showing the occurrence of 2D flow. White lines indicate flow direction.

Velocity gradients showing the direction of water flow during the rising limb of the 100-year storm were shown in Figure 30 obtained from RAS Mapper within HEC-RAS, showing a portion of the center of Sims Bayou. It was shown that there are several locations where 2D flow was occurring over the terrain.

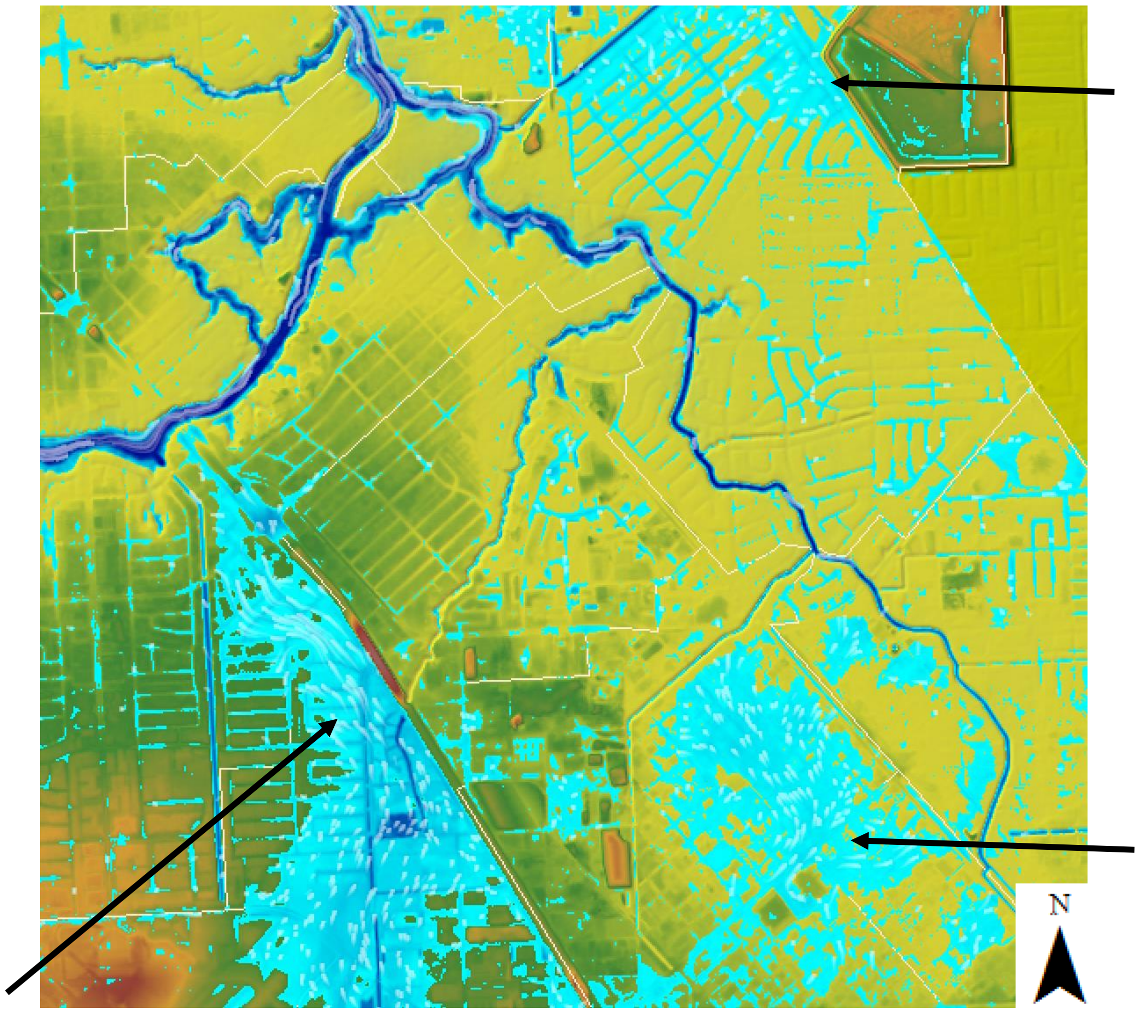

Figure 31: Velocity gradient illustration from 2D HEC-RAS from the easter region of the Sims Bayou Watershed during the falling limb of the 100-year storm showing the remained prescense of 2D flow. White lines indicate flow direction.

Velocity gradients showing the direction of water flow during the falling limb of the 100-year storm were shown in Figure 31, showing a portion the eastern region of Sims Bayou. It was observed that there are less 2D flow occurrences during the falling limb of the storm as flows leave the system; however, 2D flow did still occur at relatively slower velocities in some regions as was shown.

6. DISCUSSION

From the comparison of results, it was shown there was a drastic difference between the inundation boundary for both the 10 and 100 year storms between the 1D and 2D models. The 2D model outputs both had inundated areas over 40 square miles more than the 1D model outputs. The difference was primarily due to the 2D model utilizing rain-on-grid precipitation and the 1D model utilizing instream flows. Meaning, floods in the 1D model were created by water overflowing out of the main channel, and the 2D model water propagated flow over the entire watershed to the main channels, inundating a much larger area. Even after depths below one foot were removed from the 2D 100-year output, several inundated areas far outside of the main channels were still inundated and not covered by the 1D output. Meaning, the 2D model captured areas with over one foot of water that the currently accepted 1D model does not account for. However, from visual inspection these 2D inundated areas were significantly reduced with a smaller, 10-year storm.

The depth of the 2D outputs were consistently higher than the 1D output in the downstream sections of the Sims Bayou channels. Upon investigation of the channel geometries, this was determined to be from a difference in channel geometries between the 1D and 2D models. The 2D DEM contained shallower invert channel elevations in various cross sections when compared to the survey elevation data used for the geometry data in the 1D model. Therefore, the slightly shallower invert elevations produced a higher recorded depth for those areas.

Additionally, the velocity of the flow was typically higher in the 2D models when compared to the 1D models, especially within the main channels. This was most likely due to the fact that the 2D model isn't capable of containing bridges whereas the 1D model does have bridges. The bridges scattered throughout the 1D model most likely slowed the flow rates down within the channel; therefore, causing the 2D models to result in a higher velocity than the 1D models. Since the study was a watershed-scale study, this was not considered a large contributor to the differences in the floodplains. This was supported by the fact that upon visual inspection, the 2D floodplains became increasingly similar to the 1D floodplains as the 2D threshold depth was increased.

Finally, the 2D flow propagation was visualized using RAS Mapper since the 2D model ran an unsteady computation; meaning, the flows changed with time. Figures 30 and 31 illustrated that a 2D flow regime did occur in various areas the flatland overbanks of Sims Bayou.

7. CONCLUSION

From this study it can be concluded that 2D modelling produced a significantly different floodplain than the traditional 1D model used for generating floodplains within the Sims Bayou watershed for the larger 100-year storm with gradually less differences with gradually smaller storms. The 100-year storm 2D model output produced flood extents of over 40 square miles more than the 1D model output. From comparing the maximum depth maps, the 100-year storm resulted in more areas with two-dimensional flow regimes than the 10-year storm; therefore, the 2D HEC-RAS model realizes more advantages with larger storms when compared to the same storm modeled in 1D steady state. The usefulness of the 2D model does depend on the application though. 2D flow propagations were observed in the 2D model output; meaning, water did not flow only in the direction of the channels. Therefore, 2D modelling produces advantages in flatland areas in terms of more accurately modelling the flow propagation of large flood events. Areas with well-defined valleys and hills may not produce 2D flow regimes and would eliminate that advantage.

Of most significance, the utilization of the rain-on-grid boundary condition in the 2D model resulted in inundated areas of over one foot deep that are well outside of the accepted 1D floodplains. Meaning, areas outside of the currently accepted floodplains could be at risk of flooding from floodwaters flowing to the main channel during a large flood event. Additionally, the 2D model is versatile in its ability to easily change land use information spatially over the terrain as development occurs in the watershed.

However, the lack of bridges in the 2D model did result in slightly higher channel velocities at certain locations for the 2D model when compared to the 1D model. For a large scale study, this was assumed insignificant; however, for studies focused on a specific community or road, bridge hydraulics could have a significant role and outweigh the benefits of using a 2D model.

7.1 Limitations of 2D HEC-RAS Modelling

2D models require the availability of high resolution terrain data, which may not be available in all regions. Precipitation hyetographs input over 2D meshes are considered uniform over the computational mesh area when utilizing the rain-on-grid feature. A 1D/2D coupled HEC-RAS model was developed for Sims Bayou with each sub-catchment as a different 2D area for use for modelling measured storm events; however, the amount of components needed for this model resulted in larger computational times and extreme model instability, making it impractical unless required for a specific, warranted use. The 2D only model used in this study took about 1.5 hours to execute while the 1D steady state model had an execution time of only 10 to 20 seconds.

7.2 Future Impact

The results of this study can be combined with the efforts of the Institute for Sustainable Communities to work with the Sims Bayou community to urge public policy makers to reexamine their current floodplain modelling techniques and determine the vulnerability of communities previously not thought to be a part of the FEMA floodplains. Additionally, the results of this study could enhance studies such as one case study of South Caroline where the spatial locations of potential hazards yielded various vulnerability ratings for different areas (Cutter, Mitchell, & Scott, 2000). 2D modelling could aid in better understanding what communities are more vulnerable during large flood events in flatland areas. Another study of Bay County, Florida, linked business vulnerability with flood hazard zones, yet another study that could be enhanced by advantages of 2D modelling (Song, Peng, Zhao, & Hsu, 2016). Citizen science data collection could also be conducted to calibrate 2D areas of the model.

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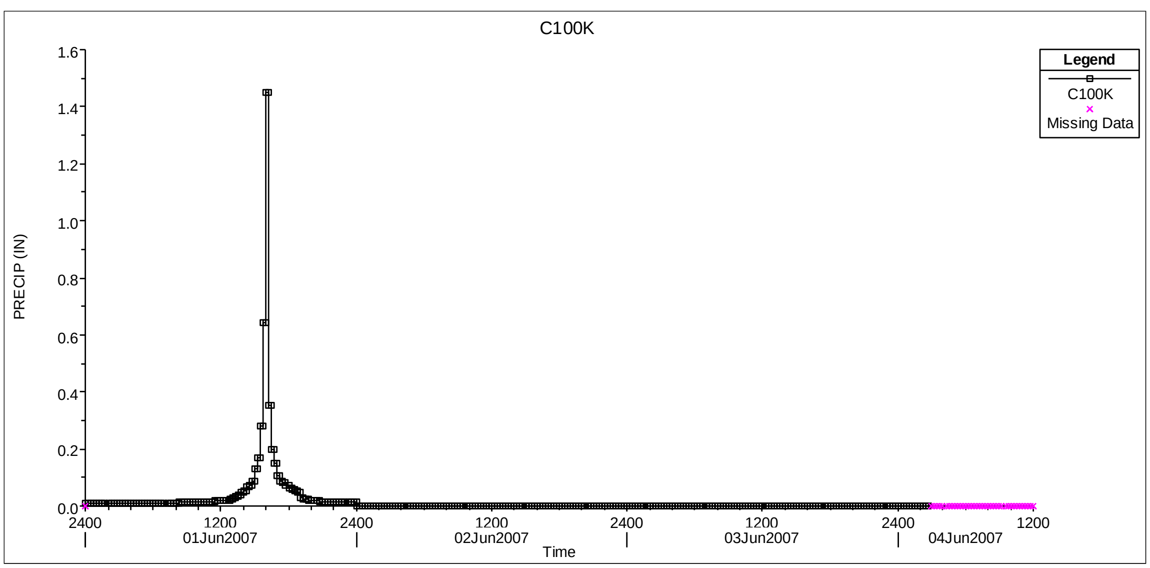
APPENDIX

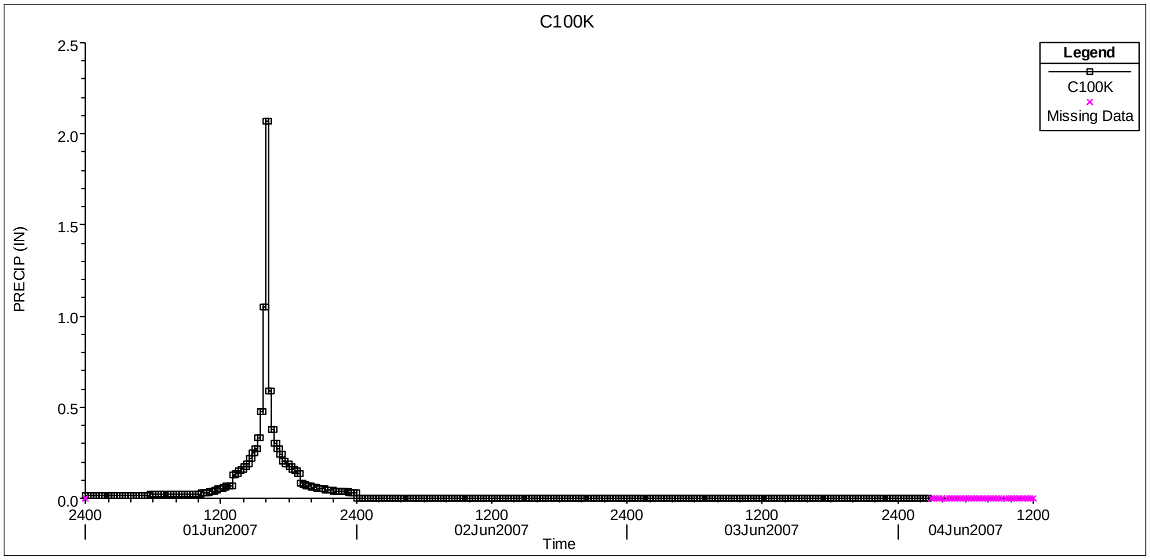
Interpreted 2D manning's values from given HCFCD draft manual:

nlcd 2006 VALUE	nlcd 2006 DESCRIPTION	2d Recommended "n"
11	open water	0.03
21	developed, open space	0.05
22	developed, low intensity	0.08
23	developed, medium intensity	0.1
24	developed, high intensity	0.12
31	barren land	0.11
41	deciduous forest	0.22
42	evergreen forest	0.22
43	mixed forest	0.22
52	shrub/scrub	0.05
71	grassland/herbaceous	0.04
81	pasture/hay	0.14
82	cultivated crops	0.07
90	woody wetlands	0.2
95	emergent herbaceous wetlands	0.2

Precipitation hyetograph for 10-year storm input into 2D HEC-RAS Model:



Precipitation hyetograph for 100-year storm input into 2D HEC-RAS model:



Screen capture of 1D/2D geometry file created for future work utilizing 1D reaches and lateral structure connections between sub-catchments and main channels: