Consortium of Universities for the Advancement of Hydrologic Science, Inc.

TECHNICAL REPORT 13

JULY 20, 2016

DRAFT

NATIONAL WATER CENTER INNOVATORS PROGRAM SUMMER INSTITUTE REPORT 2016

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Prepared in cooperation with the Consortium of Universities for the Advancement of Hydrologic Science, Inc. and the National Water Center

CUAHSI Technical Report No. 13

DRAFT

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The report is currently undergoing further review. Review process is expected to be completed by the end of August 2016 after which the report will be published online in CUAHSI web-site.

Contents

Preface

The Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) is an organization sponsored by the National Science Foundation in which more than 110 US universities are members, that advances hydrologic science through collective initiatives across the academic community. The Office of Water Prediction of the NOAA National Weather Service has developed a National Water Center on the Tuscaloosa campus of the University of Alabama to serve as the hub for the building of a National Water Model of the United States, and has established a National Water Center Innovators Program with CUAHSI to engage the academic community in research to enhance the National Water Model. The key activity of the Innovators Program is a 7-week Summer Institute at the National Water Center, bringing a group of graduate students together with faculty advisors and National Water Center staff to conduct group projects that involve rapid prototyping of new ideas. The **intent is to create an innovation incubator where students from many universities can exchange ideas** and advance concepts that, although they may be analyzed only for a short time and on a small study area, are illustrative of issues that will affect the functioning of the National Water Model across the continental United States.

The first Summer Institute was held in June-July 2015, and focused on the formation of a prototype National Water Model running in the Texas Advanced Computing Center of the University of Texas at Austin, which demonstrated that the discharge on 2.7 million stream reaches of the United States could be simulated and forecast in real-time using input precipitation and weather information produced by NOAA and a computational framework called WRF-Hydro developed at the National Center for Atmospheric Research. The results of this research are being summarized in a Featured Collection of articles in the Journal of the American Water Resources Association to be published later in 2016. The key innovation demonstrated at the first Summer Institute was a hybrid grid-catchment information framework for the National Water Model in which the land-atmosphere computations were carried out on square grid cells covering the continental US, and the resulting runoff was geographically transformed onto the 2.7 million catchments of the National Hydrography Dataset Plus (NHDPlus) and routed through the NHDPlus stream network. It was shown that the continental stream network could be treated in real-time as a single flow continuum, from atmosphere to oceans and from coast to coast.

This report contains summaries of 12 research projects carried out during the second Summer Institute, held from 6 June to 20 July, 2016, which involved 34 graduate students from 21 US universities. These students were selected in an open competition, conducted by CUAHSI, in which students from any US university were eligible to apply. By this time, a first version of the National Water Model was in the process of being made operational on NOAA computational facilities, and the focus of the research was on translating the forecasts of discharge into flood inundation mapping and flood emergency response.

To support this activity, a year-long preparatory phase took place before the 2016 Summer Institute in which the 10 meter National Elevation Dataset of the United States was analyzed on the CyberGIS facility in the National Center for Supercomputer Applications of the University of Illinois at Urbana-Champaign and transformed into a raster called Height Above Nearest Drainage (HAND), in which each cell contains the height difference between its elevation and the elevation of the cell in the NHDPlus stream reach to which it drains. If the water depth in the stream is known, then the extent of nearby flood inundation can be determined by selecting the surrounding cells whose HAND values are less than the water depth. This activity was jointly endorsed by CUAHSI and by the Universities Consortium for Geographic Information Science (UCGIS), and was announced by the White House as part of the commitments for the White House Water Summit in March 2016. Coupled with flood forecasting from the National Water Model, the HAND approach establishes, for the first time, a foundation for locally informative, real-time flood inundation mapping continuously across the continental United States.

The support of this research by the CyberGIS facility and staff is gratefully acknowledged, in particular Yan Liu and Shaowen Wang, and of David Tarboton of Utah State University and Xing Zheng of the University of Texas at Austin who made critical contributions to this activity. A particular focus for study during the Summer Institute was flood inundation in Alabama. The contributions of Leslie Durham of the Alabama Department of Economic and Community Affairs, who provided additional detailed data from FEMA flood studies, and of Joseph Gutenson, Andy Ernest and Deborah Crocker, who provided data storage at the University of Alabama, are also gratefully acknowledged.

The National Water Model will increase the spatial density of flood forecasting by a factor of 700 compared to the existing National Weather Service River Forecast Center models. This will require densified measurement to assure the forecast results. As part of the preparatory phase of the Summer Institute, two demonstration sites for radar-based streamflow measurement were established near the National Water Center where water surface elevation and surface velocity are measured continuously. The Summer Institute students, with the collaboration of the US Geological Survey, did field work at these locations to establish streambed topography and water flow conditions, and constructed FastMech hydrodynamic models showing the spatial pattern of the flow depth and velocity for these stream reaches. The intent of this phase of the Summer Institute activity was to complement the continental scale flood inundation mapping activities associated with the HAND approach with detailed scientific study of small stream reaches using fundamental fluid mechanics. FastMech models were subsequently constructed for several other locations in various Summer Institute projects to extend that activity.

The collaboration of Peter Ward of Hydrological Services America, who loaned the radar stream measurement systems for this activity, and of the US Geological Survey, in particular Jonathan Nelson and Victor Strickland, who guided the installation of this equipment, and the flow measurement and modeling, is gratefully acknowledged. The University of Alabama Geography Department and Surface Dynamics Modeling Laboratory are also acknowledged for providing field equipment (Total Station, Differential GPS and Boat Sonar) in support of this project, and computational resources for several other projects in the Summer Institute.

Real-time flood information needs to be translated into actions that improve flood emergency response. The first activity of the 2016 Summer Institute was a day-long flood emergency response exercise for Tuscaloosa County, conducted in the National Water Center's Situation Room, involving fire, police, public works staff from Tuscaloosa City and County, and local non-governmental organizations such as the Red Cross that also provide help during flood emergencies. This exercise used HAND-based flood inundation mapping for a hypothetical flood scenario based on actual conditions for a flood event that had recently occurred in Tuscaloosa County, and stepped through, stage by stage, the rise, peak and recession of the flood to assess what emergency response actions would be taken and how flood forecasting and inundation mapping could be used in decision making. A hypothetical failure scenario of the Northport Levee located on the Black Warrior River near the National Water Center was simulated using a GSSHA model created by Ahmad Tavakoly of the US Army Corps of Engineers in Vicksburg, MS. Web-based flood inundation maps created using the ESRI ArcGIS Online system were projected onto the big screens in the Situation Room. These showed the juxtaposition of flood inundation mapping with address points for residences and businesses that are used when emergency response vehicles are dispatched to particular geographic locations. The success of this approach in correctly identifying an area of persistent flood risk in the Moundville area in south Tuscaloosa county was remarkable, and this illustrated the overall goal of this effort, which is to connect national flood forecasting with local flood emergency response.

Fire trucks, police vehicles and flood rescue equipment were gathered in a nearby parking lot so the students could see how rescues are carried out. The Mayor of Tuscaloosa, Walter Maddox, described how he and the city responded to a disastrous tornado in 2011 that tore through Tuscaloosa killing 53 people and destroying some of the emergency response facilities most critically needed at that time. The cooperation of Rob Robertson, Emergency Management Coordinator for the City of Tuscaloosa, and of the more than 20 emergency response personnel engaged in the flood emergency response exercise, is gratefully acknowledged.

The key activity of the Summer Institute is the research that the students undertake in their group projects. Central to that are the relationships that they form with one another, working closely with students from other universities in cross-institutional research teams that enable exchange and connection of ideas in creative new forms. The formation and functioning of these teams was guided by two Student Coordinators, Adnan Rajib from Purdue University, and Peirong Lin from the University of Texas at Austin, both PhD students who had earlier participated in the 2015 Summer Institute. They have compiled and collated the project summaries included in this report and supervised its production. They also did valuable work prior to the start of the Summer Institute to assemble data and software ready for use in the research activity. We appreciate all the work and effort that Adnan and Peirong have contributed as Student Coordinators.

In addition, faculty from various universities served as theme leaders to help focus the research activities. These included Sagy Cohen and Sarah Praskievicz from the University of Alabama, Alfonso Mejia from Penn State University, Ibrahim Demir from the University of Iowa, and Albert Van Dijk from Australian National University. In particular, Drs Cohen and Praskievicz were resident in Tuscaloosa and worked with the students throughout the Summer Institute to provide guidance and support of the many activities involved. The support of the Theme Leaders of the 2016 Summer Institute is gratefully acknowledged. There will be another Summer Institute in 2017 at the National Water Center and planning for that event is now being initiated.

It can be appreciated that an activity of this magnitude involves a great deal of organization. Richard Hooper and Emily Clark of CUAHSI, and Pamela Harvey of the University of Alabama, were the main people who helped with the institutional arrangements and with travel, housing, and living arrangements in Tuscaloosa. Edward Clark and Fernando Salas were the key people who guided the activity and provided support from the National Water Center. The contributions of everyone who helped with the Summer Institute in ways great and small are gratefully acknowledged. We also would like to thank the University of Alabama School of Arts and Sciences for sponsoring the Capstone Event.

A key to the success of the National Water Center Innovators Program is the support it receives through the voluntary collaboration of the academic community, along with commercial and government partners. We wish to record our appreciation to the NOAA National Weather Service for this opportunity to contribute to the enhancement of water prediction for our nation.

On a personal level I wish to acknowledge that my contribution to this research was supported by NSF EarthCube Grant 1343785 and by the commercial firms ESRI and Kisters.

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Project Summary

Upon becoming operational in August 2016, the state-of-the-art National Water Model (NWM) will generate real-time water prediction and flood forecasting for the continental United States at 2.7 million river channels. The NWM architecture is the first nation-wide hydrologic operational endeavor at an unprecedented high spatial resolution, yet there is a need for academic community to continue to research dimensions that would improve upon and expand the capabilities of the NWM. In line with such motivation, the 2nd Summer Institute of the National Water Center (NWC) Innovators Program hosted 34 graduate student research fellows from 21 universities across the country from June 6 to July 20, 2016. During the seven-week program, the resident research fellows worked collaboratively on 12 projects, leveraging the NWM outputs. The projects were thematically categorized under four domains: flood modeling, inundation mapping, forecast errors, and emergency response. In this report, all the projects are collected as separate chapters. The discussion below summarizes their key findings as a glimpse of the overall accomplishments from this collaborative mission.

Flood Modeling and Inundation Mapping

Chapter 1 presents a field experiment to supplement shortage of hydrologic observations (e.g. velocity, streamflow) and channel properties (e.g. bathymetry) with remotely sensed densified measurement network. In collaboration with the United States Geological Survey (USGS), authors in Chapter 1 also carried out a prototype study to show the utility of densified measurements in improving the precision of hydrodynamic models.

Pertaining to similar motivation, authors in Chapter 2 analyzed high resolution Light Detection and Ranging (LiDAR) topography data in an effort to delineate more accurate drainage network in Texas Lower Rio Grande Valley. The overall approach presented in this study would help generating hyper-resolution hydraulic/topographic features with consideration of location-specific complexities, enabling better flood forecasting in hydrologically-challenging data-scarce regions.

Chapter 3 evaluates the relative comparability of four different hydraulics/topography-based flood modeling tools, along with their sensitivity to complex geophysical and man-made attributes such as channel bathymetry, resolution of topography data and presence of hydraulic control structures. The outcome of this particular work provides insights on the trade-off between accuracy and functionality of inundation mapping techniques across large scales, comparing simple, fast-computing, topography-driven approaches against detailed, slow-computing, physically-based hydrodynamic models.

Height Above the Nearest Drainage (HAND), as a terrain-based method adapted in the NWM architecture for near real-time flood inundation mapping, has many benefits over various hydrodynamic models in terms of its speed and reasonable accuracy. Chapter 4 in this report thematically showed another variation of the HAND method based on stream order. The modification to HAND proposed in Chapter 4 may enable the technique to better capture highly complex flooding situations like backwater effects from adjacent/downstream catchments.

To augment rapid access and post-processing of remotely sensed inundation observations, a suite of algorithms for multi-source image fusion and subsequent image segmentation are presented in Chapter 5. An important contribution of this study was to use National Hydrography Stream network (NHDPlus) and a new Moisture Enhancement Index (MEI) in extracting flood inundation extents from satellite imagery.

For a selected historical flood event, Chapter 6 showed the use case of satellite imagery for evaluating the accuracy of two hydraulics/topography-based flood modeling tools. As a future direction, research presented in Chapter 6 can be extended to explore how incorporation of semi-empirically derived channel bathymetry in models can help enhancing accuracy of simulated flood extents with reference to remotely sensed inundation observations.

Forecast Errors and Emergency Response

Chapter 7 investigates the implementation of a statistical model to produce more accurate stage height predictions from the NWM. With the statistical post-processor, the preliminary results showed generally-improved stage height and inundation extent predictions at a particular river reach, showing promise for future studies on reducing uncertainty from NWM outputs.

Chapter 8 demonstrates probabilistic flood inundation mapping with streamflow ensembles and multiple hydraulic modeling techniques. By conducting a case study in an urbanized watershed in Pennsylvania, the authors showed the differences between deterministic versus probabilistic inundation mapping approaches (e.g. the former suggests flooding while the latter only suggests 50% chance of flooding in an oil storage tank farm). The results indicated that uncertainty quantification in inundation mapping is the key to more effective emergency response.

Chapter 9 presents preliminary results on assimilating water level measurements from the Iowa Flood Inundation System (IFIS) to update the NWM-derived water depths. Authors showed a reduced error of ~50 cm in the assimilation channel, and ~45 cm in the validation tributaries where no observation was available. As a potential post-processing module of the operational NWM, this study has implications to improve inundation mapping and short-range flood forecasting.

Chapter 10 establishes a workflow through the Tethys web-platform to visualize the HAND flood inundation maps. An easy-to-use web-based platform such as the Tethys app would help public and first responders to access and view the real-time inundation maps of their own neighborhood, which would benefit emergency preparedness.

Chapter 11 shows the development of a prototype Operational Platform for Emergency Response and Awareness (OPERA) system. OPERA intends to complement the current National Weather Service's flood alert system by providing a graphically interactive web portal for the citizens, first responders, and NGOs. The authors proposed several applications of OPERA that can potentially operate along the full cycle of an extreme event, continuously regulating best possible preparedness, warning and response.

Chapter 12A features an online portal of advanced emergency response that takes into account social norms and human behavior. Chapter 12B supplements Chapter 12A by adding an educational outreach component based on flood fatality data analysis. The content in Chapter 12 is helpful in addressing the communication problem between the "science domain" and the "social domain".

This report publishes only the preliminary outcome from the aforementioned projects. Further research will be continued by the graduate student research fellows and their academic advisors in collaboration with the NWC. The ideas being exercised during the 2016 Summer Institute, as exemplified above, would essentially establish the National Water Model as the new frontier of intelligent decision support with nation-wide flood forecasting and inundation mapping capability.

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Chapter 1

Radar Measurement and Flow Modeling: Methods

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Abstract: Modern hydraulic model accuracy is limited by the quantity and density of measurements available within a reach. Currently, the hydrologic community is reliant on a combination of USGS gages, remotely sensed data, and field work to model the hydrologic properties of a river's reach. However, if hyper-resolution modeling of a reaches behavior and properties is desired, more data is necessary than the current network can provide. The most obvious way to improve upon the shortage of available data is to implement a more densified measurement network. While USGS stations are the industry standard, they are costly and their strength lies in collecting limited information very well. One way to supplement this backbone network is to install modern sensors, such as the Sommer GmbH RQ-30 radar, which are cost-effective, measure continuous velocity and stage height, and operate autonomously. However, these sensors remain untested, and should be more thoroughly evaluated before their wide-scale adoption. This paper outlines the rational and objectives behind the installation of these systems, describes the two study sites selected, and lays out the methods used to gather data and create the topology needed to model these reaches.

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1. Motivation

Modern-day stream monitoring relies on a network of United States Geological Survey (USGS) instruments. As of 2009, 6,880 active gauging stations existed within the United States [1], paling in comparison to the approximately 2.67 million reaches they are intended to represent [2]. These stations act as the gold standard of hydraulic forecasting measurements, but this widely distributed network cannot provide sufficient data to accurately forecast individual reaches or perform detailed modeling studies in areas that lack the instrumentation. The most direct way to alleviate this shortcoming is to increase the density of data collection. While the ideal situation would be to install USGS instrumentation on all reaches, the cost and manpower required for installation, maintenance, and calibration makes this impractical.

A potential solution to this lack of instrumentation is to supplement existing USGS stations with a modern, more affordable monitoring device such as the Sommer GmbH RQ-30 radar sensor. Compared with current USGS gaging stations, which cost between $20,000 and $35,000 to install and $16,000 a year to operate, this alternative costs approximately $17,000 for installation and $5,000 for maintenance [3]. This substantial price difference encourages the proliferation of such equipment and moves hydraulic science closer to the reality of a nationwide understanding of water. Additionally, unlike most USGS gages that only record stage, these radar sensors measure both stage and velocity. This is an improvement over the existing network because it adds an additional velocity variable which can be used in modeling efforts. Despite this benefit, it remains unclear how robust, consistent, and accurate these new stations are, how they will be integrated into the network, or precisely how much the added velocity measurement means to modeling efforts. This paper attempts to understand the potential benefits these stations offer by comparing several properties of the USGS gages with these new sensors.

1. By using these machines to calibrate a hydraulic model, the tendencies of these machines to over- or under- predict stream reach properties is explored.
2. Exploring whether adding a velocity measurement enhances modeling efforts using the FaSTMECH solver in iRIC. We will discuss data collection methods for both a small urban stream as well as a low gradient, low energy, natural stream, and the desired properties needed to accurately perform the above models.
3. Verify how much data is needed, whether traditional cross section surveys enough, and how much the addition of lengthwise bathymetry measurements adds to the accuracy of the model.

The aim of this paper is twofold: we will first focus on a short validation study of the sensors, using the dual installation of the USGS gage and the radars located at the same point over the Cahaba river. Though this only offers a single point of comparison, it will allow us to more accurately transition into the next portion of this research, modeling. We will model two different reaches, the first one: a short urban reach which has been heavily armored and carries minimal flow except during storm events, and the second: a large, primarily rural stream, which has a base flow of ~300 cfs.

2. Objectives and Scope

2.1. Model Description

The study will be using the "International River Interface Cooperative" (iRIC) public-domain modeling interface developed by the USGS to develop the appropriate hydraulic models. Within this suite, the FaSTMech model was used to better understand 2D and quasi-3D flow patterns. FaSTMECH stands for "Flow and Sediment Transport with Morphological Evolution of Channels" and is a river flow and variation analysis solver developed by Dr. Jon Nelson of the USGS. This solver was derived from the momentum equations, utilizes a finite difference method, and includes simple eddy viscosity turbulence closures which help account for backwater flow. It is also able to calculate helical sheer stress, which is where the quasi-3D properties are derived from. It also utilizes a flow/riverbed variation calculation under quasi-steady approximation, which allows it to perform calculations with extremely long time frames very quickly. Its primary input, and what has the greatest effect on the relative success or failure of the modeling effort, is the bathymetry of the stream.

The solution of choice for this modeling effort is the one dimensional backstep method, which makes a few assumptions. It assumes that the flow is incompressible, hydrostatic, primarily two dimensional, and not affected by strong secondary flows. In order to run this method, in addition to the bathymetry we also need to know the stage at the downstream end of the reach, and the discharge at the upstream end.

2.2. Site Description

2.2.1. Urban Stream

This work will focus on two streams reaches. The first, Cribbs Mill Creek located just below 2nd Ave E, Tuscaloosa, AL, is a highly engineered, small urban stream that feeds into a weir just downstream. This creek generally experiences limited flows ranging from 2-10 cfs. However, typical of urban streams, its peak flow discharge can be many times greater than that. This creek is crossed by a bridge built on top of a tunnel with concrete sides, which acts much like a concrete rectangular box culvert. The radar sensor is mounted on the downstream end of this bridge. Contextually, this creek is surrounded by homes and an RV park. The risk in this creek, and the obvious purpose behind the heavily engineered banks, is the sudden inflow of water that enters the reach.

The purpose for including this otherwise underwhelming stream in this research is just that, this reach will never be considered for a USGS gage installation, so the addition of the radar sensor provides the opportunity to explore both how well these smaller reaches can be modeled, as well as the potential to quantify the effects of urban runoff surges and to better understand how to engineer, adapt, and act proactively act in regards to similar stream reaches. The iRIC elevation model and a site map can be seen in figure 1 below.

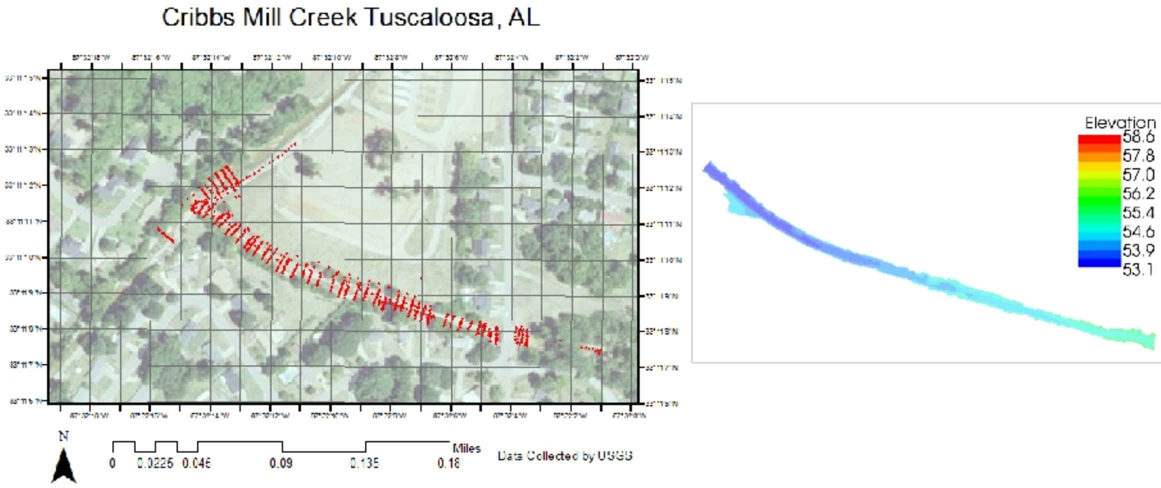

Figure 1. Cribbs Mill Creek data collection and model output (water surface elevation).

2.2.2. Low energy, low Gradient River

Unlike Cribbs Mill Creek, the Cahaba River at Centreville, Alabama represents a deeper, wider, and swifter river crossed by a major bridge between two point bar formations. Much of the near bank area also has large woody debris which hangs down into the river. Additionally, bedrock outcrops, smaller point bars, bridge piers, and left over construction debris litter the bed of the river, creating complex bathymetry. As with Cribbs Mill creek, a radar station is mounted on the bridge, in this instance co-located with the USGS gage at Centreville AL (USGS 02424000). On this reach eight cross-sections were taken using an Acoustic Doppler Current Profiler (ADCP) to record velocity profiles: three cross sections were measured downstream of the bridge, one directly under the bridge-mounted stations, and four upstream of the bridge. While these cross sections are both precise and accurate, their sparse distribution along the reach fails to capture some of the larger bed forms along the reach, which may impact the modeling efforts. An image of the survey points taken and the site map can be seen in figure 2

3. Methodology

For FaSTMECH, bathymetry is everything. To accurately capture stream bed bathymetry, there are several techniques which can be used and are outlined below. As a general rule, it is best to collect data on a single day, preferably when base flow conditions dominate the river stage. This ensures that there is minimal change in water surface elevation throughout the day, making post processing much easier. For this paper, a one dimensional backwater solver was used, requiring: bathymetry for the length of the reach and just a little further upstream of the intended modeling reach, the water surface elevation across the reach, and the discharge at the upstream end of the reach. This extra length above the intended study site gives the model time to equilibrate, and data near the top of the model is not intended to be accurate. In essence, the FaSTMECH model can be thought of as flow out of a lake which is located at the top of the reach.

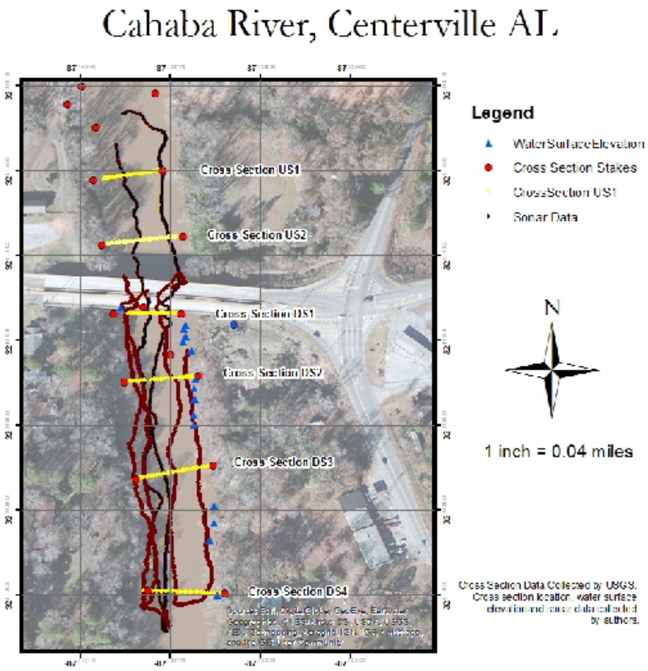

Figure 2. Location and data collection at Cahaba River

There are several ways to collect the data necessary for this model, and the means is dependent upon the equipment available and the skill of the operators. Discharge measurements may come from USGS gages the new radar sensors, or through other means. A water surface elevation is also needed for the given discharge, which is used to validate the model. The closer the model predicts the water surface is to the measured water surface, the more accurate the model. It is therefore vital to collect as many water surface elevation points across the entire length of the reach of interest as possible. In this table, the green value represents the lowest RMS, and for each of the lowest values, the velocity was calculated to determine which combination of Q and DC

To model the reach at cribbs mill, raw bank and streambed topographic data were collected using LiDAR and GPS technologies: bank topography was collected using a terrestrial LiDAR machine set up at two locations along the bend of the stream. Bed topography was collected manually using a Trimble RTK GPS unit using traditional cross-section methods. These data were then combined and stored as a .tpo file and used to generate both a gridded mesh and boundary conditions for the stream bed in the FastMECH solver. Altogether, 801 elevation points were collected along 32 cross sections. Combining the continuous discharge and stage measurements (radar sensor) with the downstream stage height and streambed bathymetry (LiDAR and GPS) provides the necessary parameters for establishing an iRIC FaSTMECH model.

If cross sections are too difficult to take, or if the reach is dominated by complex bathymetry, the use of a fish finder can help to compensate for this shortfall without the expense usually required for 3D bathymetry collection. The instrument used in this study is the Humminbird Helix 999 SI. This can be bought new for under $1000, and used units can sometimes be found used for less than $350. This instrument is mounted to the side of a boat and can be used in a canoe as well. Installation images can be seen in figure 4. Note that the antenna should be submerged, and oriented parallel to the flow. To get the data out of the unit, you will need to purchase an additional software package called the SonarTRX and the PlusPack addon for an additional $240. However, it enables you to add lengthwise measurements to your survey, and adds thousands of extra data points to even a small reach. See figure 2 for more information. Now that all the data has been collected, it needs to be converted to metric units and UTM coordinates. This is best done in arcMAP. As a correction, if you do have a cross section in a reach, you can tie the depth read off the cross section into a height above cross section, which makes the math a little easier. To supplement these sparse topography measurements on the Cahaba, stream bed depths were collected using the Humminbird Helix 999 SI sonar device from the Surface Dynamic Modeling Lab at the University of Alabama attached to the hull of a canoe, shown in figure 3. In total 5 lengthwise runs were made. For an additional ~4300 data points along the reach. They were then exported from a .dat file into a .csv file, paired with the cross sections and measured water elevation, and imported into iRIC to create to provide a dense point cloud for construction of a streambed bathymetry model.

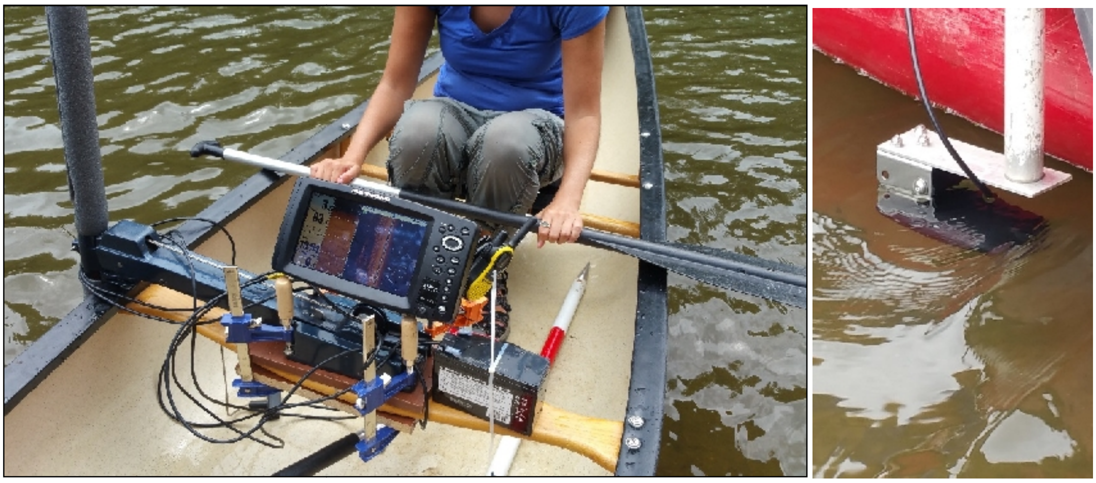

Figure 3. Images of the mounting process and orientation of the Humminbird.

4. Results

A crude validation using the duel stations located at the Cahaba indicates that the radar tends to underestimate the discharge at high flows and overestimate the discharge at low flows. It is worth noting that the radar sensor reported negative flows during the approximate month and a half of data that was available to it, and did not flag them as bad measures.

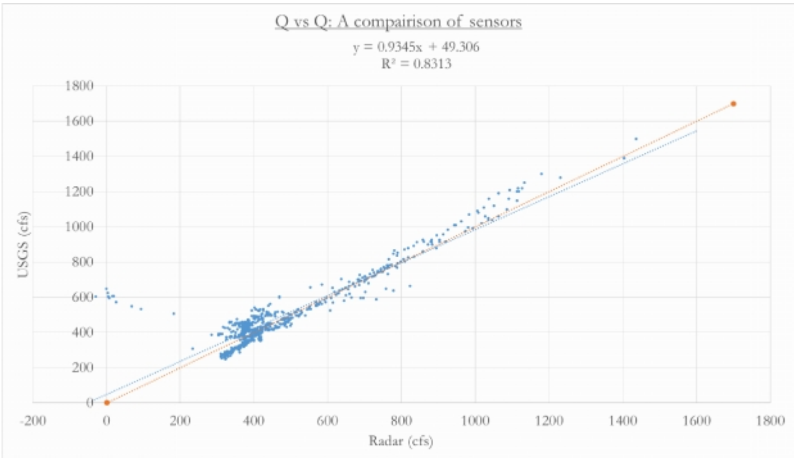

Figure 4. Comparison of discharge measurements taken from the USGS gage and the Sommer radar.

Table 1 outlines several key metrics found with the model, alongside the measured counterparts. Because extra measurements were taken at the Cahaba, there were two potential ways to create the bathymetry within the iRIC software, with the cross sections alone or with the additional bathymetry data from the fish finder. The two different elevation profiles are shown in figure 4.

Table 1. Matrix of model outputs vs. sensor readings.

	Drag coefficient	Modeled Q	Measured Q	Modeled V	Measured V	RMS
Cribbs mill:	0.005	9.00	10.02	1.910	1.870	0.1130
Cahaba (w/o sonar)	0.250	25.50	25.97	1.088	0.430	0.0769
Cahaba (with sonar)	0.040	25.50	25.97	0.596	0.430	0.0784

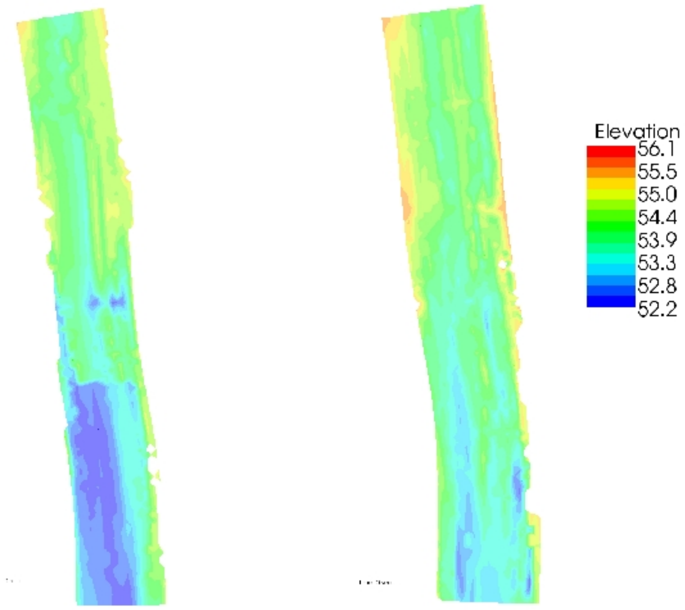

Figure 5. Bathymetry comparison using different data collection techniques. The right image is a product of five cross sections while the left is a product of these five cross sections and five sonar transects.

5. Conclusion

iRIC was able to accurately back calculate the velocity at Cribbs Mill Creek to within 0.06 m/s. For an as of yet unknown reason, the model was not able to perform well at the Cahaba site. This will be investigated further. However, through the use of the Humminbird fish finder we were able to vastly improve the results. While the roughness of the Cahaba was not entirely unreasonable when compared to similar manning's roughness [4], the incorporation of the fish finder data provided much more realistic values for both the roughness coefficient and the modeled V. Though a first step, it appears that densified measurements are needed to take advantage of the new velocity reading, and visual comparisons of the elevation plots shows that the addition of the data reduces artifacts caused by interpolation between the cross sections and resolves bed forms not previously visible.

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Chapter 2

Delineating Stream Flowlines and Watershed Boundaries in the Lower Rio Grande Valley Using High Resolution LiDAR Derived Digital Elevation Models

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Abstract: Characterized by a very flat terrain, periodic heavy rainfalls and clay soils, the Lower Rio Grande Valley (LRGV) in Texas remains an area very prone to wide-scale flooding. It is imperative that existing hydrologic models are improved and refined to further understand the potential impact of flood events and, most importantly, provide as much lead-time as possible to its more than one million residents. The National Water Model's efforts to simulate real-time and forecasted streamflow might not be enough to model this intricate and underserved area since the scale of the model cannot account for the very mild, but significant, changes in elevation in the LRGV. Taking this into consideration, high resolution LiDAR (Light Detection and Ranging) data of the LRGV was analyzed using the ROGER CyberGIS supercomputer with the objective of more accurately representing drainage networks and flood vulnerabilities in the region. Using the TauDEM toolset, LiDAR-derived digital elevation models (DEMs) were processed into hydrologic features such as stream networks and subwatersheds. Existing NDH flowlines in the area were compared visually to the high-resolution DEMs and to the TauDEM-derived drainage features. The NHD flow lines were modified in ArcGIS to pinpoint and enhance flaws, like breaks and missing lines, in the drainage systems. The NHD network used for the NWM was missing some of the main drainage features in the Brownsville Resaca Watershed. Some of these missing features were found in other NHD flowline vectors, however most were not consistent with the satellite images of the area. The LRGV is an area difficult to model due to its unique features and lack of data. This study is a big first step in gathering, consolidating, analyzing and enhancing existing hydrologic data. The results of this study will be reflected in improved hydrologic models and flood forecasting in the LRGV.

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1. Motivation

The Lower Rio Grande Valley (LRGV), located in deep South Texas, is characterized by very flat terrain, periodic heavy rainfalls, and clay soils as well as rapid urban development and a dense network of irrigation canals and drainage ditches. The LRGV is also not a true valley, but is actually the ancient river delta of the Rio Grande. Despite annual evaporation amounts being just over double annual precipitation amounts, the LRGV remains very prone to wide-scale flooding. The three major types of flooding that impact the region include: river flooding from the Rio Grande, flooding from local rainfall runoff, and the effects of storm surge during tropical storms and hurricanes.

With over a million inhabitants in the LRGV and another 1.5 living in Mexico across the Rio Grande, it is imperative that hydrologic models are improved and refined to further understand the possible impact of flood events and most importantly, provide as much lead-time to area residents as possible by the application of current technologies. The National Water Model simulates streamflow, observed and forecasted, over the entire country; however, we believe the NWM efforts will not be sufficient to model this intricate and underserved area. This project proposes to look into the topography and hydrology of the LRGV in greater detail, since an approach based on larger scales may not have the spatial resolution necessary to properly assess this area.

A notable hydrologic feature of the study region are the presence of "resacas". Resacas are old distributaries (secondary river channels) of the Rio Grande that used to convey water away from the river during periods of high flow. Their formative flow has now been interrupted, but the resacas remain. These resacas play a major role in the drainage and overland flow system in the study area watersheds; however, some of the main resacas are not included in the NHD network and the NWM.

2. Objectives and Scope

This study intends to provide reliable hydrologic data for the RGV for improved flood forecasting and modeling taking into close consideration the challenges in this hydrologically complex area. There are two essential features that needed to be sketched out, stream lines and watershed boundaries. Both of these can usually be derived from a DEM; however, as mentioned before, the terrain in the RGV is flat making the process quite troublesome and the results less reliable. In view of this challenge, other methods had to be thought of in order to create more valid stream lines and watershed boundaries. In essence, the objective was to enhance existing streamlines and watershed boundaries derived from a high resolution DEM for an intricate, challenging area for future hydrologic modeling and flood forecasting.

One of the main objectives of this of this project is to use high-resolution elevation data (LiDAR) to assist with future modeling of flood extent and drainage in the Brownsville Resaca / Lower Laguna Madre Watershed and the Arroyo Colorado Watershed - both located within the LRGV. An area-wide LiDAR derived digital elevation model will greatly assist with the determination of small scale stream network segments and their resulting sub-watershed delineations. A second objective of this project, determined only after a few weeks of deliberation and discussion with team and academic advisors, was the need to enhance and augment the NHD flow lines to more accurately reflect the real-world drainage and flow network. While a tedious and manually intensive task, mischaracterization of network vs. non-network features, errors in connectivity and paths, as well as omissions of important drainage features most likely resulting from the challenges already discussed, prohibit the use of the NHD network and the resulting NWM dataset without this careful review.

3. Previous Studies

The deep South Texas area has not been studied in significant detail with respect to area-wide flooding. Some hydrologic and hydraulic (H&H) studies focusing on the role that the Arroyo Colorado plays as an important floodway (flood diversion route) in the Lower Rio Grande Flood Protection Project [1] have been completed – but they are limited to HEC-RAS hydraulic studies in the main channel of the Arroyo and North Floodway. The only other studies related to flooding have been at the hyper-resolution scale, focusing on urban waterway flood modeling. Whitko [2] completed a master's thesis focusing on floodplain mapping of local area resacas and drainage canals using a distributed hydrologic model. This study, a cooperative effort between the City of

Brownsville, the Texas Water Development Board, Rice University and the University of Texas at Brownsville, led to a citywide Brownsville Flood Study completed in two phases (2006, 2011) [3]. Zheng et al. [4] and Bedient et al. [5] developed flood alert system technology that was to be applied in the South Texas region, but as of the present, has not been developed – largely due to the lack of detailed hydrography, complex irrigation a drainage networks that complicate overland flow analyses, and the lack of continuous high-resolution topographic data.

4. Methodology

In order to yield more representative stream lines, the available data was analyzed in three different ways. First, by comparing the NHD flowlines from the network and non-network layers to a satellite image of the area. In so doing, breaks and inconsistencies on the flowlines were found and corrected by manually editing the lines. Second, comparisons were made between NHD network flowlines and the known drainage networks as depicted by local area studies. As this approach is manually intensive, we were only able to complete this for a subset of the two watershed area – namely a subwatershed in the Brownsville region. Some of Brownsville's main flood conveyance routes were not represented as line features in the NHD network layer, and only portions were sometimes included in the non-network layer. After the comparisons were made, these features were added to the appropriate network layer since they play an essential role in Brownsville's flood water conveyance. As a third and final step, the newly determined flowlines were then compared to the streamlines derived from the LiDAR-derived DEM. LiDAR-derived digital elevation models (DEMs) were obtained from four separate surveys of Hidalgo and Cameron Counties (Figure 1). The International Boundary and Water Commission (IBWC) conducted separate LiDAR surveys in 2006 and 2011, producing 1-meter-resolution DEMs for the southern portion of the study area. The U.S. Geological Survey (USGS) conducted surveys of the northern portion of the area in 2008 and 2011. The DEM files totaled 1375 in number and 63 GB (Table 1) in size.

Table 1. Sources and characteristics of the LiDAR DEM data

Agency	Year	No. files	Resolution (m)	projection	Total size
IBWC	2006	1190	1	Lambert Conformal	27 GB
IBWC	2011	111	1	UTM zone 14	32 GB
USGS	2008	4	1	UTM zone 14	911 MB
USGS	2011	70	2	UTM zone 14	4.7 GB
Total		1375			63 GB

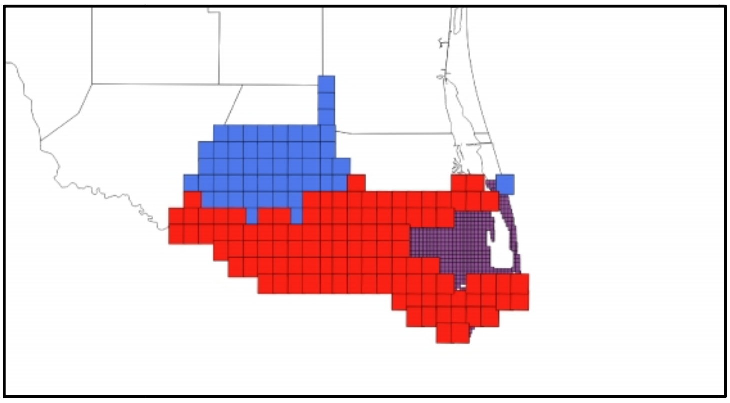


Figure 1. Locations of individual DEM files. Blue: 2011 USGS survey; red: 2011 IBWC survey; purple: IBWC 2006 survey.

The large size of the combined dataset precluded analysis on a desktop computer, and all computations were performed on the ROGER CyberGIS high-performance computing (HPC) cluster at the University of Illinois Urbana-Champaign. Geospatial operations were performed using the

Gdal open-source library, and DEM operatoins were performed using the TauDEM package. Wherever possible, parallel computing was exploited using MPI.

Data preprocessing included reprojecting all DEM files to a common projection (UTM zone 14), combining the individual files into a single virtual raster (Figure 2), and creating lower-resolution overviews of the study area. This last step allowed the combined virtual raster to be viewed on a desktop GIS platform such as QGIS or ArcGIS. Once the data were preprocessed, a small (28000 x 18000 pixel) subset was extracted from the overall DEM for use as a pilot for TauDEM analyses. The desired TauDEM workflow was as follows. First, known a "hydraulically correct" raster is computed from the raw DEM that raises local minima, forcing all pixels to drain to an outlet. Next, the d-8 slope and flow direction are computed for each pixel in the corrected raster, producing two separate rasters containing this information. These are then used to calculate a separate raster with pixel values representing each cell's upstream drainage area. A final raster of stream locations is then computed by setting any cell with a contributing area greater than a specified threshold to have a value of 1 (representing "stream") and all other cells to have a value of zero ("no stream"). Finally, these raster files are processed through a stream network function that produces a shapefile of stream lines and a raster of sub-watersheds.

5. Results

Although automated methods to extract streamlines and watershed boundaries using high resolution DEMs already exist, the results were proven to be inconsistent in our flat area of study. Methods to calibrate this workflow had to be set in place, which resulted in better but not perfect streamlines.

5.1 LiDAR DEM

Results of the LiDAR DEM analysis include the imagery itself, now compiled and reprojected to facilitate viewing in a GIS desktop environment, as well as the stream networks and subwatersheds obtained through TauDEM. These products reveal high-precision drainage features that will assist the refinement of hydrologic models and inform flood planning and management in the area. It is hoped that ongoing efforts to integrate high-resolution imagery and expert knowledge will lead to a more flood-resilient Rio Grande Valley. Figure 2 below represent a composite snapshot of the

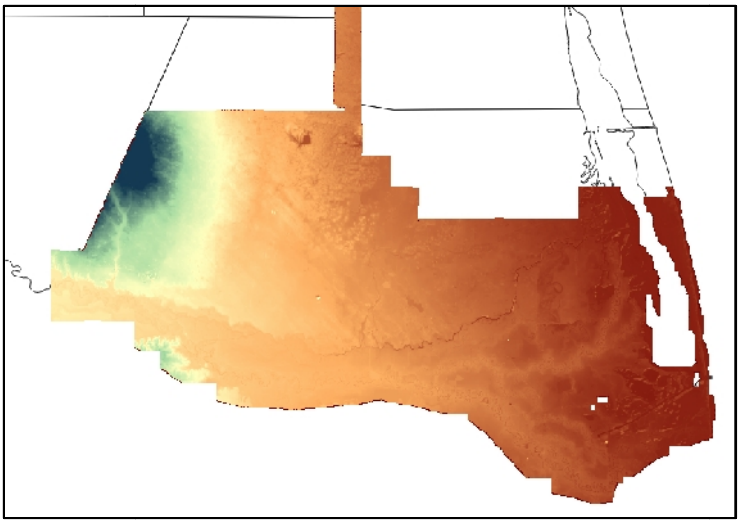


Figure 2. Combined DEM of Arroyo Colorado – Brownsville Resaca study area.

combined LiDAR-based DEM for the study area. The image represents the first continuous high-resolution DEM for the study area and is already being used to reveal topographic features such as resacas (shown in higher color detail in figure 3) and their depositional nature (topographic banding due to natural levees).

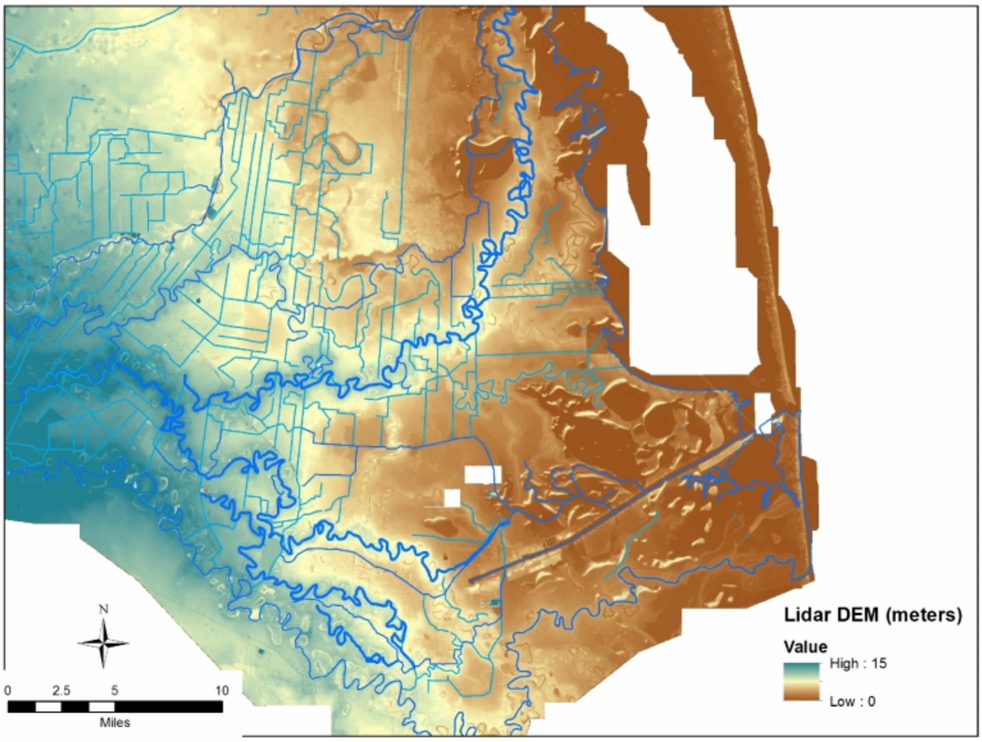


Figure 3. Close-up of Brownsville Resaca area watershed showing Resacas (wide lines) and drainage features.

While useful in that it exploits the high-resolution topographic data from the DEM, the above discussed workflow and methodlogy misrepresent non-topographic flow conduits such as bridges, culverts, and pipelines. Thus such features were artificially "burned in" to the DEM using the NHD vector files that had been previously enhanced. This approach combines a priori knowledge with remote-sensed data to optimally infer fine-scale hydrologic behavior. The workflow detailed above using TauDEM was repeated using the burned-in features, producing a second set of stream lines and sub-watersheds (Figure 4). Once the workflow was verified using the pilot study area, a larger section of the Brownsville region was processed in a similar fashion. While mostly successful, the products of this analysis have proven problematic in that the derived rasters include missing pixel values, and flow lines become truncated when they intersect these pixels.

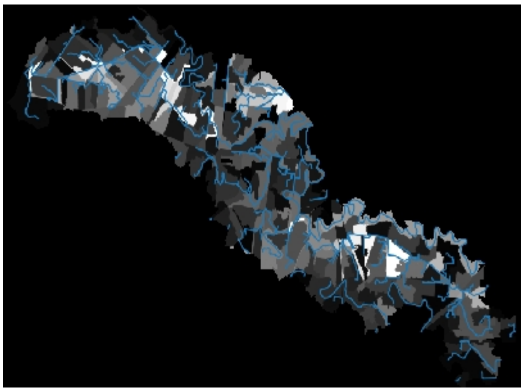
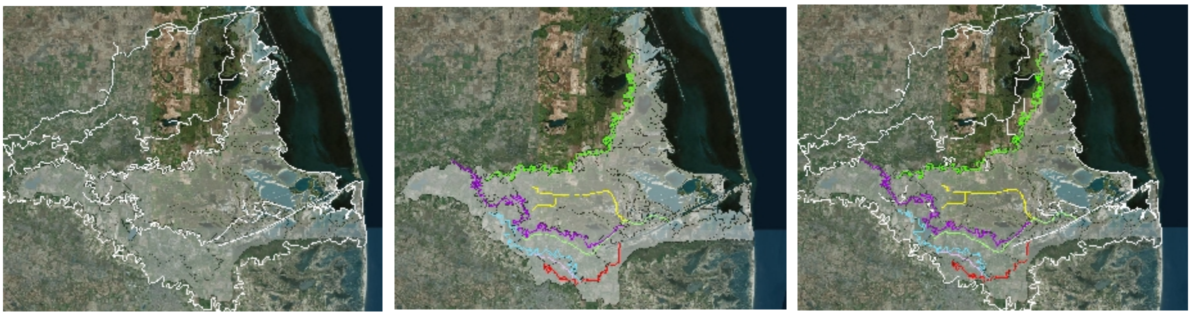


Figure 4. TauDEM analyses results from the DEM with burned in streamlines.

5.2 Streamline Delineation

Streamlines from the NHDPlus Version 2 Network and Non-Network files were manually analyzed. Breaks and missing features on the lines were found and corrected by comparing them to a satellite image. Essential features of the Brownsville drainage network were missing on the NHD Network but were included in the NHD Non-Network. These streamlines were manually selected and added to the NHD Network. (Figure 5)



(a) (b) (c)

Figure 5. (a) NHD Network flowlines; (b) Brownsville's drainage network created by merging some Non-Network features with some Network features and manually enhanced by adding, removing and clipping streamlines; (c) NHD Network + Brownsville drainage network.

Streamlines were also extracted from high resolution DEMs, however the streamlines yielded were not consistent with the streamlines we had delineated and were sometimes faulty including nonexistent streamlines. In short, streamlines for areas as complex as Brownsville have to be delineated by a combination of methods, both automated and manual, to yield reliable results.

6. Conclusion

The Lower Rio Grande Valley is a hydrologically-complex area due to its flat terrain, complex hydrography, rapidly changing land use, and periodic heavy rainfalls in a semi-arid area. Although efforts to model and forecast flood events in the area have been made before, the lack of sufficiently detailed data (both topographic and hydrologic) has prevented the development of useful, area-wide and integrated hydrologic models. An extensive amount of work has gone into laying the foundation for such future work – illustrated by the development of a GIS desktop friendly, continuous LiDAR derived DEM at hyper-resolution scale and the start of a methodology to enhance the NHD / NWM network so that hydrologic modeling can commence at this scale. It is expected that this work will continue in cooperation with local, South Texas researchers throughout the year and that a specific case-study may be considered for further work at next summer's institute.

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Chapter 3

Relative Sensitivity of Flood Inundation Extent by Different Physical and Non-physical Models

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Abstract: Various hydraulic/GIS-based tools can be used for illustrating spatial extent of flooding for first-responders, policy makers and the general public. The objective of the current study is the comparison of four flood inundation modeling tools: HEC-RAS-2D, GSSHA, AutoRoute and HAND. In trade-off between accuracy and reliability of flood inundation models, simple and fast-computing non-physical models (AutoRoute and HAND) despite being insensitive to detailed topography and effects of hydraulic infrastructures (levee, dams, etc.) on flood dynamics, are highly demanded than detailed, slow-computing, relatively accurate physical models (HEC-RAS-2D and GSSHA). Current research was carried out on a 15km-long reach of Black Warrior River near the Northport levee and between Holt and Oliver dam and lock, in Tuscaloosa County, Alabama. Same geo-physical inputs (e.g. 10mX10m NED-DEM including river bathymetry and hydraulic infrastructure for physical models; low-, medium-, and high-friction values of bed-roughness associated with National Land Cover Dataset 2011 and inflow boundary conditions provided by the National Water Model for December 1-31, 2015) were incorporated while setting up these models. Concerning the different response of the four models and the small magnitude of flood (less than 5-year return period) being considered, the water did not significantly overflow to the surrounding floodplains, however the inundation extents varies noticeably for low- to high-friction land cover settings. Comparability analysis between inundation extents produced by HAND and AutoRoute with either HEC-RAS-2D or its union with GSSHA (~65% overlapping), showed that in average, HAND has ~16% more non-overlapping area than AutoRoute. Besides, joint-inundated regions of the four models only occupy ~35% of overall flooded extent. Further research will be carried out focusing on a different study area in order to ascertain relative comparability of these models and their sensitivity to geophysical as well as man-made attributes.

1. Motivation

A flood inundation maps are being produced to show the spatial extent and depth of flooding at specific stream stage intervals along an individual stream section. These maps are created using hydraulic and topographic modeling, not observed or historical flood boundaries, and can provide more comprehensive and dynamic outlines of various flooding extent than relying on past experiences alone. Concerning inundation models, advanced physical hydraulic and hydrologic models can be set-up for local study domain which is either labor intensive or requiring detailed modeling initialization. On the other hand, uncomplicated non-physical models are going to be considered as an alternative to complicated physicals since they are much faster and easy to be initialized. However, there will always be trade-off of losing essential landform, geologic, geo-morphologic, and meteorological features of the local study domain, e.g. topographic elevations, bathymetric depth, soil and land cover type, cloudiness, precipitation, etc., especially while existing hydraulic structures and water regulations affecting stability of riverine flow and its response to flooding through time. Hence, physical and non-physical models comparability and their assessment is crucial for evaluating their strengths and weaknesses.

2. Objectives and Scope

Physical models of HEC-RAS-2D[1] and GSSHA[2] besides non-physical models of AutoRoute[3] and HAND[4] are employed in current research for producing and comparing flood inundation extent for a 14km-long reach segment of Black Warrior River, at Tuscaloosa County, Alabama which is considered as urbanized zone study locating between Holt and Oliver lock/dam and also protected by ~3.3km Northport levee.

Physical and non-physical models capabilities in producing flood inundation maps will be evaluated according to the following approaches:

1. Building up the four models based on low-, medium-, and high-friction bed-roughness sets
2. Utilizing inflow time-series established by NWM[5] for the December 1st-31st, 2015, representing ranges below 5-year flood (~3400 m^3/s)
3. Capturing the joint-inundated area of four models and contrasting it with the union of predicted flooding regions
4. Considering HEC-RAS-2D as true model and assess the overlapping and non-overlapping inundated regions reported by the other three models
5. Considering the union of inundation area produced by HEC-RAS-2D and GSSHA as true model and assess the overlapping and non-overlapping inundated regions reported by the other non-physical models

3. Previous Studies

Due to advances in computational speed and facilities, the application of 2D than 1D flood inundation modeling is accelerating researchers globally. The 2D models incorporates topographic information for the channel and floodplains allowing for estimations of inundation extent and river hydraulics [1, 2]. Besides, recent studies argued about the impacts of horizontal resolution, vertical accuracy in topographic data, and inclusion of channel bathymetry in reducing the inundation area [3-5] along with the effects of different landcovers (e.g. urban zones, vegetation, etc.) in accelerating/decelerating floodwave propagation into the inundation zones [6-8].

4. Methodology

The objective of this paper is to explore the difference between physical and non-physical 1D and 2D flood inundation models, their sensitivity to landcover change, and models components. Non-physical models will be weighed against the physical models in terms of comparing inundation maps using following three quantities: 1) inundation area, 2) average inundation width, and 3) *F-Overlapping* inundation statistics [1, 3] that is,

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1 Hydrologic Engineering Center – River Analysis System 5.0.1 of U.S. Army Corps of Engineers

2 Gridded Surface Subsurface Hydrologic Analysis of U.S. Army Corps of Engineers approved by Federal Emergency Management Agency – National Flood Insurance

3 AutoRoute Rapid Flood Inundation Model produced by of U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory

4 Height Above Nearest Drainage terrain model established by Nobre et. al., 2011

5 National Water Model – National Water Center – National Oceanic and Atmospheric Administration

$$F = 100 \times \frac{IA_{pred,obsr}}{IA_{obsr} + IA_{pred} - IA_{pred,obsr}} \; or \; 100 \times \frac{IA_{obsr} \cap IA_{pred}}{IA_{obsr} \cup IA_{pred}} \quad (1)$$

where, IA_{obsr} is observed (true) inundation extent, while IA_{pred} denotes the predicted inundated area. $IA_{pred,obsr}$ refers to the area which is reported inundated both by observation and prediction.

In this section, four models and the associated setting will be succinctly described, and in turn, the required inputs, e.g. inflow boundary conditions, terrain model, and landcover types, will be introduced.

HEC-RAS is an advanced 1D/2D simulator of hydraulics of water flowing through natural rivers while various type of flow conditions, designing and installing hydraulic infrastructures (dam, levee, weir, bridges, etc.), and flood inundation mapping can be achieved. Especially, HEC-RAS-2D computes inundation boundaries from the zero-depth contour of flood depths for the selected water surface profile. Hence, it can provide the users with water depth variation across the floodplain. The RAS-Mapper module of HEC-RAS-2D adds more mapping and visualizing capability to users for manipulating and extracting required information concerning inundation extents directly from HEC-RAS platform than referring to GIS-based tools (e.g. ArcGIS, etc.).

GSSHA is a two-dimensional physical-based model which uses mass-conserving equations to simulate hydrologic systems including: 1-D/2-D stream and overland flow routing, groundwater movement, precipitation, infiltration processes. Being spatially explicit and scalability of GSSHA in various study domain makes it a flexible to be set-up for different problems. For current study, we also considered the effect of Northport levee on inundation area. Compared with HEC-RAS-2D and other two non-physical models time of computation of GSSHA found to be significantly longer (however, in future studies more elaboration on GSSHA model's structure and ways for expediting the computation will be made) [9, 10].

The AutoRoute model was developed by the Coastal and Hydraulics Laboratory (CHL) personnel in 2011, to determine route vulnerability caused by hydrologic factors and provide required information for the Military Hydrology Program. The AutoRoute is a one-dimensional model. By using the Digital Elevation Model (DEM) data, it can efficiently calculate the flood extents, flood depth and stream cross-section profiles. The AutoRoute neglects the details of channels and thus it is more computationally rapid than typical physical hydraulic models such as HEC-RAS-2D. The input of AutoRoute includes high resolution DEM, stream mask derived from the DEM and flow through rivers. Because of the simplicity of required input, it has an advantage over other physical hydraulic models especially when limited information, for example only DEM, is available [11].

HAND (Height above the nearest drainage) is a terrain model developed by Nobre et al. [12]. HAND normalizes the terrain topography based on the local relative heights along the drainage network. The procedure of HAND modeling include the transformation of streamflow into flow height, comparison between the normalized terrain elevation and flow height, and then generation of flood extent maps. The transformation from streamflow to flow height is fulfilled by using a rating curve which is derived from Manning's Equation based on the NED terrain data. The input of HAND includes the normalized topology data (i.e. HAND raster data), streamflow along the rivers and the data defining the unit drainage boundary [12].

In this work, we use the 10 m National Elevation Dataset (NED)[6]. Stream network information is obtained from National Hydrography Dataset Version 2[7]. Streamflow data is derived from National Water Model simulation.

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6 https://gdg.sc.egov.usda.gov

We also integrated the land use information to account for the roughness effects on the flood extents. The land use data is from National Land Cover Dataset (NLCD) 2011, and for each associated landcover type three bed-roughness (Manning's n) categories were set (consistent with roughness values pertaining to AutoRoute's nomenclature): Low-, Medium-, and high-friction.

5. Results

Three separate approaches were investigated to study the behaviour of the four models in predicting inundation area, average inundation width, and *F-Overlapping* inundation statitics.

5.1. Trade-off between four models

Given three bed-roughness sets, multiple inundation maps can be generated for each of physical and non-physical models. Figure 1 illustrates the segment of Black Warrior River where the union of inundation area (red-color group) associated with four models can be contrasted with overlapped area (green-color group) for each bed-roughness categories. The two inset figures (A and B) highlight the notion that more bed-roughness bring about extended inundations (areas having darker face).

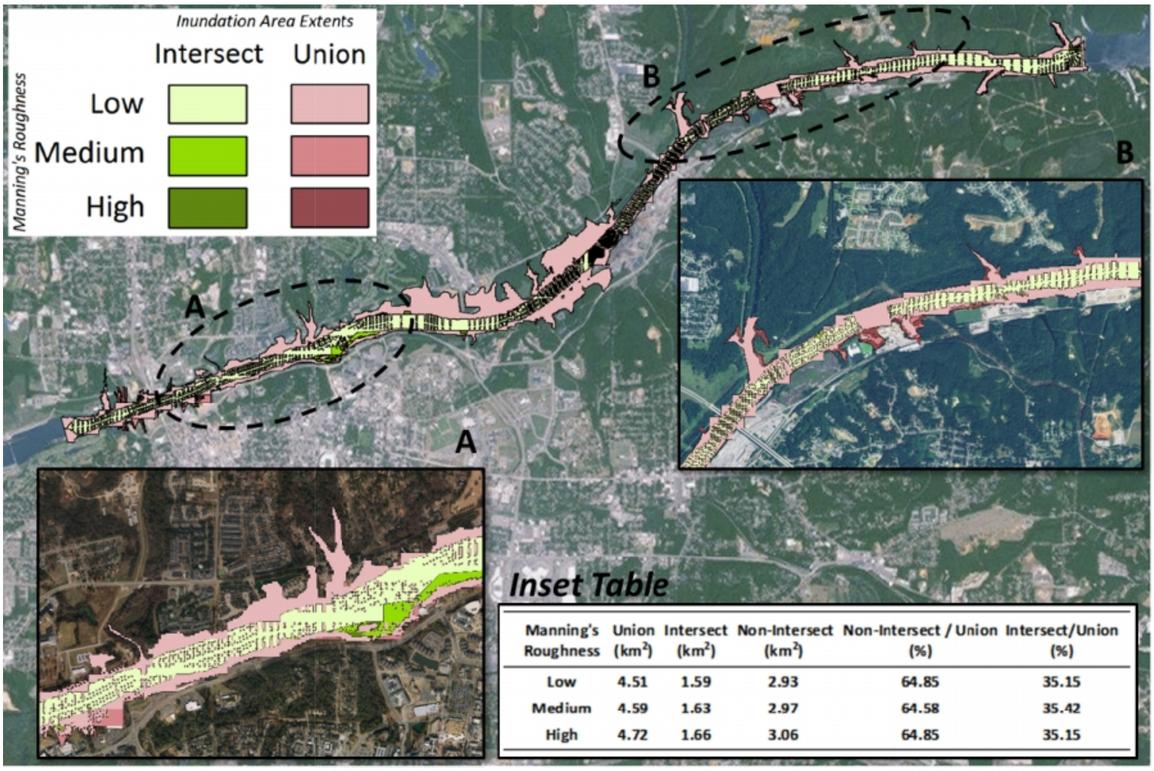

Figure 1. Flood inundation extents considering the intersected (overlapped) and union (blend) of four maps established by HEC-RAS-2D, GSSHA, AutoRoute, and HAND based upon three Manning's roughness categories (low-, medium-, and high-friction) along the floodplain.

Table 1 demonstrates the flooded area and average inundation width for each model corresponding to different bed-roughness settings. It can be inferred that since non-physical models will not take into account the river bathymetry (~5 m deep for ~14 km reach), while being engaged with 10mX10m NED-DEM as terrain models, they cannot highlight the effect of main channel capacity to hold the water even for low flood magnitudes. Concerning such a manner, HAND is the worse model by resulting in ~16% more inundation than AutoRoute. Besides, backwater effects of Oliver Lock and Dam in immediate downstream side of study domain was not acknowledged by non-physical

7 http://www.horizon-systems.com/nhdplus/NHDplusV2_home.php

models. Meanwhile, HEC-RAS-2D and GSSHA were set-up considering river bathymetry and accounting for hydraulic infrastructures (Levee and Dam) along the study region which caused less water intrusion to floodplains.

5.2. HEC-RAS-2D as true model; HEC-RAS-2D plus GSSHA as true models

Assessment on flooding extents generated by GSSHA, AutoRoute, and HAND were made on condition that the inundation boundary produced by HEC-RAS-2D considered as true extent. GSSHA revealed more consistency with HEC-RAS-2D than two non-physical models. The second approach was to consider the union of inundation area established by both physical models as true extent. Concerning either approaches, HAND demonstrated more consistency than AutoRoute with presumably true extent. Table 2 shows the outcomes for the two afore-mentioned circumstances.

Table 1. Inundation area average inundation width of flood maps established by physical (A and B) and non-phisical (C and D) models based upon three Manning's roughness categories, *n* (low-, medium-, and high-friction) along the floodplain.

Index	Models	Low *n*	Medium *n*	High *n*	Low *n*	Medium *n*	High *n*
		Inundation Area (km^2)			Inundation Width (m)		
A	HEC-RAS 2D	3.05	3.07	3.27	218.01	219.19	233.38
B	GSSHA	2.73	2.86	2.93	195.35	204.04	209.61
C	AutoRoute	2.13	2.16	2.23	152.03	154.28	159.04
D	HAND	3.84	3.84	3.84	274.13	274.13	274.13

Table 2. *F-Overlapping* inundation statistics (equation 1), where presuming inundation maps established by: a) HEC-RAS-2D, and b) HEC-RAS-2D plus GSSHA, as true extents, the other models' were scored according to their consistency.

Index	Models	Low *n*	Medium *n*	High *n*	Low *n*	Medium *n*	High *n*
		F-overlapping statistics (%)[a]			F-overlapping statistics (%)[b]		
B	GSSHA	66.58	66.81	65.92	-	-	-
C	AutoRoute	55.88	53.89	51.22	52.93	52.18	49.81
D	HAND	59.65	59.67	60.19	61.14	61.68	61.92

[a] considering HEC-RAS-2D as the true extent;
[b] considering combined inundation by HEC-RAS-2D and GSSHA as the true extent

6. Conclusion

The objective of the current study is the comparison and study of flood inundation extents produced by the four flood inundation analysis tools: HEC-RAS-2D, GSSHA, AutoRoute and HAND, being made for the 14km-long reach of Black Warrior River near by Northport levee and between Holt and Oliver dam and lock, in Tuscaloosa County, Alabama. Accounting for three types of bed-roughness categories (low-, medium-, and high-friction) overlaid on top of 10mX10m DEM as terrain model (including river bathymetry for HEC-RAS-2D and GSSHA) along with inflow forcing provided by National Water Model (for the December 1st -31st, 2015 less than 5-year flood event), followings are the deliverables of our research:

1. Simulation made by physical models for low magnitude flood event did not result in major flood inundation since for semi-large rivers water will stay in main channel. On the other hand, non-physical model due to their drawback in not accounting for channel bathymetry will overestimate inundation extent even for not really large flow.
2. Bed-roughness variation will not yield major effect on flood inundation extents as main channel inflow measures are not significantly large. In the future studies we will further scrutinize the four models' action and assess the different kinds of effects of large flood events (e.g. 100-year

flood) on extending flood inundation boundaries while domain is possessed by hydraulic infrastructures (dam, levee, etc.) and different landcovers.

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Chapter 4

The Modified HAND Method

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Abstract: The National Water Model (NWM) is a hydrologic and hydraulic model that forecasts streamflow over the entire continental United States. Upon becoming fully operational one of the most anticipated products from the model will be live flood inundation mapping. This is a difficult task given the computational demand of hydraulic models. It is imperative to use a simpler method for this task that may otherwise be impossible given economic and computing constraints. Some have suggested that the Height Above the Nearest Drainage (HAND) method be used for this task, but some improvements in this method are possible. We propose that a modified HAND method—based on stream order—be used to complement the weaknesses of the original method. These enhancements include enabling non-uniform inundation within a catchment, accounting for backwater effects in catchments with precipitation and flooding downstream of the catchment, and bypassing hard flow paths that are shorted during large flooding events. We expect that other benefits that are not so obvious to become more apparent as the method is further analyzed. We have successfully generated the modified HAND rasters for all stream orders in Alabama and its 9 related HUC4 basins (8 stream orders in total). We demonstrate that the modified HAND method retains the strength of the original method in cases where the original HAND is more appropriate (e.g. uniform inundation conditions), but better represents cases in which the original HAND has performed poorly. There are two computational demands of these methods: setup and operation. The modified HAND method requires slightly more setup computation but certainly less than a 50% increase in computation (for initial raster creation at each stream order). The operational computation is comparable to the original method and can even be less due to the potential to group catchments and perform somewhat of a lumped parameter analysis. The main point here is that the modified HAND provides far more flexibility for a potential water balance computation, whereas HAND is at least more difficult to implement water accounting if it is even possible. We recommend that the modified HAND be implemented in any and all cases where HAND is currently employed for superior results and potentially smaller computational demand.

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1. Motivation

The National Water Model (NWM) uses hydrologic and hydraulic modeling to yield streamflow for every NHDPlus v.2 catchment for the entire continental United States. Upon becoming fully operational the output from the NWM can be used for emergency management, municipal and regional planning, water resource management, water quality modeling, drought management, etc. However, even when fully operational, there will still be limitations of the NWM, many of which arise from a constrained computing environment. Hydraulic modeling in particular quickly becomes computationally expensive. The challenge presented is to achieve expedient modeling results at a resolution and comparative accuracy of typical hydrologic and hydraulic models that can be used to coordinate local, regional, and national planning and relief efforts for various water sectors in the United States. Obviously, these models must perform well under normal conditions, but many times it is actually the extreme conditions that we care more to know about. Flooding and drought in particular are examples of extremes that are constant threats to the economy and infrastructure but more importantly to life. In its current state the NWM does not have the capability to model flooding nor is it likely that it should be included in the near future given the highly simplified channel routing component, which is based on simple Muskingham calculations and assumed trapezoidal channels. There is a discussion about potentially integrating 2D hydraulic modeling for the routing portion of the NWM. This will require significantly more computation on an already strained system. Our motivation for this work is founded on the belief that there must be a simpler way to achieve accurate flood modeling without having to move to a higher dimension of hydraulic modeling.

2. Objectives and Deliverables

This project is primarily a flood mapping endeavor, which utilizes cyber GIS infrastructure, with implications that could lead to improved flood modeling. Therefore, all the objectives of this study relate to one or more of the three areas including: flood mapping, flood modeling, and cyber GIS. We have focused our efforts on the first of these three, which is flood mapping. Conclusions regarding future work and likely outcomes for each of these study areas will be provided in the conclusion. We realize many of our objectives will not be solved on the first iteration of this new method if any, especially in such a short time frame. Still, we include them because they are the metrics by which we will continue to evaluate our work using the modified HAND method. Our primary objectives include the following:

1. mapping real-time flood inundation for spatially significant areas
2. modeling multiple basin flood interactions (which create backwater flood scenarios)
3. modeling overbank spills (which attenuate flood waves)
4. modeling temporary storage losses (which affect the extent and duration of floods)

Our first objective may seem obvious, but various obstacles have made this a difficult task using conventional hydraulic models. This almost demands that a simple method such as the HAND method be used in order to map the entire continental United States. We believe that if we can demonstrate the concept of light computation flood mapping that it would prove the scalability of the method for larger areas. Each of the last three objectives will be discussed more in the conclusion. Some deliverables for this study (both completed and planned) include:

- modified HAND workflow and methodology (completed)
- HAND and modified HAND rasters by stream order for study area (completed)
- HAND and modified HAND library of inundation rasters (in progress)
- inundation mapping workflow and methodology (under development)

There is also a significant potential to improve water accounting in the flood mapping and modeling feedforward structures in subsequent iterations within the NWM. We consider this to be the ultimate goal of flood mapping and modeling, and it is well within the scope of our study, but it is not likely to be achieved in the first implementation of either HAND or the modified HAND.

3. Methodology

The Height Above the Nearest Drainage or HAND model is a terrain model that normalizes DEMs according to the local relative heights found along the drainage network [1]. Using the raw DEM as the input, several fundamental hydrological terrain analyses are performed such as pit removal to ensure a coherent DEM, flow direction calculation to identify the flow paths and flow accumulation calculation to define and delineate the drainage network. With this hydrological terrain information, HAND then generates a nearest drainage map, or in other words, calculates each cell's relative vertical distance to the closest stream cell it drains into. Although the model was originally developed for soil water dynamics and the determination of local draining potential, HAND has been proved applicable to flood inundation mapping and analysis as well. In a study by Nobre et al. [2], the HAND terrain model was used to determine the inundated potential of grid cells in a study zone by utilizing the same logic as [1]. The study proved that the relative drop in vertical elevation as determined by HAND is an effective predictor of flood potential. Using a contour concept, the study developed an approach for mapping inundation extent of flooding events that doesn't depend on flood observations but instead, drainage-normalized topography and flow paths. See the workflow of the HAND method and the proposed modified HAND method below (Figure 1).

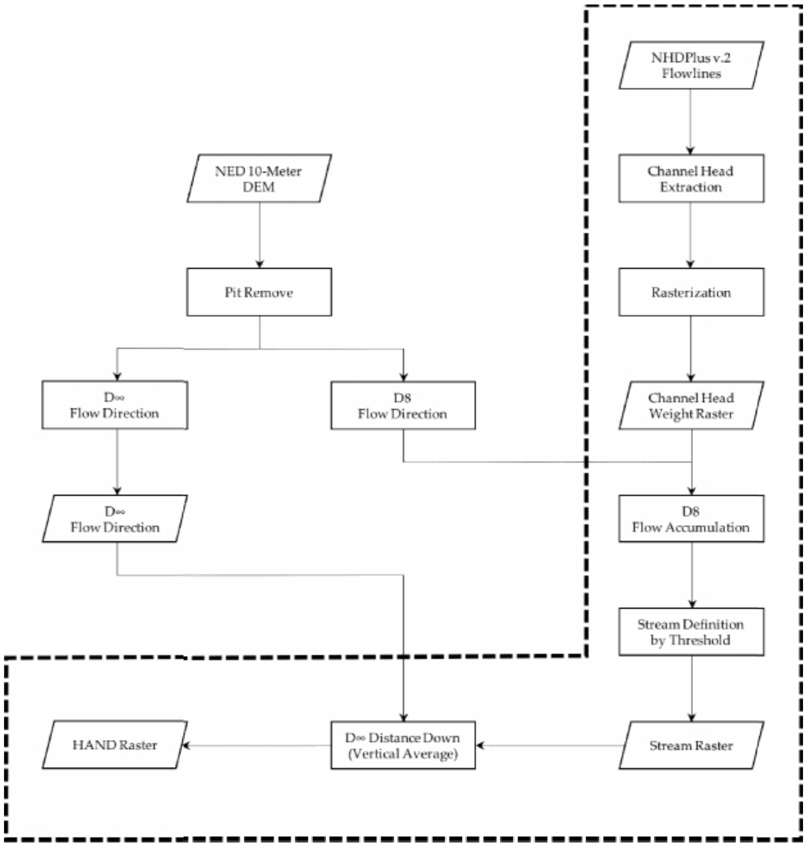

Figure 1. Workflow of the modified HAND method where items enclosed in the dashed area must be repeated for each stream order of the entire drainage network being mapped. Objects are identified with parallelograms and processes by rectangles. Adapted from [3].

The modified HAND method differs from the HAND method in that it takes stream order into account when determining the nearest drainage. HAND is generated using all NHDPlus v.2 or later flowlines (as pictured above). The modified HAND is a combination of HAND rasters based on each stream order from 1st order to the highest order within the drainage area of interest plus the DEM, which is used in coastal flood inundation mapping. HAND is identical to HAND1. HAND2 uses the same workflow as HAND, but the flowlines have had all 1st order streams removed from the analysis. This means that HAND2 is calculated for all flowlines 2nd order and higher. HAND3 is for 3rd order and higher and so on until the stream order has reached the maximum. That concludes the modified HAND method, which is really quite simple. Do not be confused with the inundation mapping method which is to follow this method. The modified HAND method has already been well received in our group of scientists and engineers at the National Water Center, even among the center's staff, our faculty advisors, and our theme advisors. We are still working on the implementation of the modified HAND method for flood inundation mapping, although we already have seen many cases where it already improves inundation mapping over the HAND method. We are looking into a number of possible implementations and will compare the results of these in the future. This is certainly an area that has a high impact factor on flood mapping and modeling, and we invite others to research in this area too. In general, we find it is easy to implement the modified HAND for inundation mapping and for that to be better than the original HAND method. Other groups from the Summer Institute are reporting similar findings regarding the limitations of HAND and the better performance of modified HAND. An optimized implementation will yield even further gains of the modified HAND method due to its computational and structural flexibility.

4. Results

The modified HAND method was successfully created for the State of Alabama and all of its 9 related HUC4 watersheds. There were a total of 8 stream orders in Alabama, which brings the total number of rasters required for this drainage area to 9 including the DEM. See Figure 2 for more general input output information.

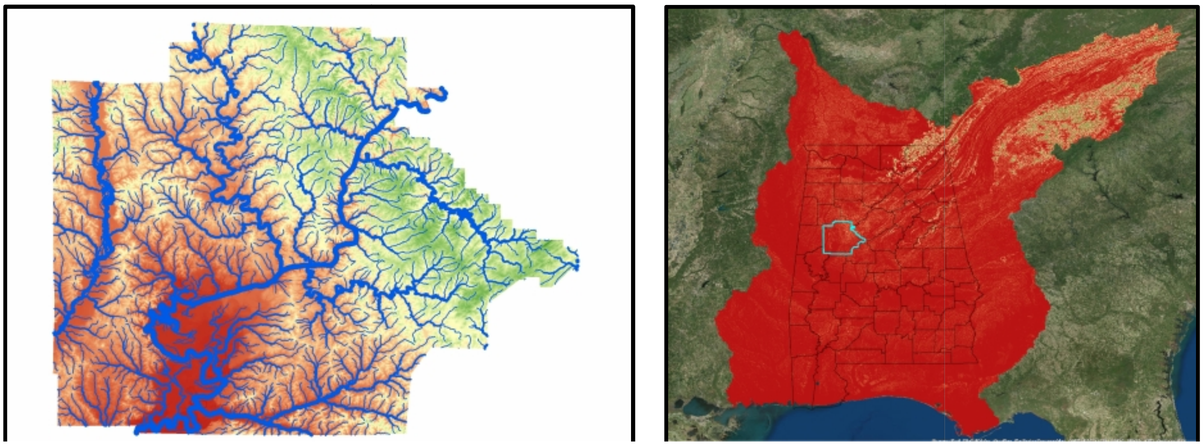

Figure 2. Input and output visualization for the modified HAND method: (**a**) Tuscaloosa DEM and NHDPlus v.2 flowlines with widths according to stream order (for visualization); (**b**) Output HAND raster for the study area.

4.1. The Modified HAND Method Output

Figure 3 displays the results of the modified HAND method for Tuscaloosa County, AL with nth stream ordered flowlines according to the nth HAND raster.

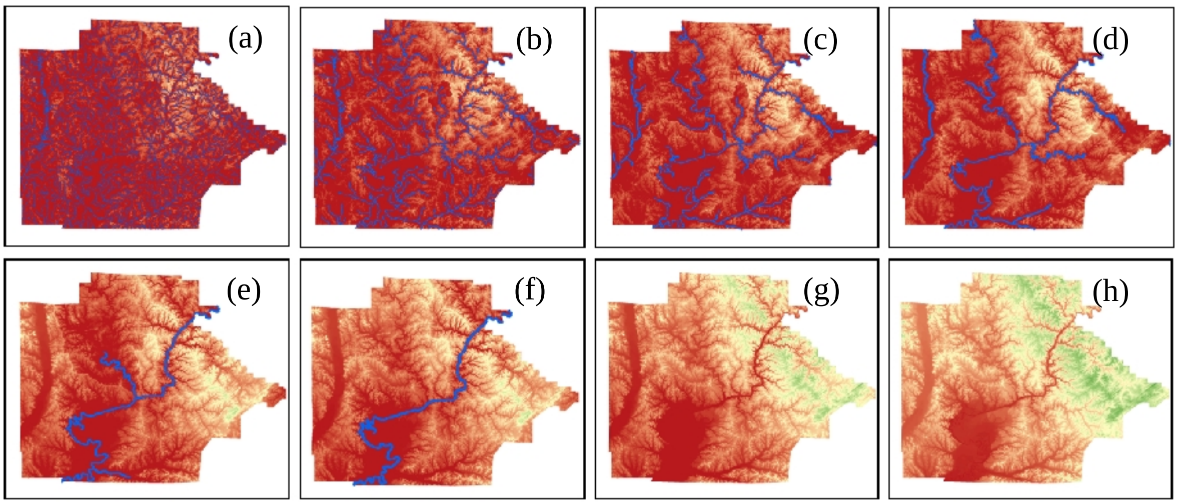

Figure 3. Modified HAND rasters based on stream order (denoted in the form HANDn) with the relevant stream order network overlaid where red indicates likely to be flooded conditions and green indicates unlikely to be flooded conditions: (**a**) HAND (identical to HAND1); (**b-h**) HAND2-HAND8 respectively. The method adapts particularly well with the stream network. Notice how there is a significant change from HAND4 to HAND5 (d) to (e) because the number of drainages at that scale for Tuscaloosa County changes rapidly. Also note that despite lacking a seventh or eighth order stream within Tuscaloosa County, there is still a small risk of flooding from these stream orders. The event would need to be very large in order for this to happen, but the modified HAND preserves these realistic physical relationships very well, when it is difficult for us to even conceive that this county could receive flooding from those downstream catchments. Finally, note that larger order HAND rasters (based on larger drainage areas) present a 'scaling' picture of flood risk, and that areas at risk for flooding become more sensitive to elevation as the scale of the drainage increases.

Upon the completion of the modified HAND method it is easy to begin inundation comparisons using the original HAND method and various nth order HAND rasters.

4.2. Modified HAND Flood Inundation

To compare HAND inundation to modified HAND inundation is to compare a vector to a matrix. HAND of course is like a vector in that there are a set of values that can be changed along a single dimension, whereas the modified HAND can be changed over two. In order to illustrate this we have included two figures: Figure 4 and Figure 5. Figure 4 demonstrates how the modified HAND can be changed over the stream order dimension for a given inundation depth (5 meters in this case). Figure 5 demonstrates how both HAND and the modified HAND can be changed over the inundation depth dimension. These are critical images for understanding the potential of the modified HAND method for superior flood inundation modeling despite using the same or less calculation than that of HAND. Neither of these figures have an implementation method based on water balance or empirical relationships to improve flood inundation mapping, but when they do, the modified HAND stands to gain much more than HAND alone can possibly achieve.

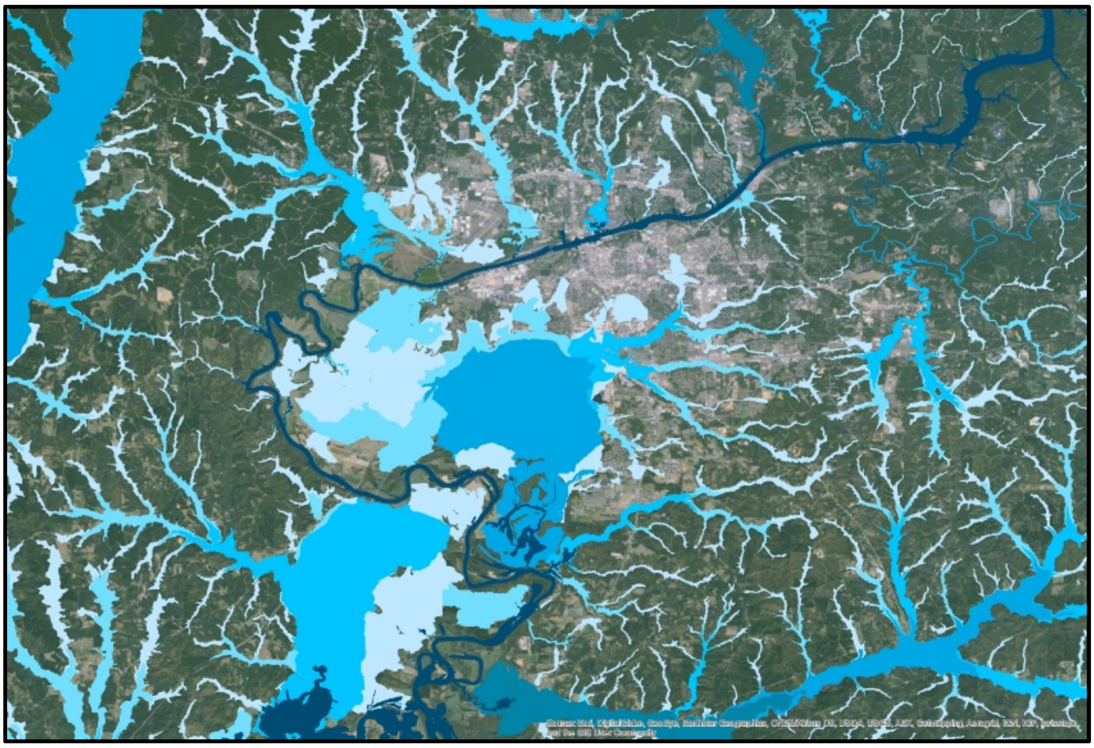

Figure 4. The modified HAND method displaying (from lighter to darker colors) HAND to HAND6 5-meter inundation (there is no flood inundation for HAND7 or HAND8 at this depth). Notice that darker colors shift toward larger streams.

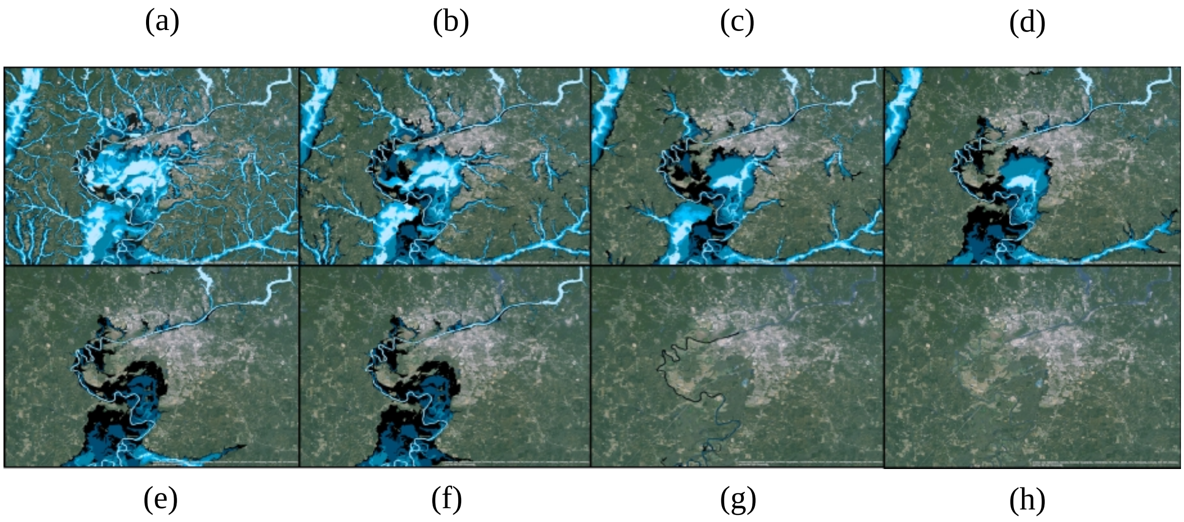

Figure 5. HAND and modified HAND displaying (from lighter to darker colors) small inundation (0.5-meter) to larger inundation (10-meter): (**a**) HAND or HAND1 inundation; (**b-h**) HAND2-HAND8 inundation. Note how little control over the inundation HAND or HAND1 has compared to the remaining suite of modified HAND rasters. The modified HAND not only controls the shift toward larger streams, but it can also control (to varying degrees) the shift to lower elevation streams, which is subtly but importantly different from Figure 4 and the original HAND method.

5. Discussion of the HAND and Modified HAND Methods

We have demonstrated that the methodology of the modified HAND is sound, and have delivered it here. This methodology was used to generate rasters for a large area to validate the new method, also included here. These rasters were then used to demonstrate the difference in flood mapping between the original HAND and the modified HAND method. It is now appropriate to begin a discussion of the limitations of the HAND method, when it applies, when it does not, and how to implement that in flood mapping especially for the post-processing of NWM outputs.

In our short time studying this method we have identified a few primary weaknesses accompanied with figures when appropriate and convenient for a clearer understanding. All weaknesses we have identified for the HAND method belong to one of four sources listed below.

The Original HAND Method:

- allows only uniform inundation within a catchment
- lacks handling of networked catchment inundation
- must have well-defined drainage and flow path
- built upon a rigid computation structure

5.1. Uniform and Non-Uniform Inundation

The first of these issues is one that occurs frequently in floods. HAND always assumes that the inundation water slope is equal to that of the bed slope. In some cases, this will be true, especially those in which either a) precipitation is small compared to the size of the channel or b) precipitation is completely upstream of the catchment being modeled. If it is not one of these cases, the assumption is jeopardized. Modified HAND has the potential to outperform HAND in cases where precipitation is large within a catchment because it will be the contributing areas within the catchment that dominate the flooding (as the channel approaches the outlet the routing of upstream catchment areas and contributing downstream catchment areas will produce flooding more similar to Figure 6b).

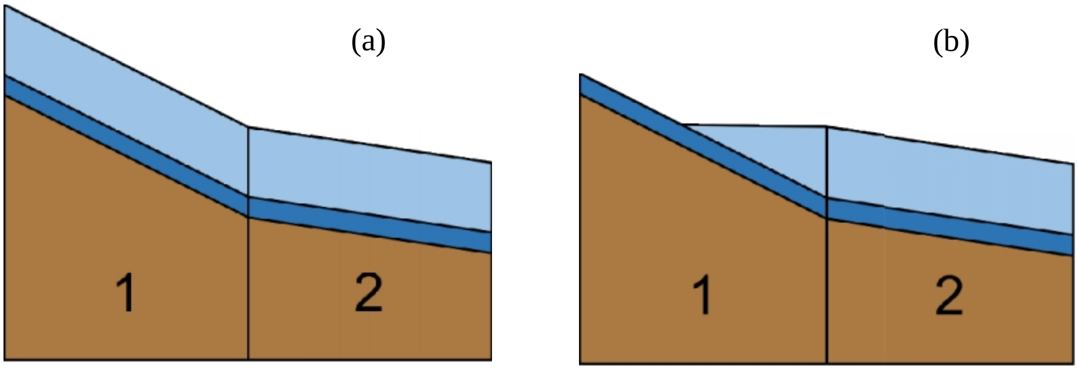

Figure 6. A comparison of HAND and modified HAND inundation models for two catchments—a first order catchment and a second order catchment where light blue is flood inundation on normal flow conditions and the elevation model: (**a**) Uniform inundation for each catchment as modeled by HAND; (**b**) Uniform inundation in the lower catchment—identical to HAND—and non-uniform inundation in the upper catchment. The extent of the non-uniform inundation is dictated by a combination of inundation depth and stream order. Slopes and shapes exaggerated for effect.

5.2. Networked Catchment Inundation

There are at least two great examples where HAND falls short in mapping and modeling floods when it comes to a network of catchments. The first case that is easy to visualize that is the case when there is only precipitation in downstream catchments simulated in Figure 7 for HAND and the modified HAND. In these cases, the modified HAND will always outperform HAND. The difference can be relatively small in lower order catchments and extremely large in higher order catchments, but it will always be better.

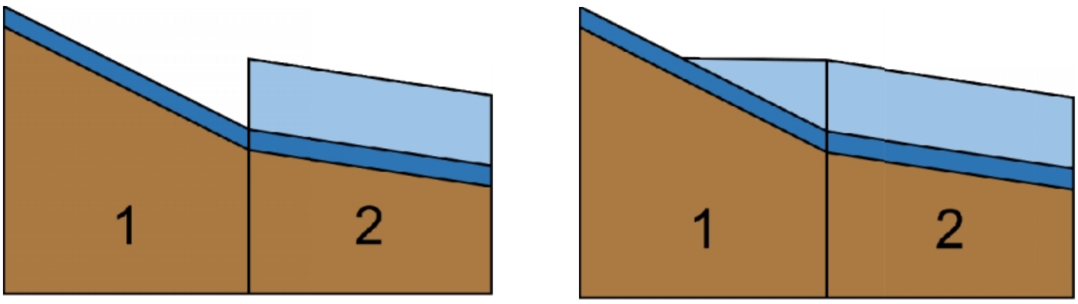

Figure 7. A comparison of HAND and modified HAND inundation when there is only downstream precipitation: (**a**) HAND fails to produce inundation in catchments with no excess runoff; (**b**) Modified HAND can map floods across catchment boundaries—even upstream backwater effects from downstream precipitation. Slopes and shapes exaggerated for effect.

The second network case that is too difficult to illustrate efficiently, is a case when perhaps only one second order catchment in a third order catchment network is receiving flow from upstream. In this case the modified HAND method allows for that second order catchment to be mapped using HAND, while the remaining second and first order catchments are mapped using HAND2 or HAND3 (whichever is more appropriate to that specific network). There is potential here to perform a water balance that HAND is completely incapable of modeling. In this case overlapping inundation in that catchment from HAND and modified HAND can be redistributed into all the remaining catchments of the third order catchment. This makes it possible to account for the effect of that one contributing catchment on the network of streams. This is not an easy task, and runs the risk of complicating the method depending upon how often this case occurs. Nonetheless, it is a viable option for the modified HAND method whereas HAND has no option for complicated cases like these.

5.3. Well-Defined Drainages

An often overlooked area involves inundation mapping in coastal areas. It is commonly overlooked for good reason. It is difficult to map coastal flooding. There are tidal effects, storm surge, flood waves from river networks, estuaries and bays with sometimes complex routing networks, and not to mention the high water table usually prevalent in these areas. Our initial modified HAND method did not have an answer for these areas, though we knew that the uniform inundation produced by HAND would be even more spectacularly shortcoming in these areas due to daily oscillations of sea-level. Thus, the idea of a HAND that could expand to the sea was birthed. We call it (very appropriately) Height Above Sea Level or HASL for short. It is the exact same as the DEM, but we use it in the same manner that we use higher order HAND rasters, which is for level-pool inundation. At the moment, this method assumes uniform sea-level (probably a good assumption for many conditions though certainly not all), but as we learn of sea-level oscillations and fluctuations from storm systems, we plan to update this with a non-uniform sea-level. Again, the addition of water accounting can significantly improve this sector of hydrology, especially since flooding in these areas carries a significant risk of shorting or bypassing well-defined flow paths.

5.4. Computation Structure

Lastly, HAND turns out to be quite an inflexible method when it comes to computing structure. This is inherent with the HAND method and not much can be done to change this. In plain terms, the HAND method must always be calculated for every catchment in order to obtain mapping for every catchment, and one must hope that the flood conditions are those within the capability of HAND to capture. The modified HAND has the ability to 'scale' computationally with the scale of the event or drainage of interest. One flow rate from the NWM (converted to depth using rating curves or another comparable method) can generate flood mapping for an entire nth catchment order. For example, Tuscaloosa has a single 6th order stream running through the county but hundreds and almost on the order of thousands of 1st order catchments in the county. HAND must calculate each and every catchment and cannot afford to lump the catchments of interest into a single entity, for the result would beyond terrible, especially in 1st order catchments. The modified HAND allows for the flexibility to compute flood mapping on the scale most appropriate to the catchment order and is inherently more accurate due to the non-uniform inundation mapping that is so critical to this method's success.

5.5. Future Work

The bulk of the work still lies ahead, not behind. There is still some significant work that must be completed in getting the flow rate from the NWM to a useable depth for the inundation maps produced by HAND or modified HAND. We have pursued two options currently: one which uses SPRNT to develop rating curves for each stream, which seems like the ideal choice, but it takes a long time to compute, even on supercomputing resources. The other possibility involves bathymetry data and the National Elevation Dataset (NED) DEM which can be used to obtain stream cross-sections and profiles for determining depth at given points, likely to be just above catchment outlets. There are still a number of issues that must be worked out in this second method. Once we have a reliable depth, we can generate reliable flood inundation from HAND or modified HAND. It is important to remember that HAND is a great method in some cases, but the goal of the modified HAND is to greatly expand on those cases and to enhance the ones that are already fairly good.

Subsequent to flood inundation mapping, it is possible to determine new channel parameters, which is not currently achieved in the NWM. In addition to this, losses from evaporation and infiltration will impact flood extent and duration. It is foreseeable that a post-processed flood map could be used to define new channel routing components for the following time step in the NWM. Then this channel could be continually reduced by outflow and losses until conditions return to normal. This would fulfill a great need of the NWM in the aspect of flood modeling. We look forward to potential collaborations with those who have ideas to implement these methods or other promising light-computation, post-processing to the NWM outputs for an improved NWM.

6. Conclusion

Our observation of the HAND method was that it tended to produce too much flooding in lower stream order, higher elevation catchments and too little in higher stream order, lower elevation catchments. The limited aspect of HAND appears in lower stream order, lower elevation catchments because of an inherent limitation preventing an accounting for nearby high stream order catchments which spill over into neighboring smaller catchments. This is a frequent occurrence in flooding in which HAND will produce no flooding in cases where the flood wave is arriving from upstream (in a neighboring catchment) and no precipitation is occurring in the catchment of interest. Even when there is precipitation, there will be a discrepancy between the amount forecasted by the NWM and HAND inundation.

In short, it is difficult to imagine a scenario where the modified HAND would perform worse than the original HAND due to its flexibility to use HAND when appropriate. The modified HAND does require more upfront computation for its generation, but it also offers the capability for operationally superior computation expense and results. Our preliminary evaluation suggests that the modified HAND be used in every case where the HAND method is currently employed for a much more flexible method and better physical representation of flood inundation. We look forward to refining the inundation mapping implementation of the modified HAND, specifically into that of which stream order raster to use for various weather, hydrologic and hydraulic cases.

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Chapter 5

Object-based Flood Inundation Mapping

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Abstract: In an effort to prevent loss of life and property, flood inundation mapping is generated in order to assess the impacts and costs of flooding events. However, the spatial and temporal limitations of remote sensing platforms offer little support towards instant mapping efforts. Optical satellites perform poorly in the presence of cloud cover, but collect information across a wide spectrum. Active sensors are able to penetrate clouds and have high spatial resolution, but are limited in spectrum. Most studies using object-based image classification focus on a single source. Our study concentrates on combining multiple data sources, specifically SAR and Landsat 8, in order to include the widest possible information set for improving the quality of segmentation. We apply existing image pre-processing techniques such as pan-sharpening to improve spatial accuracy, while retaining spectral characteristics. Image filtration is used to reduce speckle noise in SAR imagery. A new moisture enhancement index (MEI) was developed, to gather more information about water. Finally, image segmentation algorithms such as Ward, Morphological Snakes, and Random Walker are compared using unsupervised measures, as ground truth is not available. Initial results have shown the effectiveness of using image pre-processing techniques, as well applying different sources to detect water bodies. Using existing river shapefiles and combining with MEI has proved useful in detecting small rivers, which are nearly invisible in both SAR and Landsat. SAR, on combination with other moisture indices by Principal Component Analysis (PCA) accurately detects shapes of large water bodies. Based on the unsupervised measures: weighted variance and Moran's I, Hierarchical segmentation, achieved comparatively better segmentation on when run on the principal components generated from PCA performed on several moisture indices and SAR.

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1. Motivation

Floods are one of the most devastating natural disasters in the United States. In 2015, floods were responsible for 176 deaths [1]. In particular, the state of Texas had been hit by two large floods between January to July 2016, which contributed to 100% of the total flooding losses in the United States ($2.5 billion), only secondary to severe storms [2]. With the advancement of various freely-available remote sensing (RS) sensors and products (including Landsat 8, Sentinel 1, ASTER and Formosat-2 etc.), with high spatial resolution, we now have more detailed information to identify flooding extents. However, current techniques are limited by: a) no large-scale dataset with finer spatial resolution (i.e. less than 30 meters) is available to assist in classification; b) most improvements of existing classification techniques mainly focus on overall accuracy [3], while flood inundation mapping only emphasizes on identifying water. Object-based image analysis seems to provide solutions for flood inundation mapping. Grouping similar values together can be used to increase classification accuracies [4]. Segmentation, which is gathering similar values, can be performed by capturing certain features before the classification procedure, to improve its accuracy.

2. Objectives and Scope

The main objective of this project is to be able to delineate water bodies from RS images, specifically using Landsat-8 and SAR. We aim to: (1) improve image quality in order to well segment water, (2) integrate multiple sources for water detection, (3) perform visual and statistical evaluation of the segmentation techniques.

3. Previous Studies

Optical satellites have been widely used by thresholding and pixel-based classification. Thresholding methods such as [5] applied MODIS products as training sites to identify water, but no training data is available for finer spatial resolution, and the thresholding is limited in complex landscapes. While improved classifiers can achieve better water and flood detection, there are difficulties such as detecting water under aquatic vegetation and the high errors associated with small flooding events [6-7]. Furthermore, the signals of optical satellites cannot penetrate clouds. In contrast, active sensors, such as synthetic-aperture radar (SAR), perform better in the presence of clouds. However, SAR is limited in spectrums, and the identifiable characteristics depend on open-smooth water surfaces [8], making it inefficient in identifying water in complex landscapes. Also, the temporal resolution of SAR images is limited. Most studies using SAR imagery still focus only on one image. An integration of multiple sensors would provide a better chance at capturing flood extents. Optical satellites provide more accurate estimations of flooding extents, while passive microwave has better correlation with observed flooding extents [9]. While pixel-based classification remains as the mainstream for integrating multiple sensors [10], our study focuses on investigating an object-based flood inundation mapping.

4. Methodology

A series of procedures for object-based analysis are examined. First, image pre-processing is performed based on existing literature to best prepare images. Second, a new moisture index is created to best extract water features in Landsat 8. Third, principal component analysis, existing shapefiles and water features extracted from Landsat 8 are applied to assist segmentation. Finally, visual and statistical unsupervised segmentation evaluations are applied.

4.1 Study Area and Data Preprocessing

Our first study area (*S1*) is located in a suburban setting, the San Antonio River Basin, and the second study area (*S2*) is located in a meandering of the Brazos River. In *S1*, the challenge is separating water from built-up areas, as SAR images may not capture complex landscapes well, and simple thresholding may not handle multiple land cover types. In *S2*, the challenge is identifying small rivers, because the small rivers are not clearly visible either in Landsat 8 or SAR images. For evaluating our results, we select two images without cloud coverage: *S1*: 2/26/2015, *S2*: 5/28/2016.

Preprocessing of Landsat 8 includes creating image composite and image fusion, while that of SAR involves eliminating speckle noise. Speckle noise, refers to granular distortions that appear in SAR imagery. This can be attributed to how the roughness of surface impacts the coherent imaging systems such as SAR [11]. It results in distortion of SAR imagery, turning them uninterpretable. We filtered our SAR data using several post processing techniques [12-15]. We evaluate the outcome of our results using the speckle suppression index [16].

Pansharpening refers to the procedure of fusing multispectral bands (30m) with Panchromatic band to get uniform 15m spatial resolution, while retaining spectral characteristics. We use the Gram Schmidt (GS) method in ENVI Classic 5.3, for better water change detection [17]. While Spectral

Angle Mapper is used to evaluate spectral distortion, RMSE is used to evaluate spatial distortion [18]. Correlation coefficient is used to evaluate the general trend of each band.

4.2 Moisture Enhancement Index (MEI)

Numerous moisture indices [19-23] have been described in literature. They are composed of the largest differences between bands, such as the green band and the near-infrared band. As water reflection is usually weak when compared to other land cover categories, the confusion between water and other land cover categories is expected. As a result, our study uses a two-step procedure: (1). two moisture indices are combined. Thus, areas with abundant vegetation would become strongly negative. (2) the difference between band 1 and the green band is used to eliminate urban. Thus, higher values are prone to indicate water. Our study tests whether the new index work for improving the accuracy of segmentation.

$$MEI = \frac{G - NIR}{G + NIR} + \frac{G - SWIR1}{G + SWIR1} + 3 * \frac{Band1 - G}{Band1 + G} \quad (1)$$

4.3 Segmentation

Some segmentation-based algorithms from literature include Region-Based techniques (for e.g. eCognition), Clustering Based [24], Level-Set based [25] and Graph Based segmentation [26] have been explored.

4.4 Integrating multiple sources

4.4.1. Principal Component Analysis

Principal Component Analysis (PCA) is a statistical technique which focuses on converting a set of variables (correlated/uncorrelated), into another set of linearly uncorrelated variables, known as principal components. PCA is a very popular technique for dimensionality reduction in remote sensing [27]. In this project, we use PCA as an image fusion technique.

4.4.2. Existing Shapefiles

NHD Plus, one of the most commonly used hydrological vector dataset, is used. The goal is to improve accuracy of segmentation, in detecting either rivers, water bodies or flooding areas.

4.5 Segmentation Comparisons and Evaluations

In any good segmentation, the intra-segment variations are smaller than the inter-segment variation. Given that there is no ground truth, we use weighted variance [28], an unsupervised evaluation measure, to calculate the intra-segment goodness and the z- value of Moran' s I statistic to measure inter-segment goodness [29-30]. Lower spatial autocorrelation (from Moran's I) and low weighted variance indicate better inter and intra segmentation.

5. Results

5.1 Improvements by image pre-processing

5.1.1 Pansharpening Techniques

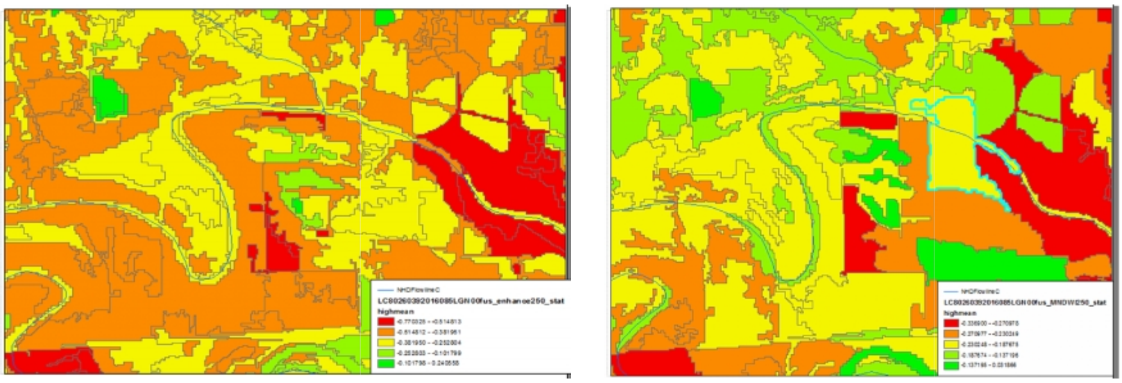
The correlation coefficients of band 1 to band 7 are over 0.7. However, the correlation coefficients of band 9 to band 11 are diverse from 0 to 0.99, depending on different techniques and the study area. Using the angle SAM index, the pansharpening has resulted in larger changes in spectral characteristics in S2 (rural setting). In the case of the RMSE value, the two study areas are similar in spatial characteristics, and band 9 to band 11 have contributed more variations. In other words, the results are consistent, regardless of study areas and pan-sharpening techniques.

5.1.2 Image Filtration for SAR

We filtered our SAR imagery using several post processing techniques [12-15]. We evaluated the quality of our filtration using the Speckle Suppression Index (SSI) [16]. A value close to one or less for SSI indicates a good speckle suppression [16]. While there is less amount of variation in SSI in S2 (rural setting), S1 (urban) shows variation in different filtration techniques. Mean filter [20] performed optimally in both cases with an SSI value of 0.5977 for S2, and 0.6078 for S1, with Enhanced Lee filter [14] coming very close in the S2 SAR image with an SSI of 0.6089.

5.2 Improvements by Moisture Enhancement Index for segmentation

Through initial segmentation using multiresolution segmentation, the results have shown that MEI takes the advantage of two moisture indices to detect the small river bodies otherwise undetectable by other techniques. Further research will be continued in this direction (Figure 1).



(**a**) (**b**)

Figure 1. Visual evaluation: Multiresolution segmentation results based on (a) MEI; (b) MNDWI.

5.3 Principal Component Analysis (PCA)

We extracted the first three principal components from two combinations: 1) post-fused Landsat 8 imagery with SAR; 2) 17 moisture indices in addition to MEI with SAR. Table 1 depicts the variances of the first three principal components against some of the Landsat 8 bands and Moisture bands respectively for S2. From Table 1, we can observe that while bands 5-10 show high variability with respect to the three principal components, SAR has close to zero variability, indicating that it is not contributing to the total variance. This is because SAR's weak signal is being dominated by Landsat 8. On the other hand, in Table 1 (b), it can be seen that SAR is dominating in the second component, indicating the potential ability to detect water.

Table 1. First 3 principal components in feature space, representing direction of maximum variance for data select bands of (a) Landsat + SAR (b) Moisture Indices + SAR

Landsat + SAR					Moisture Indices + SAR				
Band 5	**Band 7**	**Band 9**	**Band 10**	**SAR**	**NDWI1**	**SAVI**	**TCT-wetness**	**NDII**	**SAR**
0.35	0.27	**0.53**	**0.49**	0.00	0.00	0.00	**1.00**	0.00	0.00
0.54	**-0.57**	0.19	0.19	0.00	0.00	0.00	0.00	0.00	**-1.00**
-0.75	-0.19	0.41	0.37	0.00	-0.33	**0.64**	0.00	**0.36**	0.00

5.5 Evaluation for segmentation on PCA data within different segmentation techniques

We evaluated the impact of performing PCA with (Landsat + SAR) and (Moisture Indices + SAR) separately and then performed segmentation using Random Walker and Ward methods. We compared the outcomes of running segmentation on the three principal components mentioned in the previous sections for each segmentation. Based on the comparisons, hierarchical segmentation, performing on moisture indices + SAR, has shown low weighted variance and Moran's I.

5.5 Integrating existing shapefiles

We use existing information from NHD Plus river network for S2, and integrate it with MEI to provide information for Morphological Snakes segmentation. This combination has been able to detect small rivers, even if the spatial resolution of Landsat 8 is not sufficient to identify (Figure 2).

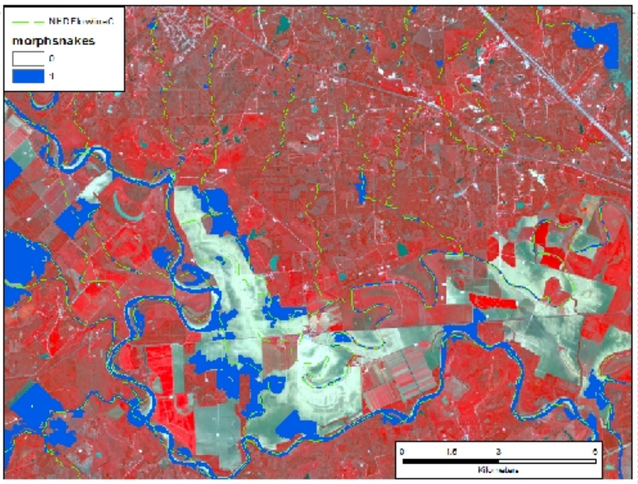


Figure 2. Visual evaluation on integrating existing shapefiles

6. Conclusion

Various data cleaning and integration methods were explored to improve the identification of water. Combining various moisture indices, including MEI together with SAR data has resulted in better water identification. Combining the river network information from existing NHD Plus database with MEI has been resulted in extraction of information about smaller river bodies. Integrating the data obtained from real-time mapping services such as UAVs and Q-SAT satellite with the information available from satellite imagery, is a potentially great area of research.

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Chapter 6

Comparison of Flood Inundation Mapping Techniques between Different Modeling Approaches and Satellite Imagery

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Abstract: Flood inundation extent serves as a crucial information source for both hydrologists and decision makers. Accurate and timely inundation mapping can potentially improve flood risk management and reduce flood damage. In this study, the authors applied two modeling approaches to estimate flood inundation area for a large flooding event that occurred in May 2016 in the Brazos River: The Height Above the Nearest Drainage combined with National Hydrograph Dataset (NHD-HAND) and the International River Interface Cooperative - Flow and Sediment Transport with Morphological Evolution of Channels (iRIC-FaSTMECH). NHD-HAND features a terrain model that simplifies the dynamic flood inundation mapping process, which is suitable for large-scale application. iRIC-FaSTMECH is a hydraulic model that simulates flood extent under quasi-steady approximation. In terms of data source, HAND and iRIC utilized the National Water Model (NWM) streamflow output data and the United States Geological Survey (USGS) stream gage data, respectively. The flood inundation extent generated from these two modeling approaches were validated against the Landsat Satellite Imagery data. Four remote sensing classification techniques were used to provide alternative observations: supervised, unsupervised, normalized difference water index and delta-cue water change detection. According to the quantitative analysis that compares inundated and non-inundated areas with different remote sensing classifications, the advanced fitness index of iRIC simulation ranges from 57.5% to 69.9% while that of HAND ranges from 49.4% to 55.5%. We found that even though HAND better captures some details than iRIC in the inundation extent, it has problems in certain areas where subcatchments are not behaving independently, especially for extreme flooding events such as in May 2016 (Water level reaching 16.8 meters at Brazos River near Hempstead). The iRIC performs better in this case, however, we cannot simply conclude iRIC is a better-suited approach than HAND considering the uncertainties in remote sensing observations and iRIC model parameters. Further research will include more comprehensive assessments based on a larger variety of flood events. The findings from this study indicate that, for extreme events, simplification on the intricacy of flow dynamics have relatively minor influence on prediction, which in the authors' opinion positively justifies the utility of HAND on large-scale riverine inundation mapping.

1. Motivation

Floods are one of the leading causes of the death from natural disasters in the United States. Floods can damage and devastate homes and farms, displace families, damage crops, disrupt agriculture and business. Therefore, flood inundation extent serves as a crucial information source for both hydrologists and decision makers. Accurate and timely inundation mapping can potentially improve flood risk management and reduce flood damage. Precise mapping of the maximum flood extent is also required for detecting deficiencies in existing food control measures and for arbitrating damage claims later. Flood inundation maps produced in near-real time are invaluable to state or national agencies for disaster monitoring and relief efforts. However, traditional methods of flood mapping are based on ground surveys and aerial observations, but when the phenomenon is widespread, such methods are time-consuming and expensive.

2. Objectives and Scope

Using a large flood event that occurred on the Brazos River as a case study, this paper aims to achieve the objectives as outlined below:

1) To simulate flood inundation maps using the *Nearest Drainage combined with National Hydrograph Dataset (NHD-HAND)* and *International River Interface Cooperative (iRIC)*, respectively.
2) To generate observed flood inundation maps from Landsat 8 data using four classification techniques, i.e. supervised, unsupervised, normalized difference water index and delta-cue water change detection.
3) To compare the resulted inundation maps to gain perspectives on the advantages and disadvantages of individual mapping tool.

3. Previous Studies

The Height Above the Nearest Drainage (HAND) concept was first introduced by a research group in Brazil [1]. HAND model normalizes topography based on relative heights found along the nearest drainage network [2]. Liu et al. calculated HAND raster at national scale combined with National Hydrograph Dataset (NHD), which eventually resulted in NHD-HAND model [3].

The USGS iRIC model framework is upgraded from the USGS MD-SWMS (Multi-Dimensional-Surface Water System Modeling System). It implements the Computational Fluid Dynamics General Notation System, originally developed at NASA for stable and computationally-fast modeling of complex 2D+ fluid dynamics [4]. There are some plug-in models that can be used in iRIC, including flow simulation, sediment transport, landform evolution, and habitat modeling. iRIC [5, 6], a 2D hydrodynamic model, employs a cylindrical coordinate system, and it is accessible for the calculation with long timeframes because of its steady or qausi-steady approximation. In this study, FaSTMECH is selected because it is fast to simulate flow, easy to use, favorable for less gage data, and it can show the maximum inundation area with the peak discharge.

Floodplain boundaries have been delineated with the Landsat campaigns almost since its inception in 1972 [7]. They have been used in many studies to map inundated areas over regions characterized by very different conditions in climate, morphology and land use.

4. Methodology

In this study, the research team focused on a flood event along Brazos River in Texas in May, 2016. The USGS gage at Brazos River near Hempstead (ID: 08111500) recorded a peak discharge of 4445.7 m^3/s at 2 p.m. on May 27th. The total rainfall was 255.8 mm within 30 hours according to the same USGS gage.

4.1 Models

4.1.1 NHD-HAND

The Nation Water Model provides the discharge of each NHDPlus flowline as input for HAND. These flow hydrographs are further translated into stage height using rating curves (stage-discharge relationship), which are generated from channel properties in HAND model. Next, the HAND raster further determines the inundated area, which has lower elevation than stage height. Figure 1 shows a schematic flowchart of the procedure for creating inundation maps.

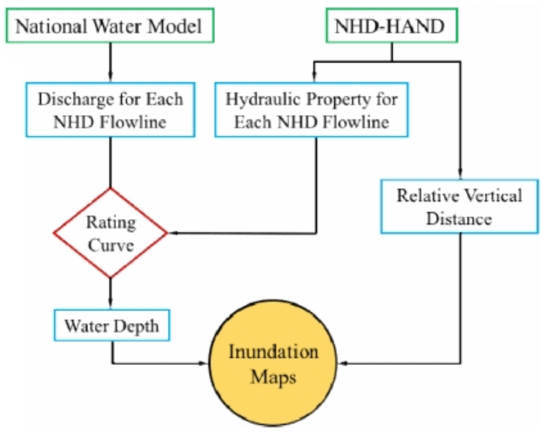
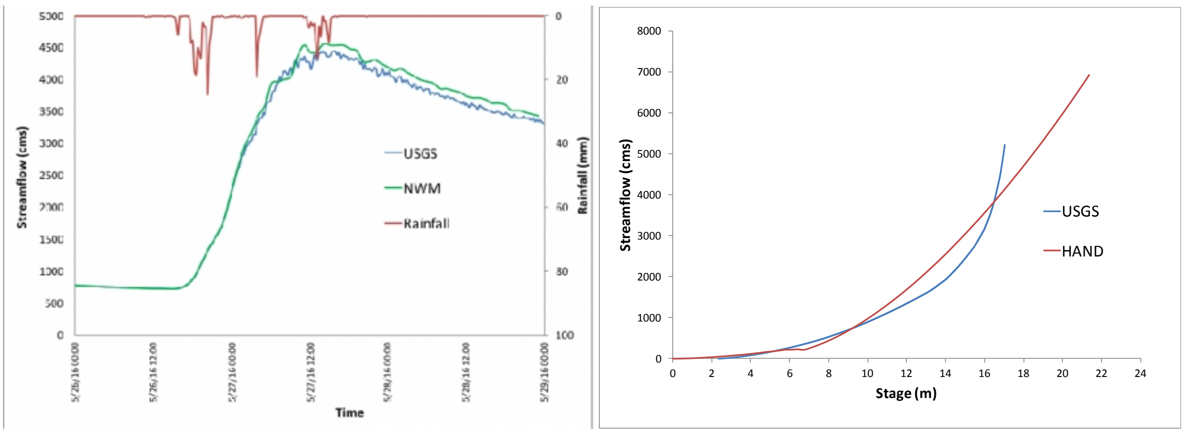


Figure 1. Flowchart of generating inundation maps from HAND

We also compare the streamflow from USGS gage in Brazos River at Hempstead, TX with NWM output and rating curve generated by HAND with the same gage. From Figure 2, the simulated hydrograph from NWM almost perfectly matches the observed hydrograph and rating curves also show good agreement in the low to moderate flow range. Therefore, such comparison, to certain extent, excludes the uncertainty from the model input, hence narrowing down the source of uncertainty to observation and HAND itself.



(A) (B)

Figure 2. Comparison between USGS gage with (A) NWM discharge output and (B) rating curve from HAND

4.1.2 iRIC-FaSTMECH

The iRIC model herein utilized USGS gage data as the only downstream boundary condition. Two tests were conducted: (1) various grid size and (2) various roughness. Changing grid size from 5 m × 5 m into 10 m × 10 m, the inundation area shows little change but greater details can be obtained with smaller grid size. For the test on toughness, land was classified into three types: main channel, wooded area, and pasture or cultivated areas with Manning's numbers being 0.03, 0.05 and 0.035 respectively. The results showed that better details can be captured by considering various land types than by applying uniform roughness across the modeling domain. Therefore, applying various roughness zones is more reasonable/realistic. However, in order to compare with HAND in this study, we keep the uniform roughness with the Manning's coefficient being 0.05. The final settings are showing as Table 1.

Table 1. iRIC model settings

Setting Menu	Description
Initial Condition	Initial Water Surface Elevation: 1D [illegible]-back water 1D Discharge: 4445.7 m^3/s 1D Stage: 49.7 m 1D Drag Coefficient: 0.3
Grid Size	5 m × 5 m
Iteration	1500
Discharge	constant (4300 m^3/s)
Stage	constant (49.7 m)
Drag Coefficient	0.014
Lateral Eddy Viscosity	Variable (from 0.5 to 0.05; started from 500th iteration, and ended at 1000th iteration)
Re-wetting	On

4.2 Satellite Image Analysis

The remotely sensed imagery used in this study include Landsat 8-Operational Land Imager (OLI) multispectral images (http://earthexplorer.usgs.gov) of pre-flood (25 March 2016) and during flood (28 May 2016) days. Erdas Imagine®- 2015 Image processing software (Hexagon Geospatial, Norcross, GA, USA) was used for image pre-processing and subsequent data manipulation. Geometrically and Radiometrically rectified images were subject to: (1) Unsupervised Classification based on the K-means classification algorithm, (2) Supervised Classification based on the maximum likelihood classifier, (3) Delta- cue change detection on Pre/During flooding scenarios and (4) The use of the Normalized Difference Water Index [8], a spectral water index for the delineation of the spatial extent of floods. Spatial interpolation and filling techniques were applied to pixelate clouded regions with water. Accuracy Assessments were performed on the classified imagery prior to being post processed through a 3×3 high pass kernel to accentuate the water features for improved visualization.

4.3 Advanced Fitness Index

As a common areal statistic, the fitness index is the ratio of fitted inundated areas to the jointed inundated areas. This index was widely used to indicate the agreement/discrepancy between satellite observation and the model simulations [9]. However, the fitness index only accounts for inundated areas, but not non-inundated areas. In this study, the advanced fitness index was calculated to account for both the inundated and the non-inundated areas as shown by Equation 1:

$$\text{Advanced Fitness (\%)} = \frac{IA_{obs} \cap IA_{model} + IA_{obs} \cap NIA_{model}}{A_{obs} \cup A_{model}} \times 100 \quad (1)$$

where IA_{obs} /NIA_{obs} is inundated/non-inundated area from the satellite imagery; IA_{model}/NIA_{model} is inundated/non-inundated area from the model, and A_{obs}/A_{model} is the entire calculated area from the satellite imagery/model.

5. Results

Figure 3 below shows inundation maps generated from iRIC, HAND and four remote sensing classification techniques. These preliminary results show some discrepancies between modeled and observed inundated areas. Based on the advanced fitness indices, the inundation map derived from iRIC fitted satellite imagery better than HAND, as HAND missed two inundation areas in the simulation domain. However, as highlighted by the red circles, HAND better captured details than iRIC in some inundated areas. Figure 4 compares that the advanced fitness indices between the two simulations and the four observations (from four classification methods).

Figure 5 shows the two missing areas (in yellow circles) resulted from HAND model. In Figure 5A, the red line is subcatchment boundary; the blue lines stand for flowline; the green color stands for inundation area; the yellow circle is the missing part; and the white number is COMID for each flowline. Figure 5B shows the selected cross-section, where the blue line is the modeled water depth; the red dotted line stands for subcatchment boundary and the black line is the HAND elevation. HAND calculation is subcatchment-based, which means the inundation extent on different sides of the subcatchment boundary is calculated based on two different water depths. Consequently, in the HAND simulated results, the left side of the subcatchment got flooded while the right side did not. However, in this case the two catchments should have been considered as a whole, and the inundation calculation should have considered the interaction between the subcatchments.

Figure 6 shows flow velocity vectors and inundation calculated from iRIC with two white circles highlighting the two inundated areas missed by the HAND simulation. The velocity vectors indicate that the main stem got overflown at two circled areas, which explains how the two models performed differently for this particular event.

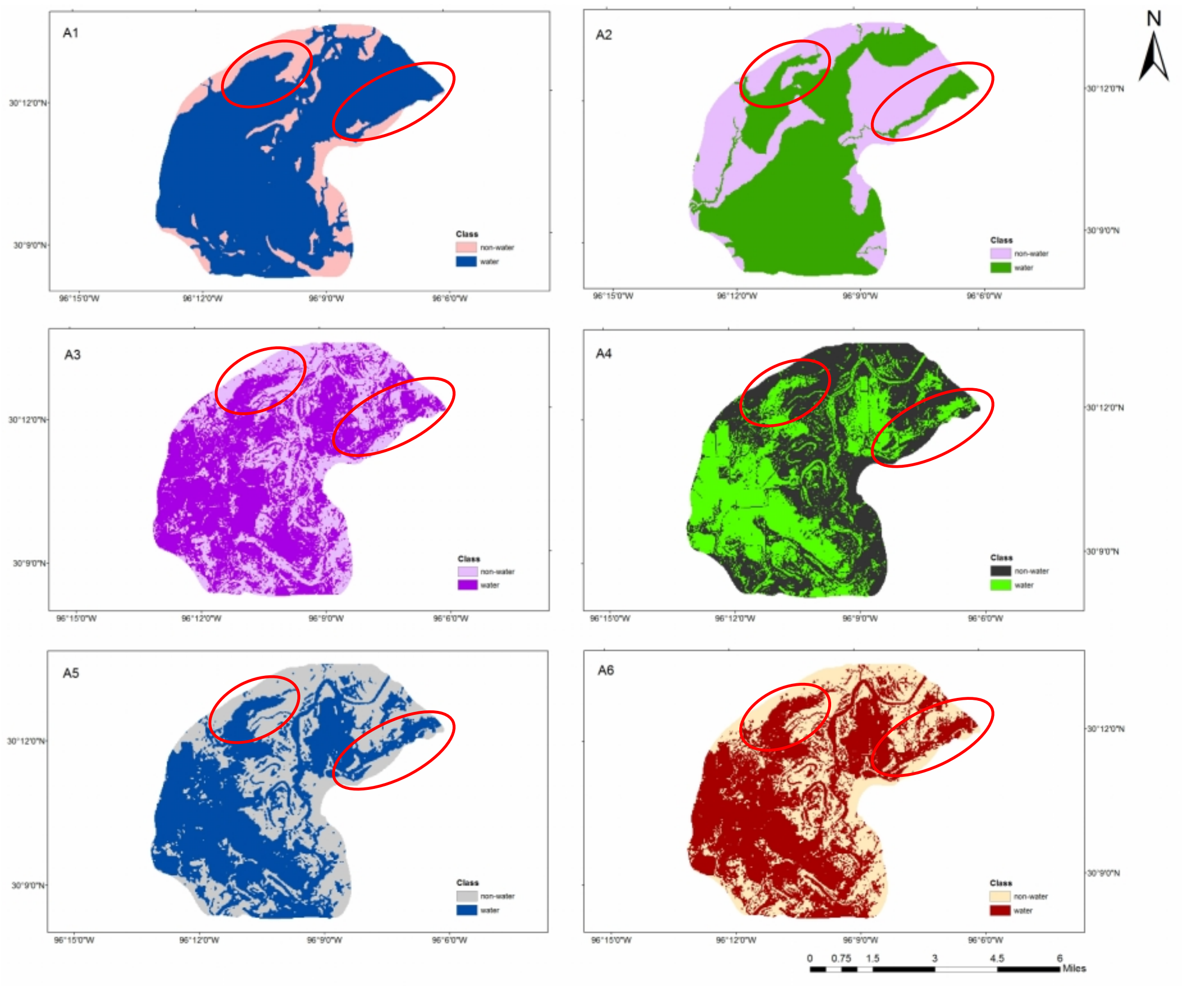


Figure 3. Inundation maps of different models and remote sensing techniques: (A1) iRIC, (A2) HAND, (A3) Delta-Cue, (A4) NDWI, (A5) Unsupervised and (A6) Supervised

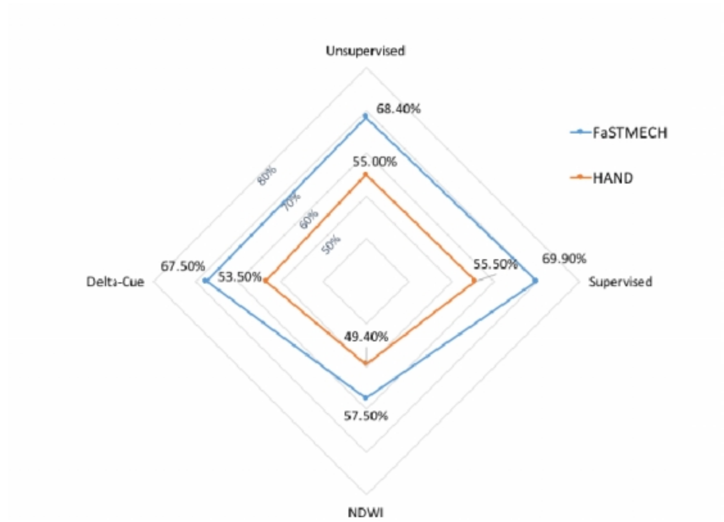
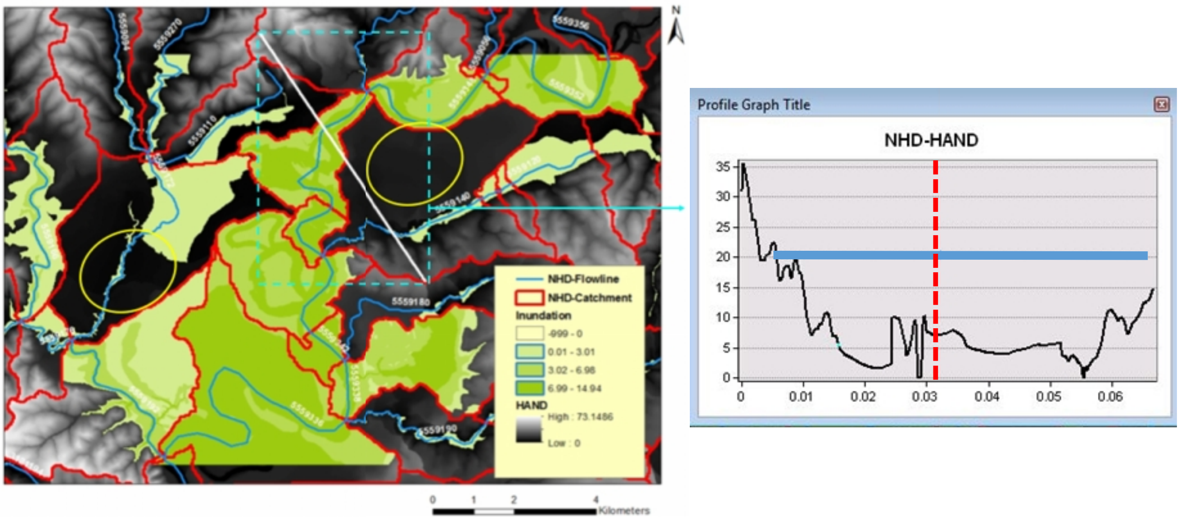
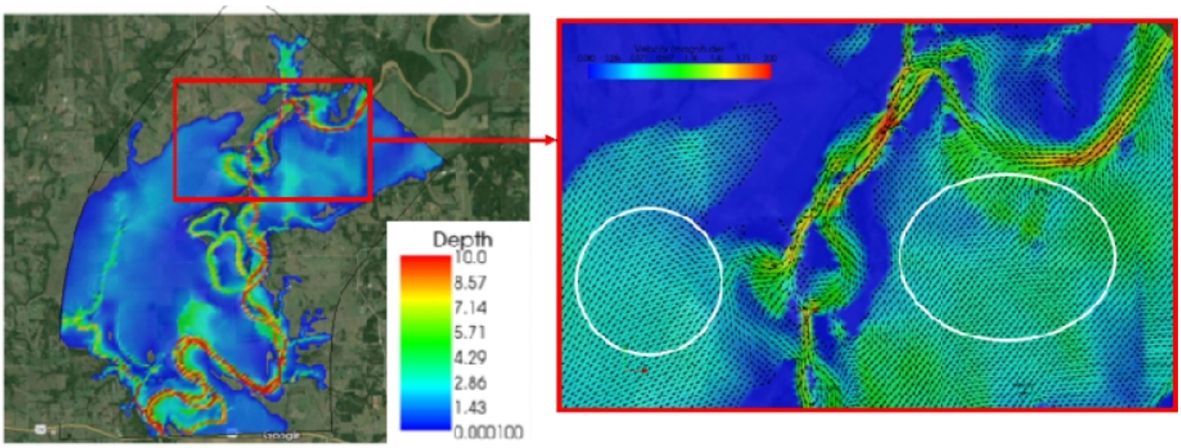


Figure 4. The advanced fitness index within iRIC, HAND and different classification method in satellite imagery (UN stands for unsupervised classification, SUPER is supervised classification, NDWI is Normalized Difference Water Index, and DELTA is delta-cue).



(A) (B)

Figure 5. Two inundated areas missed by HAND (A) and HAND profile for selected cross-section (B).



(A) (B)

Figure 6. Simulated inundation water depth from iRIC (A) and velocity vectors in the selected area (B).

6. Conclusion

Both HAND and iRIC generated fair (> 50% of Advanced Fitness Index) fit with the satellite imagery. iRIC performed better (~ 70% in fitness index) in this extreme flood event, where water level reached 16.8 m at Brazos River near Hempstead Gage. However, HAND better captured details than iRIC in some inundated areas. There were two inundation parts missed by HAND modeling, because subcatchments were behaving interactively during this event. Simply based on the studied flood event, one cannot simply conclude iRIC is a superior approach than HAND considering the uncertainties in remote sensing observations and iRIC parameters. Further research will include more comprehensive assessments based on a larger variety of flood events. The findings from this study also indicate that, for extreme events, simplification on the intricacy of flow dynamics have relatively minor influence on prediction, which in the authors' opinion positively justifies the utility of HAND on large-scale riverine inundation mapping.

Although our results based on 10 m DEM are promising, there are several directions through which performance variation of the two models can be tested. With the availability of high quality digital elevation models (DEMs) acquired through Light Detection and Ranging (LiDAR), the representation of floodplain processes may get better. However, most areas in United States lack LiDAR availability due to the higher cost of data acquisition. It is also a well-accepted fact that LiDAR DEMs still do not include information on channel cross-sections. Better representation of channel shape, in addition to LiDAR-based floodplain topography can significantly improve simulations both from HAND and iRIC. Because our study domain does not have surveyed channel cross-section data, a semi-empirical approach proposed by Merwade and Maidment [10] will be used in our future endeavors.

Supervised classification of remote sensing yields the best observation results because unlike other classification algorithms sample pixels representative of flood water were manually selected and training sites were created. Subsequently, flood water pixels of the entire image were classified based on this accumulation of spectral signatures. This method yields a definite advantage over the other methods simply because user experience and knowledge allows for the clustering of flood water pixels, which is a mixture of water, soil, sediment and vegetation. In comparison, as spectral signatures of flood water could be different depending on the mixture, they have a very high likelihood of being classified into different landuse classes which is highly probable in other classification algorithms. It is envisioned to use image fusion techniques and the Modified Normalized Difference Water Index (MNDWI) as future research in order to obtain comparable results. Image fusion on OLI imagery allows the user to improve spatial resolution based on the fusion of the higher resolution panchromatic band with other band composites while the MNDWI is expected to enhance open water features while efficiently suppressing and even removing built-up land noise as well as vegetation and soil noise to accentuate water features more than the NDWI [11].

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Chapter 7

Real Time Postprocessor Towards Improving Flood Inundation Mapping

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Abstract: The objective of this study is to evaluate the potential for real time post processing of flood inundation maps. In order to support and facilitate the effective communication of flood forecasts and flood risk, we implement a statistical model to produce unbiased, reliable and skillful flow-stage output from the National Water Model (NWM). For the statistical model, we evaluate a first-order auto regressive (AR1) model to encourage efficient processing times. Post processed streamflow-stage outputs were verified against stage observations from USGS and bridge sensor operated by the Iowa Flood Center as a case study. For the case study, we select the main stream of the Shell Rock River at Iowa. We selected the Shell Rock River because i) it contains a densified network of stage-flow observations, and ii) it has historical records for severe flooding. We compare three main results, each comprised by a characteristic flood inundation map generated by using Height Above Nearest Drainage (HAND) method. A first map displays NWM simulation result. A second map displays the observations from bridge sensor. A third map shows the post-processed results. Overall, the post processed map shows improved capabilities in matching the observed map.

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1. Motivation

Accurate geospatial information about flood extent is essential for effective communication of flood forecast and to assess the risk related to floods [1]. For these reasons, flood maps have been widely used in practice to assess the potential risk of floods. However, the shortcomings associated with meteorological forcing variables, topographical representation, structural parameters of the hydrologic model, flow information and inundation mapping techniques lead to uncertainties in flood inundation maps [2]. It is essential to understand and account these uncertainties to produce reliable and accurate streamflow information, which facilitate to produce accurate flood maps.

With the recent development in quantifying the meteorological and hydrologic uncertainties, the greatest issue still is to develop an effective way of communicating the meaning and values of the hydrologic and hydraulic model output. In streamflow forecasting system, the general trend is to display the streamflow information in the form of hydrographs, which are sometimes very confusing and often add difficulties in interpreting the information. Study has rarely focused toward improving the ability to communicate what will happen during a flood event. In order to translate flood forecasts into an easy-to-use format, it is necessary to make a shift from the verification of hydrographs to flood inundation maps.

2. Objectives and Scope

In this study, our primary goal is to assess and verify the potential of real time post-processing of flood inundation maps. We employ here the statistical model to produce unbiased, reliable and skillful simulation product from the National Water Model (NWM). For the statistical model, we first evaluate a first-order auto regressive (AR1) model to encourage efficient processing times. We use the observations from USGS gauge and bridge sensors for training the postprocessor and verifying the raw and post-processed NWM stage simulation. Finally, we use the Height Above Nearest Drainage (HAND) method to display a characteristic flood inundation map. The ultimate goal here is to encourage a shift from the verification of forecast hydrographs to flood maps, which are a more appealing display for purposes of general communication.

3. Previous Studies

Bias in meteorological forcing variables propagate through the hydrologic forecasting model and lead to uncertainties about streamflow forecast. In order to correct systematic forecast biases in forcing variables, several preprocessing techniques (e.g., extended logistic regression, heteroscedastic extended logistic regression, Bayesian model averaging, and quantile regression) are frequently applied. However, preprocessor cannot account the uncertainties arising from the model parameterizations together with the uncertainties in structure. Therefore, post processing techniques (e.g., general linear model [4], auto-regressive model [5], and Bayesian postprocessor [6]) are applied aimed at accounting these additional uncertainties.

The majority of studies has been focused on producing accurate and reliable streamflow forecast. But, very few studies have been carried out to examine the best way of communicating the hydrologic model output. Especially in streamflow forecasting, there is a necessity to make a shift from the verification of forecast hydrograph to flood map with effective visualization technique. A promising work has been done in Iowa Flood Center (IFC) to develop a user friendly and interactive web platform, which provides flood conditions, flood forecasts, and data visualizations applications for over 1000 communities in Iowa. Similar example is from the Federal Emergency Management Agency's (FEMA) flood hazard mapping program, which provide accurate flood hazard maps to guide policy makers and community to mitigation actions.

4. Methodology

For implementing the postprocessor, we use simulation output from NWM. Simulated stage was obtained by transforming discharge to stage, for the selected station, by using the rating curve. We apply the statistical post-processing technique to the transformed stage, aimed at correcting the bias in stage simulation result. The quality of the post processed stage is then verified against the corresponding observation from bridge sensor and USGS gauges. Finally, three different flood inundation maps are compared to display the raw, post processed and observed flood extent. The schematic of the overall process is shown in Figure 1.

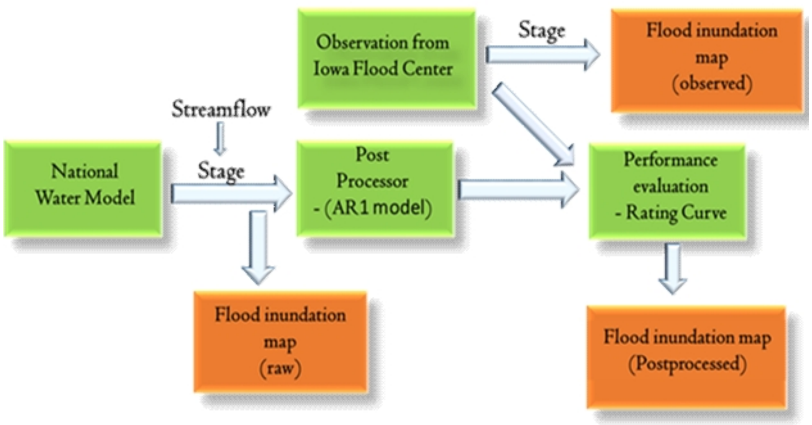

Figure 1. Framework for verification of flood inundation maps.

4.1. Study area

We use the Shell Rock River at Iowa as a case study. The geographic location and main stream of the Shell Rock River is illustrated in Figure 2. We select the Shell Rock River because i) it contains a densified network of stage-flow observations, and ii) it has historical records for severe flooding. This study focus in the downstream reaches of the Shell Rock River, which contains 2 USGS gauge stations (Stations 1 and 5) and 3 bridge sensors (Stations 2, 3 and 4) (Figure 2). NWM assign a unique identifier, or COMID, for each reach catchment and the flowline corresponding to these observation stations. The area of the reach catchment, for the selected 5 stations, varies from 1.5 sq. miles to 3 sq. miles. The NWM computes the flow in all these reaches, considering the flow within that catchment.

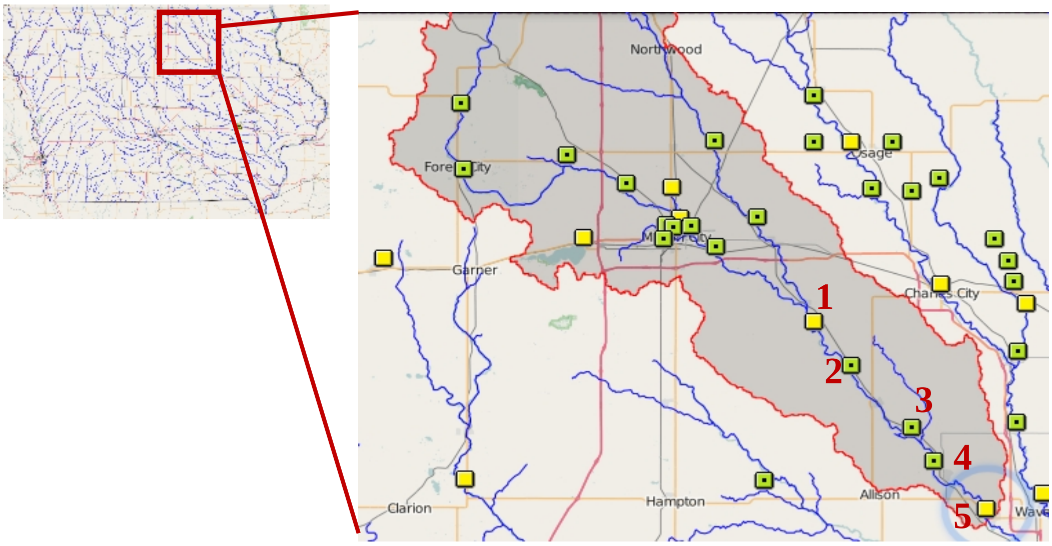

Figure 2. Case study area: Shell Rock River, Iowa.

4.2. Data

In order to evaluate the potential of postprocessor, we use retrospective and real-time NWM hourly test simulations output for year 2015. National Water Center (NWC) is the lead organization that in charge of developing the NWM in collaboration with the National Centers for Environmental Predictions (NCEP) and the National Center for Atmospheric Research (NCAR). Raw and post processed stage is verified using the observations from USGS gauges and IFC bridge sensors. USGS gauges provides continuous record of stage. IFC operates the densified network of bridge sensors, which make river stage measurements every 15 minutes. These measurements are made available to the general public in real-time via the IFC flood information system (IFIS).

4.3. Postprocessing technique

In order to produce a reliable and accurate NWM streamflow simulation, we apply here the first order autoregressive model (AR1) [5] with prior observation and NWM simulation stage output as predictors. The selection of the AR1 model is motivated by the i) effectiveness of the parsimonious model, ii) limited amount of historical data, and iii) efficient processing time. In order to remove bias in the model output, the sum of regression coefficient was constrained to one. Further, computation was facilitated through the Markovian assumption, implying that the stage at one step ahead in the normal space is dependent on the stage at current time step and independent of stage at the preceding time steps. This can be represented as

$$Y_{0,t+1} = (1 - a_{t+1})Y_{0,t} + a_{t+1}Y_{s,t+1} + E_{t+1}, \tag{1}$$

where $Y_{0,t+1}, Y_{0,t}$ denote the Normal Quantile Transformed (NQT) observation at time step *t+1* and *t*, respectively; a denotes the regression coefficient; $Y_{s,t+1}$ denotes the NQT stage simulation at time step *t+1*; E_{t+1} is the residual error term given by

$$E_{t+1} = \frac{\pm_{E_{t+1}}}{\pm_{E_t}} \circ (E_{t+1}, E_t) E_t + W_{t+1}; \quad (2)$$

$\pm_{E_{t+1}}$ and $\pm_{E_t}$ denotes the standard deviation of the error terms; $\circ(E_{t+1}, E_t)$ denotes the serial correlation between the error terms; and W_{t+1} denotes the white noise defined as

$$\pm^2 W_{t+1} = (1 - \circ^2(E_{t+1}, E_t)) \pm^2 E_{t+1}. \quad (3)$$

Using the NQT-transformed observation and NWM simulation stage output, we estimate b_{t+1} following the parameter estimation procedure proposed in [3].

4.4. Hand method

We use the Height Above the Nearest Drainage (HAND) [7], a digital elevation model (DEM) normalized using the nearest drainage for mapping reach scale flood inundation and for determining reach scale hydraulic properties. Along with the DEM, the national hydrography datasets plus (NHDPlus) streams provide the information needed to generate the height of each grid cell above the nearest drainage. Selection of the HAND method is motivated by its efficient reach scale computation time.

5. Results

5.1. Rating Curve

To investigate the potential of the postprocessor in improving the flood maps, the study is focused on the particular flood event of 2015-06-23 for 24-hour duration, which has the highest flow record (6000 cfs, USGS 05460400 Shell Rock River near Rockford) in year 2015. Figure 3 shows the stage versus time plot for raw stage from NWM simulation (ComId- 6561261), observed stage from bridge sensor (Station Id-SHLRK02) and post processed stage. The difference in stage provided by the bridge sensor and NWM is ~ 3 ft. With the implementation of postprocessor, this difference limits to less than 0.5 ft. Further, the post processed stage follows the trend of the observation and matches well for the high flows.

In figure 4, we compare the raw rating curve for NWM simulation with the rating curve from USGS data. Rating curve from USGS is for the location: USGS 05462000 Shell Rock River at Shell Rock, Iowa, and corresponding ComId from NWM is 6561217. We notice that the raw rating curve is significantly different than the rating curve provided by the USGS. It is necessary to have an accurate rating curve to produce an accurate flood maps. In order to produce an accurate rating cure, we apply the postprocessor to the NWM discharge simulation output. Post-processed stage and discharge are plotted in Figure 4, and called as post-processed rating curve. Overall, the post processed rating curve match well with the USGS rating curve, and further fits well for the high flows.

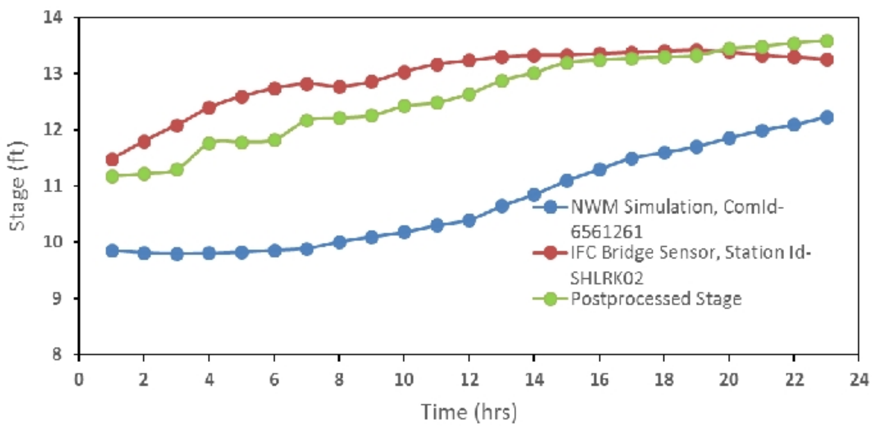

Figure 3. Stage from NWM simulation, post processed stage and observation from bridge sensor for a flood event of June 23, 2015.

In figure 4, we compare the raw rating curve for NWM simulation with the rating curve from USGS data. Rating curve from USGS is for the location: USGS 05462000 Shell Rock River at Shell Rock, Iowa, and corresponding ComId from NWM is 6561217. We notice that the raw rating curve is significantly different than the rating curve provided by the USGS. It is necessary to have an accurate rating curve to produce an accurate flood maps. In order to produce an accurate rating cure, we apply the postprocessor to the NWM discharge simulation output. Post-processed stage and discharge are plotted in Figure 4, and called as post-processed rating curve. Overall, the post processed rating curve match well with the USGS rating curve, and further fits well for high flows.

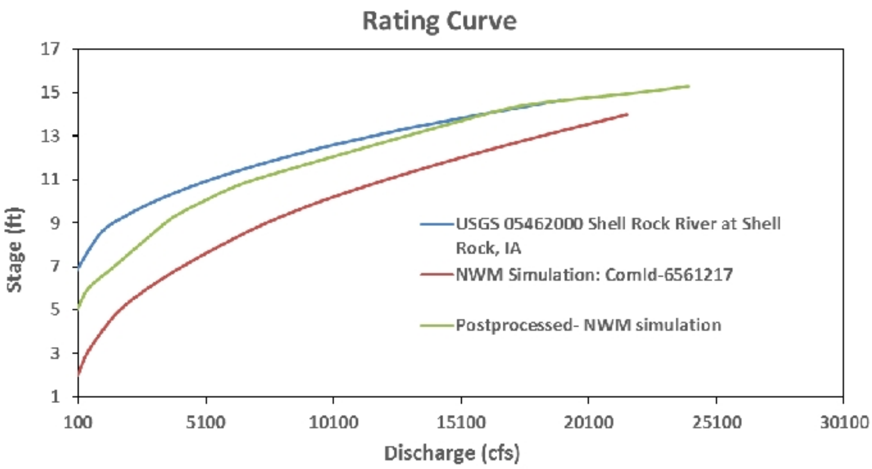

Figure 4. Raw and post-processed rating curve comparison for Shell Rock River at Shell Rock, IA.

5.2. Postprocessor performance evaluation

We use the correlation coefficient and root mean square error (RMSE) as the measure of raw and post processed stage quality. We compare in Figure 1, for five stations considered, the correlation coefficient (Figure 4a) and RMSE (Figure 4b) for both raw and post processed flood stage. The stage result is compared with the corresponding observed data from IFC operated bridge sensor. The overall trend in Figure 1 is for the correlation coefficient to increase and RMSE to decrease with the application of postprocessor to the NWM simulated stage output.

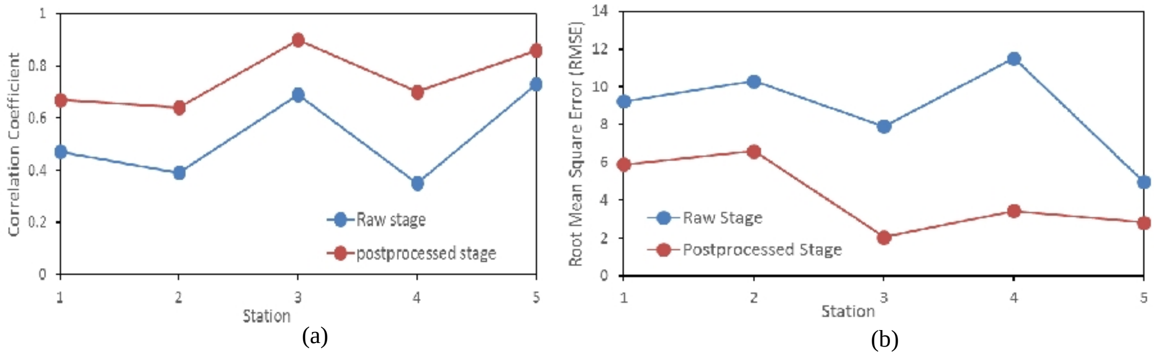

Figure 5. (a) Correlation coefficient and (b) RMSE for the raw and post-processed stage corresponding to the observation from bridge sensor and USGS station.

5.3. Inundation maps

We show in Figure 6, the inundation maps developed by using the HAND method for a reach catchment with ComId- 6561261. Figure 5a-c displays the flood extent at 2015-06-23 12:00, respectively, for NWM simulation stage, bridge sensor stage observation, and post-processed stage. While Figure 6d-f displays the similar information at 2015-06-23 18:00. We develop the similar plots for different reach catchment for different time. On considering all the five reach catchment, we notice that the raw inundation maps differ up-to 19% in underestimating the inundation area as compared to the observed map. Overall, the post processed maps show improved capabilities in matching the observed map.

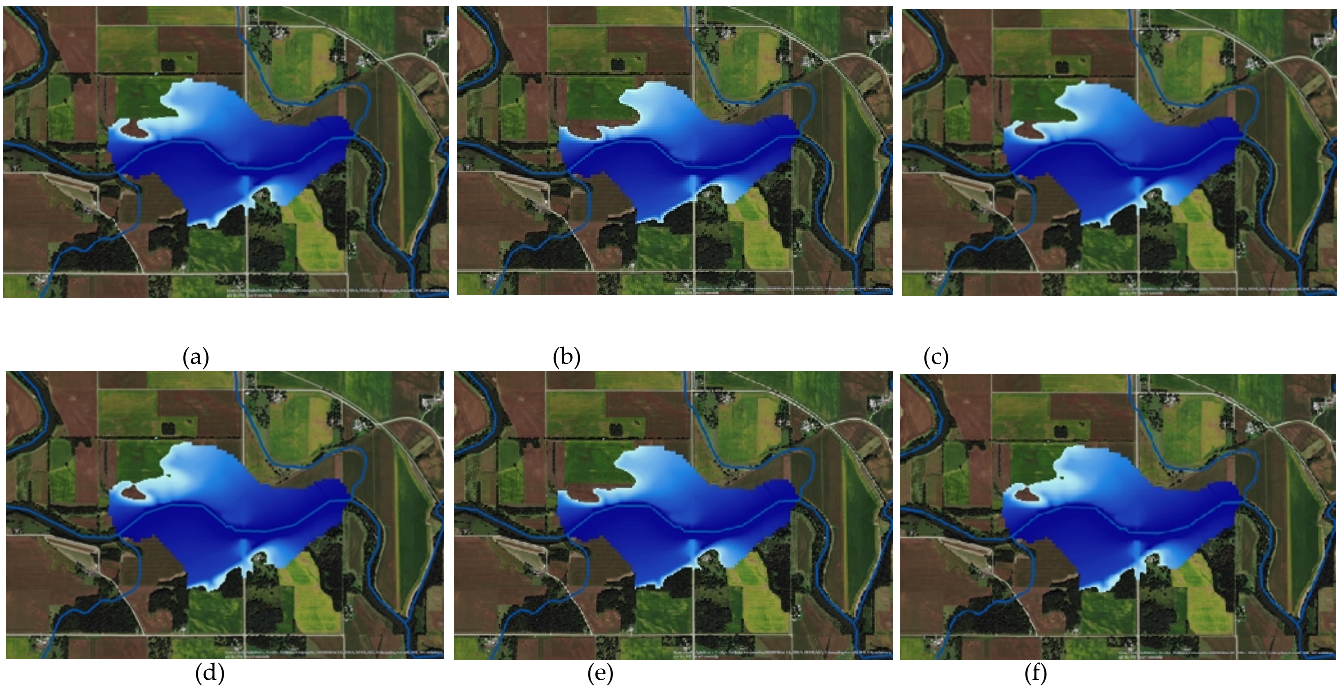

Figure 6. Raw, observed and post-processed map for a reach catchment (ComId- 6561261) for a flood event of 2015-06-12.

6. Conclusion

The ultimate goal of this study is to encourage a shift from the verification of forecast hydrographs to flood maps, which are a more appealing display for purposes of general communication. We implement a statistical model to produce unbiased, reliable and skillful stage output from the NWM. In summary, based on our analysis and comparison, post-processed flood stage shows higher correlation coefficient and lower root mean square error as compared to raw stage. Overall, post-processed map shows improved capabilities in matching observed map. Also, post processed rating curve match well with that of USGS.

Accurate streamflow information is the pre-requisite to produce improved flood hazard and risk map. Further assessment of rating curve is fundamental in making effective flood management decision. The benefit of using the post-processed streamflow and post-processed rating curve is that the accurate streamflow transformed to stage using the accurate rating curve will lead to an accurate flood map. Further study could be done considering the larger study area. However, this may come at a considerable computational cost, particularly when considering a range of lead times and multiyear simulation or forecast datasets.

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Chapter 8

Quantifying Uncertainty in Flood Inundation Mapping using Streamflow Ensembles and Multiple Hydraulic Modeling Techniques

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Abstract: The National Water Model (NWM) provides a platform needed to operationalize nationwide flood inundation forecasting and mapping. The ability to model flood inundation on a national scale will put invaluable information into the hands of decision makers and local emergency officials. Often, forecast products use deterministic model output to provide a visual representation of a single inundation scenario, which is subject to uncertainty from various sources. While this provides a straightforward representation of the potential inundation, the inherent uncertainty associated with the model output also needs to be conveyed for better decision making support. To this end, our goal in this study is to produce ensembles of future flood inundation conditions (i.e. extent, depth, and velocity) to quantify and visualize uncertainties associated with the predicted flood inundation maps. The setting for this study is located in a highly urbanized watershed along the Darby Creek in Pennsylvania. A forecasting framework involving the NWM coupled with multiple hydraulic models was developed to produce ensembles of future flood inundation conditions. Time lagged ensembles from the NWM short range forecasts were used to account for uncertainty associated with the hydrologic forecasts. The forecasts from the NWM were input to the International River Interface Cooperative (iRIC) and HEC-RAS software packages, from which water extent, depth, and flow velocity were output. Quantifying the agreement between output ensembles for each forecast grid provided the uncertainty metrics for predicted water extent, depth, and flow velocity. For visualization, a series of flood maps that display flood extent, water depth, and flow velocity along with the underlying uncertainty associated with each of the forecasted variables were produced. The results from this study demonstrate the potential to incorporate and visualize model uncertainties in flood inundation maps in order to identify the high flood risk zones.

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1. Motivation

Floods are one of the major and most frequent natural disasters across the world including the United States [1]. Each year floods cause numerous death tolls alongside billions of dollar worth of damages to properties. Thus, flood management and flood emergency responses put a substantial financial burden on federal and state agencies. Despite all the research efforts and money spent, decision making during a flood emergency still remains a challenge due to the unavailability of accurate and informative flood inundation maps. Effective and efficient flood emergency management depends heavily on the accuracy of the flood inundation maps. An accurate flood inundation maps is a tool that provides the emergency officials additional information about flood risk and enables them to warn people ahead of time that are living in a flood risk zone. Till now, flood maps are mostly deterministic which are generated using a hydraulic model forced with a single discharge output from hydrologic model. These deterministic flood maps can be subject to uncertainties from many different sources including the hydrologic model output and the hydraulic model itself. These uncertainties needs to be quantified and portrayed well in flood inundation maps so that the decision makers have a better understanding of the flood extents and inundation depths. To this end, our goal in this study is to quantify uncertainty using multiple hydraulic models and ensemble streamflow forecast outputs to create multiple realizations of flood inundation maps. As a final product, we plan to integrate all these realizations into a single map and thus, create a probabilistic inundation map which will demonstrate percent chance of flooding for each cell within the river reach based on model agreement. This approach of inundation mapping will help the forecasters and emergency responders to identify the high risk zones through applying a critical condition threshold.

2. Objectives and Scope

1. Select a highly urbanized flood prone zone as study area.
2. Select multiple hydraulic models (i.e. HECRAS 2D, iRIC)
3. Produce time lagged short range forecast ensembles from National Water Model (NWM).
4. Development of a high resolution River Terrain model (1 X 1 m cells).
5. Generate the mesh with the appropriate resolution for capturing changes in the underlying topography.
6. Select the boundary and initial conditions and calibrate the hydraulic models by changing the roughness parameter throughout the domain.
7. Generate inundation maps for the variables of interest (i.e. Velocity and Water Depth) for different forecast ensembles using different hydraulic models
8. Integrate different realizations of flood maps from different hydraulic model setups and produce a final probabilistic flood inundation map showing the uncertainties.

3. Previous Studies

In previous studies, uncertainties in flood inundation mapping are well discussed. Merwade et al. [2] mentioned different issues and elaborated on different sources that may add to the uncertainties in the flood inundation mapping. In many studies, channel roughness parameter was mentioned as the most influential source of uncertainty in inundation mapping [3-5]. Among others, topographic data and hydraulic modeling techniques are also mentioned as a significant contributors towards flood mapping uncertainty [6; 7]. Pappenberger et al. [8] mentioned that flow input data is one of the major sources of uncertainty since stage-discharge curve is used to obtain the observed flow data to produce flood inundation maps. Pappenberger et al. [9] also discussed how uncertainty in short to medium range forecasting may influence the flood inundation maps. Therefore, in this study, we made effort to incorporate the hydraulic modeling uncertainty with applying multiple hydraulic models. Forecast uncertainty is addressed using time lagged ensembles.

4. Methodology

4.1 Study Area and DEM data

The river selected for this project is The Darby Creek located at Philadelphia, PA from the Mt. Moriah Cemetery to its confluence to the Delaware River (Figure 1).

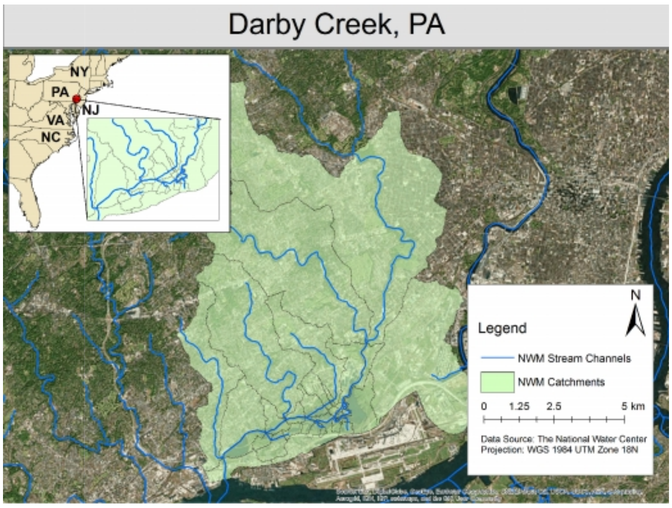

Figure 1. Study area.

The length of the reach is approximately 15 kilometers. The floodplains of the Darby Creek are 100% developed as can be seen in figures 2a and 2b. A quick analysis showed that the variation in the developed areas for the region from years 2001 to 2011 is less than 0.1% of the total area. The mean slope of the river is 0.001 m/m and average width of 50 meters.

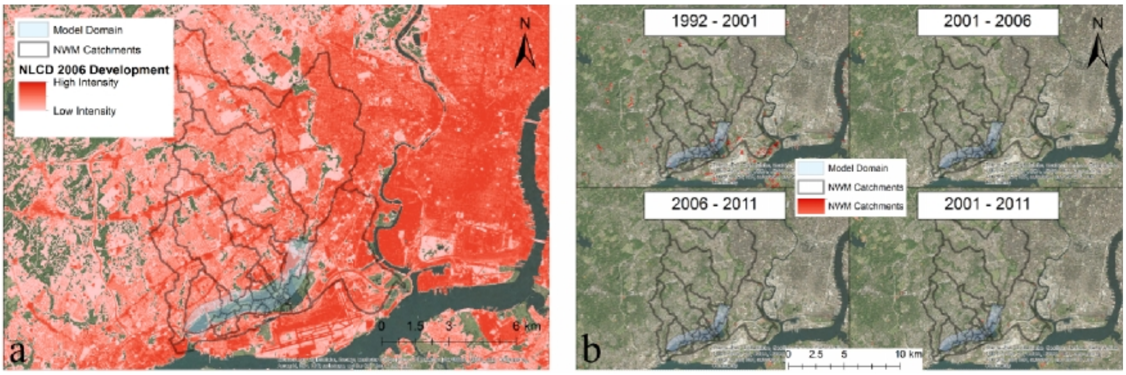

Figure 2. a) 2006 National Land Cover Database (NLCD) impervious land cover classification; b) NLCD land cover classification change to developed.

Due to the highly urbanized floodplains in the study area, we considered it necessary to use high resolution data to correctly represent the terrain. For this, we used a 1 meter Lidar derived Digital Elevation Model (DEM) obtained from the Pennsylvania Spatial Data Access (PASDA) website, the latter of which was combined with a bathymetry dataset collected by NOAA. Manual corrections were applied to the river terrain model in zones where Bathymetry data was missing.

4.2 Selected flood event and flow observations

The USGS gage number 01475548 located in the Coobs Creek at Mt. Moriah Cemetery located at upstream end of our model was used to get the flow data. This gage has records from October 2015 to the present, the datum of the gage is 6.10 meters above the National Geodetical Vertical Datum of 1929 (NGVD29). The event selected to force the hydraulic models is a flooding event that took place in the study area during April 30 to May 1 of 2014.

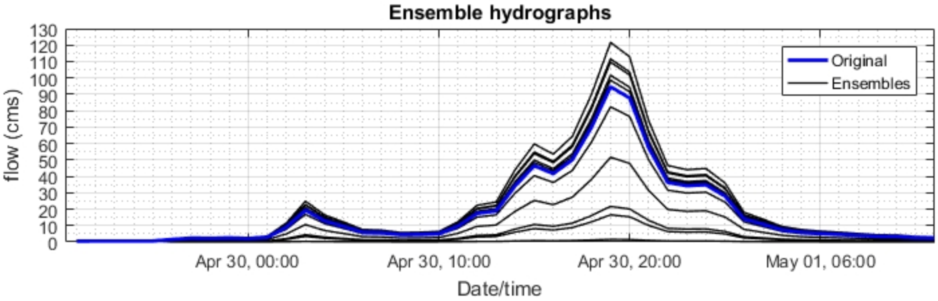

Figure 3. Ensemble hydrographs for the flooding event of April 30, 2014.

4.3 Methods Time lagged ensembles from NWM short-range forecasts

For this project, we plan to use time lagged ensembles to account for uncertainty in NWM short-range forecasts. NWM current operational setup archives only last few months (June-July, 2016) of hindcasts/ historical forecast runs. This period of record does not have any major flood in our study area. As alternative to forecast ensembles, we used NWM historical simulation runs as input to our hydraulic models to demonstrate the proposed study. We have used a time series (AR1) model to generate multiple realizations of streamflow discharges for the selected flood event (April 14, 2014) in order to account uncertainty in NWM outputs. The statistical model can be described as below:

$$Z_{0,k+1} = (1 - b_{k+1})Z_{0,k} + b_{k+1}Z_{f,k+1} + E_{k+1} \quad (1)$$

where $Z_{o,k+1}$ and $Z_{o,k}$ denote the NQT-transformed observed flow at time steps $k+1$ and k, respectively, b_{k+1} denotes the regression coefficient at time step $k+1$, $Z_{f,k+1}$denotes the NQT-transformed forecast flow valid at time step $k+1$, and E_{k+1} denotes the residual error at time step $k+1$. At time step $k+1$, $Z_{o,k}$ corresponds to the actual observed streamflow at time step k, whereas time step $k+2$ onwards $Z_{o,k}$ is the estimated observed value at the preceding time step, i.e., $Z_{o,k+1}$, using Eq. (1.1).

Regonda et al. [2] at the National Weather Service (NWS) used the above model to generate ensembles from short-range deterministic forecasts. For this study, we used USGS gage observations as observed flow and NWM model simulations as the exogenous variable.

4.4 Hydraulic modeling with HEC-RAS

The Hydrologic Engineering Center – River Analysis System Version 5.0.0 is an unsteady 2D hydraulic model developed by U.S. Army Corps of Engineers that solves the 2-dimensional Shallow Water Equations (SWE) using an implicit Finite Volume algorithm over a unstructured computational mesh, this allows the user to add more detail where needed like in dikes, roads, buildings, etc.

The model mesh is composed of 82349 irregular shaped cells (3 to 8 sides), with an average cell size of 385 m^2, the Manning's n value for the main channel is 0.5 $m^{-1/3}$ s, the spatial variability of the roughness parameter in the floodplains was determined by using the NLCD of 2011, it varies from 0.04 to 0.15 $m^{-1/3}$ s. For the calibration of the model, the discharges recorded by the stream gage at the upstream end of the domain were used. By manually changing the roughness parameter in the model, we adjusted the stage hydrograph recorded by the gage to that created by the model at the gage site.

The upstream boundary condition was modeled as a hydrograph with 1 hour time steps, the input hydrograph is from April 29 at 0:00 am to May 1 12:00 pm. The downstream boundary was considered to be a normal flow condition because the slope of the Darby Creek at the downstream part of the reach is very mild. As an initial condition the domain is considered to be dry, but to account for the fact that the reach is not dry at the moment of the flooding event, the hydrograph was extended 24 hours before the event to create a more realistic condition. After running the HEC-RAS model, three inundation maps were generated for each ensemble in the form of raster files; the first for water surface elevation, the second for water depth and the last one for flow velocity.

4.5 Hydraulic modeling with iRIC

The International River Interface Cooperative (iRIC) software provides a flexible integrated multi-dimensional river simulation along with various solvers. For this study, the two-dimensional steady state solver of FaSTMECH is used to set up the model, while for unsteady state Nays 2D Flood solver is used.

Despite the high resolution of the topographic data, a mesh size of 5x5 meter is used to map the topographic data in FaSTMECH. This helped to ease the ensuing visualization procedures. Although, for Nays 2D Flood such grid sizes would result in too high computational time. Therefore, the grid sizes increased to 250x250 meter. Table 1 shows the computational time in both solvers regarding the grid sizes.

Table 1. Computational time for iRIC models.

Nays 2D Flood	
Size of Grid (m*m)	**Computational time(hr)**
1*1	~ 3600 (1-2 Months)
50*50	12-15
160*160	1
250*250	0.25
FaSTMECH	
1*1	0.1

While Nays 2D Flood needs the upstream boundary condition, in FaSTMECH both upstream and downstream boundary conditions need to be addressed. Two NOAA gages at the main Delaware River (8545240 and 8540433) are used for gage estimates at the downstream. Although the downstream part of the Darby Creek is considered a marsh zone and affected by the Delaware River tides, back calculating the time series resulted in a decent estimate of the downstream stage of one meter. Nevertheless, a sensitivity analysis showed that the flood extent is not much affected by the minor changes in downstream gage. Due to lack of measured data and any satellite imagery of flood extent for this region, the upstream USGS gage is used for calibration as well. Finally, the lateral eddy viscosity and roughness coefficient are set so that the water surface elevation is raised to a value close to 10 meters.

While in FaSTMECH, regardless of event duration, just a single value of peak discharge is used for flood modeling, in Nays 2D Flood a 1-day hydrograph with time steps of 0.01 seconds is simulated. An arbitrary triangle hydrograph with the desired peak discharge is fabricated and introduced to the model. In order to compare the flood extent resulted from different solvers along with velocity fields, simulation results are exported in a CVS format file in which the grids coordinate and associated calculated fields are tabulated.

4.6 Hydraulic model outputs post-processing

Outputs from the hydraulic models were post-processed to convert the output to a common 5 meter by 5 meter gridded raster format. During this conversion processes, numerous threat metrics were extracted from the data (Table 2).

Table 2. Four primary flood threats with listed metrics

Flood Extent	Water Depth	Flow Velocity	Critical Conditions
	> 0.5 ft	> 1 mph	> 0.5 ft water flowing at > 4 mph
	> 1 ft	> 2 mph	> 1 ft water flowing at > 4 mph
	> 2 ft	> 4 mph	> 2 ft water flowing at > 4 mph
	> 3 ft	> 6 mph	> 0.5 ft water flowing at > 6 mph
	> 4 ft	> 8 mph	> 1 ft water flowing at > 6 mph
	> 5 ft		> 2 ft water flowing at > 6 mph
	> 6 ft		> 3 ft water flowing at > 2 mph
			> 4 ft water flowing at > 2 mph
			> 5 ft water flowing at > 1 mph
			> 6 ft water flowing at > 1 mph

All output produced from the different initializations and different hydraulic models were combined into threat-based composite rasters, where each grid value equated to the percentage of outputs in agreement that a certain threat metric would be exceeded. The metrics were created with emergency management preparation and response operations in mind. For example, a metric extracted from the data tested whether a grid exceeded a depth of 1 foot of water flowing at a rate faster than 4 miles per hour. These conditions are hazardous conditions to try to stand in, much less walk [11]. The final product produced is a comprehensible prediction of whether those defined hazardous conditions will exist in each grid along with a measure of uncertainty based on model agreement. In other words, the final product uses the uncertainty underlying the forecast as a measure of risk, where high risk corresponds to grid with greater model agreement.

Unfortunately, data corruption of iRIC FaSTMECH output limited this current report to those output produced by HEC-RAS 2D. Therefore, the next step, which is currently in progress, is to overcome these challenges and incorporate output from additional hydraulic models, like iRIC FaSTMECH and iRIC Nays2D. This will provide additional skill to the forecast by encompassing additional realizations of the predicted flood.

5. Results

The value of this study is best demonstrated through a comparison between the flood extent generated by a deterministic HEC-RAS 2D model associated with a discharge of 98 cms and the flood extent generated by the ensemble HEC-RAS 2D composited raster associated with a range of potential discharge scenarios (Figure 4).

The flood extent in figure 4 look similar, but the real advantages of this composited ensemble method can be seen when zoomed into the Sunoco Logistics crude oil storage tank farm. Where it appears imminent that a couple of these oil tanks are at threat of flooding based on the deterministic output, the actual threat of flooding to these takes is not so certain. The composited output shows that only about 5 out of 10 (50%) of the outputs agree this area will be inundated. In an emergency preparation situation, this may indicate that this is an area to keep a close eye on, but maybe not an area where resources will be needed immediately. In addition to the flood extent, it was mentioned earlier that other flood threat metrics were also extracted from the data that could be useful towards emergency preparation operations. It would be challenging to s**h**ift through the great amount of flood threat metric information provided from the output in a typical GIS platform, especially if these products are used in emergency situations. Therefore, the flood metric information was compiled into a BYU app platform called Tethys to disseminate the information contained in the final deliverables in a highly accessible way.

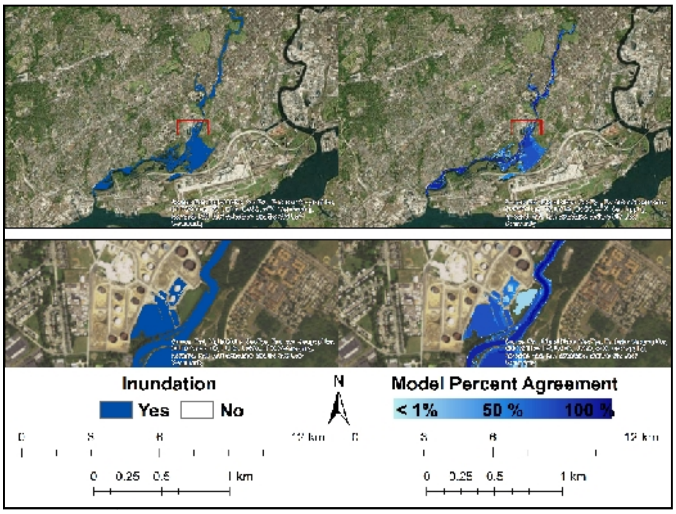

Figure 4. Side by side comparison of 98 cms HEC-RAS 2D deterministic model output (left) and composited HEC-RAS 2D model output (right).

Continuing with the previous example about the potential flooding at the Sunoco Logistics crude oil storage tank farm, what if there is a limit to the depth of water that these tanks can be subjected to? Beyond that, maybe they can only be subjected to a certain water flow velocity, or maybe a combination of both. The great advantage of integrating the output from this study into the Tethys platform is that all of these metrics can be easily and quickly viewed to assess the probability and severity of the situation (Figure 5).

Figure 5. Tethys interface. Zoomed to Sunoco Logistics crude oil storage tank farm.

So, while geared towards emergency response agencies, the Tethys platform allows for the integration of the composited raster output into a publicly accessible user-friendly framework that can be used for many more applications outside of the emergency response community.

6. Conclusion

This study aimed to show uncertainty in flood inundation maps for a highly urbanized watershed of Darby Creek in Pennsylvania. To do that, based on the predicted discharge from the NWM, flood discharge ensembles were generated. The flood extent, depth, and velocity domains were calculated by means of two dimensional hydraulic models: HEC-RAS and iRIC. Overlaying all the flood inundation ensembles defined a probability for each grid on the domain based off on the percentage of the model agreement. The results from this study demonstrate the potential to incorporate and visualize model uncertainties in flood inundation maps in order to identify locations at higher risk of hazardous conditions. The methods and results from this study have tremendous potential to help in flood mitigation and preparation. By disseminating these results through the Tethys platform, it is hoped that these results will be help decision makers more efficiently and effectively prepare for flood events.

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Chapter 9

Assimilation of Water Level Observations in River Models to Update Flood Inundation Maps

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Abstract: This study proposes a framework that (i) uses data assimilation methods as a post processing technique to update water depth in order to generate more accurate flood inundation maps, and (ii) updates the flows generated by National Water Model (NWM). Predicted flows by NWM for each stream were converted to the water depth using the Height Above the Nearest Drainage (HAND) method. Then, the water level measurements provided by Iowa Flood Inundation System (IFIS) were converted to water depths and then they were assimilated into the model in order to update the water depths. After assimilation of water depth measurements, the updated depths were converted to the river flows using rating curves generated by HAND model. These updated flows can be used as new initial condition for running National Water Model. Ensemble Kalman Filter (EnKF) was used as assimilation technique. This method is easy to implement and computational requirements are affordable. Results showed that after assimilation of water depth for a flood event during 2015, normalized root mean square error was reduced by 0.50 m for training tributaries. Comparing the updated results with observations of testing locations showed that proposed methodology is also effective on the tributaries with no observation. The overall error was reduce from 0.89 to 0.44 m for testing tributaries.

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1. Motivation

Flooding is one of the most destructive natural disasters in the United States. Flood inundation maps can be used to provide reliable information to the public about the flood-risk. Assimilation of water depth measurements, as a post-processing technique, can help to reduce the error between model predictions and observations in order to generate more reliable flood inundation maps. Moreover, the improved water depths can be converted to the corresponding flows using rating curves generated by hand in order to update the initial conditions of National Water Model.

2. Objectives and Scope

The main objectives of this study include:

- Assimilate water depth measurements to update the model predictions in order to create more accurate flood inundation maps.
- Use updated water depth to improve the flows predicted by NWM and run the NWM using updated initial conditions. However, due to computational limits, this part is not done in this study.

3. Previous Studies

Sequential data assimilation techniques can be used for updating of model's state variables when new observations become available [1]. A data assimilation process is also able to reduce the uncertainty in prediction by integrating real-time observations from a variety of monitoring technologies [2]. Kalman filter [3] is a commonly used data assimilation technique that was initially developed to update the state variables of linear systems [4]. However, this method has been used for nonlinear problems as well [5]. Ensemble Kalman filter (EnKF) is another data assimilation technique that was introduced by Evensen [6]. In case of non-linear models that assumption of linearity cannot be used, EnKF can be used as an effective technique. Multiple studies have also used this method in the past to update hydraulic, hydrologic and hydrodynamic models [7, 8].

4. Methodology

4.1. Study area

Squaw Creek watershed located in the middle of Iowa State was selected as study area (Figure 6). There are 85 tributaries and 20 bridge sensors that measure the water levels. Since the cross sections were not available for all of these sensor locations, measurements of only 10 sensors were assimilated into the model. Six sensors were randomly selected for training and the other four sensors were selected for testing to make sure that this approach is also suitable for tributaries with no observation. NWM predicts the flow at the outlet of each sub-basin, however, bridge sensors are located upstream of outlets. Assuming the equal soil type and land use for each sub-basin, flow at the outlet was linearly distributed along the river.

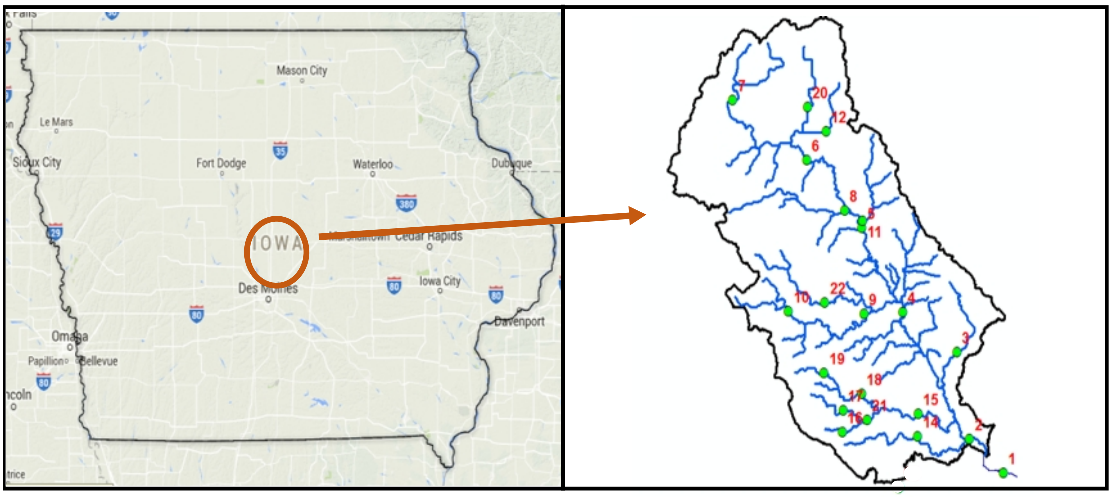

Figure 6. Squaw Creek watershed. Blue lines show the tributaries and green dots show the location of bridge sensors.

4.2. Proposed approach

Figure 7 illustrates the proposed methodology. Flow for each tributary was estimated by NWM. HAND [9] method was used to predict the water depth. Water level observations from Iowa Flood Information System (IFIS) were converted to water depth and then they were assimilated into the model. Updated water depth can be used to create the flood inundation maps. Also rating curves generated by HAND can be used to estimate the flow and updated flows can be used as new initials conditions to run the National Water Model.

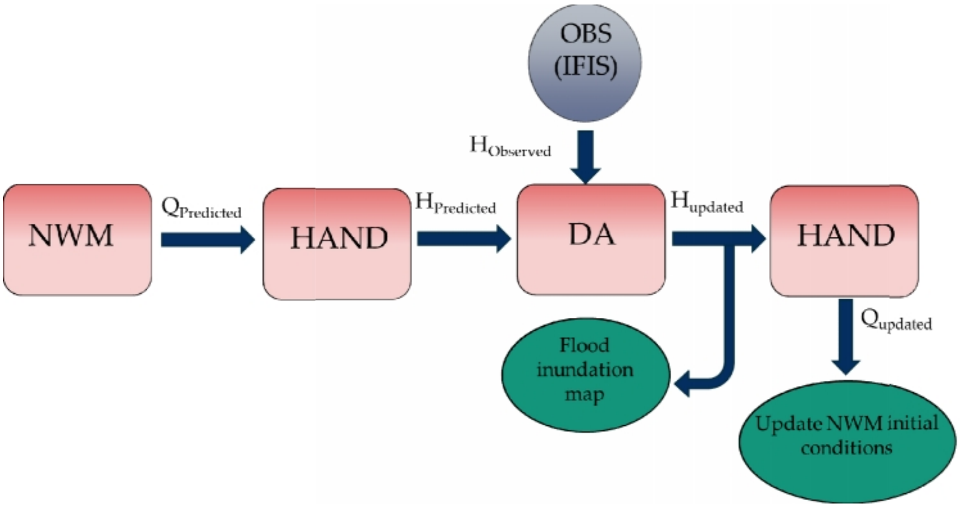

Figure 7. Schematic methodology.

4.3. Ensemble Kalman Filter

The ensemble Kalman filter algorithm was used in the proposed methodology to assimilate water depth observations into the model. In the ensemble Kalman Filter, the prediction model is represented using:

$$h_k = F(Q) + w_k \quad (1)$$

where h denotes the vector of state variables (water depth), Q is the flows from National Water Model, w_k is stationary zero-mean white noises, F represents the prediction model (HAND model), and the subscript "k" denotes the time step. If an ensemble of n predicted state variables is available, h^f can be written as

$$h_k^f = (h_k^{f1}, \ldots , h_k^{fn}) \quad (2)$$

where superscript "fi" represent the i^{th} forecast ensemble member. In order to create the ensembles, different flows at different times before the selected events were selected and then converted to water depth using rating curves generated by HAND. For this study, 10 ensembles were created to estimate the error matrix in the model.
The average of ensemble is defined by

$$\hat{h}_k^f = (1/n)\Sigma\, h_k^{fi} \quad (3)$$

Since true states are not known, we estimate them using the average of realizations in the ensemble. Then the error matrix can be estimated by

$$P_k^f = 1/(n\text{-}1)\{(h_k^f - \hat{h}_k^f)(h_k^f - \hat{h}_k^f)^T\} \quad (4)$$

The error matrix is then used to calculate the Kalman gain matrix by

$$K_k = P_k^f\, H_k^T\, (H_k P_k^f\, H_k^T - R_k)^{-1} \quad (5)$$

where H is the linear transformation which relates the state variables to observations. The updated state vector (h^a) is taken to be a linear combination of the forecast and the observations. The observations should be treated as random variables to get consistent error propagation in the ensemble Kalman filter [10]. Hence, the actual measurements were used as reference and random noise with zero mean and covariance R was added to measurements. The updating equation is given by:

$$h_k^a = h_k^f + K_k(h_k^* - H_k\, h_k^f) \quad (6)$$

5. Results

Figure 8 shows the water depth at training locations a) before data assimilation and b) after data assimilation comparing with observations from IFIS. We found that by assimilating water depth, the overall error was reduced from 0.98 cm to 0.48 cm. We also calculated the error for the testing locations to make sure that Kalman Filter can improve the model predictions for the sites that there is no observations. It was found that the overall error was reduced for testing locations as well (from 0.89 to 0.44 cm). Table 1 compares the water depths before and after data assimilation with observations from IFIS for training and testing tributaries. Results show that overall error was reduced by 48 cm.

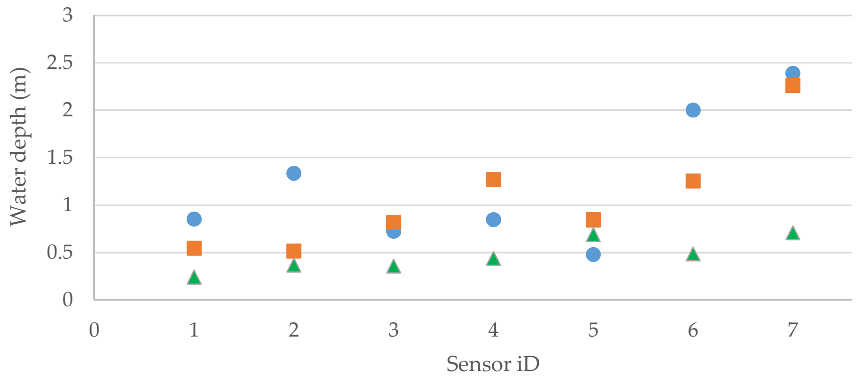

Figure 8. Water depth at each sensor location. Green triangles are model predictions from HAND before data assimilation, red squares are updated water depths after data assimilation, and blue dots are water depth observations from IFIS.

Table 1. Water depth before and after data assimilation comparing with water depth measurement from ISIF for training and testing tributaries.

	Water depth (m)		
	Observation	Before Data assimilation	After Data Assimilation
Training tributaries	0.85	0.24	0.55
	1.34	0.37	0.52
	0.72	0.36	0.81
	0.85	0.44	1.27
	0.48	0.69	0.84
	2.00	0.49	1.25
	2.39	0.71	2.26
Testing tributaries	1.30	2.01	1.67
	0.32	1.01	0.71
	1.50	0.30	0.81
	1.86	1.01	1.99
Overall error (m)		0.95	0.47

Figure 9 illustrates the time series of flow predicted by NWM versus flow observation at USGS station at Squaw Creek at Ames. After updating water depth, rating curve from USGS station was used to estimate the corresponding flow. Because of time limitation, only for different time during June 24, 2016 were selected to assimilate the water depth and then update the flow (green dots in Figure 9). It was found that overall error between USGS measurements and updated flows from NWM was reduced by about 35% for selected times. It is recommended to assimilate all the available observation when they are collected, then update the water depth and create more accurate flood inundation maps. Afterward, use updated water depth to also update the flow from NWM and use corrected flows as new initial conditions for running NWM.

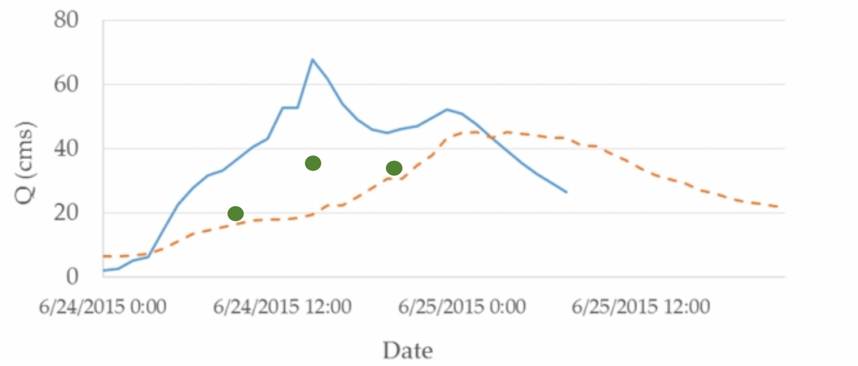

Figure 9. River flow at USGS station at Squaw Creek at Ames. Solid blue line shows the NWM predictions, dashed-red line shows USGS gauge observations, and green dots show the updated flows.

6. Conclusion

National Water Model prepares water depth for 85 tributaries in the study area, as all models have uncertainty, it seems reasonable to implement data assimilation model in order to reduce the uncertainty. After assimilation of water depth measurements, the root mean square errors of the estimated depth reduced by 50 cm. It was found that the proposed methodology is also effective for the tributaries without observation. The error was reduced by 45 cm for tributaries that their observations were not assimilated in to the model. In the next step, the updated water depths can be used to calculate the flows using rating curves and then use them in National Water Model which would be a future study.

More accurate observations are required in order to minimize the error. It is recommended that cross sections are collected at the locations that bridge sensors are placed. It helps to convert water level to water depth more accurately.

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Chapter 10

HAND Flood Mapping through the Tethys Platform

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Abstract: The Height Above Nearest Drainage (HAND) model is a method for generating flood inundation maps. Currently, HAND is calculated with a 10 meter digital elevation model (DEM) in ArcMap. The purpose of the project is to create an online application to easily view the flood maps generated from HAND. The online application is run through Tethys, which is a platform created by Brigham Young University (BYU). The online app uses streamflow forecasts generated by the National Water Model (NWM) to predict potential flooding.

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1. Motivation

The flood maps show where and how deep floods can be for a particular area. The flood maps are important tools for emergency preparedness and first responders. Being able to properly show where a flood could occur has the potential to keep people safe from harm. By creating an online flood mapping application, anyone could go on and see the potential harm that their home could be under. It would be as simple as checking the weather forecast in your area. A flood map program could help better inform the public so necessary precautions could be taken. It would supply better understanding and knowledge to first responders and the citizens in danger.

2. Objectives and Scope

The HAND model takes a DEM and a user defined height to generate a flood map. There are three parts to this project:

1) Create preprocessing tools to generate inundation maps from the HAND raster.
2) Create an online Tethys application that shows possible flood areas with potential homes threatened and use the NWM streamflow forecast to predict floods.
3) Create an online Tethys application that focuses on specified areas to create flood maps for each stream reach in the NHDplus stream network based off real-time NWM data predictions

3. Previous Studies

Recently, several models have been developed and implemented for high-resolution, large-scale, real-time inundation mapping, including the two-dimensional physical model (LISFLOOD-FP) [1], the one-dimensional physical model (AutoRoute) [2], and the GIS-based non-physical model (NHD-HAND) [3, 4]. However, no convenient inundation user interface has been developed for a large area and provided to the emergency response community to guide their preplanning and response activities before and during flood events. In this study, the NHD-HAND method is chosen among several methods mentioned above because of its simplicity and effectiveness. Xing et. al. (in preparation for publication) have performed a real-time inundation mapping case study for Travis County, Texas during the Memorial Flood in May, 2015. From this study, a framework has been designed for inundation mapping with the NHD-HAND method. Following that framework, two web applications will be designed using the Tethys platform.

Tethys is a platform that can be used to develop and host water resources web applications or web apps. It includes a suite of free and open source software (FOSS) that has been carefully selected to address the unique development needs of water resources web apps. Tethys web apps are developed using a Python software development kit (SDK), which includes programmatic links to each software component. The Django Python web framework powers the Tethys Platform. This gives it a solid web foundation with excellent security and performance.

4. Methodology

4.1 Preprocessing Tools Workflow

In order to increase the real-time responding speed of the Tethys web apps, two geoprocessing tools have been developed during this student project to provide preprocessed inundation results hosted on the Tethys server. This first tool is designed to create an inundation library for each NHDPlus reach in the study area. Given a minimum stage height, a maximum stage height and an increment, a water depth raster is generated from the HAND raster for each incremental stage height within the predefined water level range. All the water depth rasters for the same reach make up a floodplain library named by the COMID of that reach. The second tool is designed to transform the National Water Model short-term and medium-term forecast discharge into real-time inundation maps for each NHDPlus reach at each time step. A rating curve has been generated for each reach in the study area from the NHD-HAND-SPRNT method. By looking up the discharge-stage height pairs in the rating curve, the National Water Model forecast discharges could be transformed into forecast stage heights. Inundation maps corresponding to these stage heights are selected for different reaches, and put in the folder for the same time-step.

4.2 Tethys HAND Flood Map Applications Workflow

Two separate apps were created for visualizing flooding. The first area is centered on Tuscaloosa, AL with the second app focusing on the recent floods that killed 23 people in West Virginia. Below in Figure 1, the workflow of the app is shown.

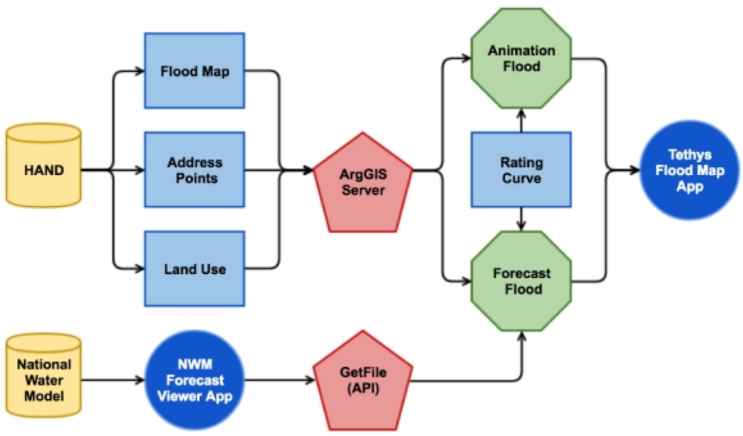

Figure 1. Tethys app workflow for generating flood maps in Tuscaloosa, AL and West Virginia.

The Tuscaloosa and West Virginia tethys flood apps each show the following:

a) View a flood by depth as it would potentially grow in the area
b) Use the NWM data to predict flooding in the area based on a main stream reach in the area

The West Virginia app additionally has the ability to use historical NWM forecast data from the time around June 24, 2016 when the deadly floods struck this area. This shows the predicted flooding that the app would have predicted through the NWM and is an example of how the app can be used in the future.

4.3 Tethys App for Flood Mapping at Each COMID Stream Reach

This application was intended to focus in on each Comid and populate a flood map for each of these reaches. A study area of Tuscaloosa was chosen to use as an example to set up the main structure of the application, which can be seen below in Figure 2.

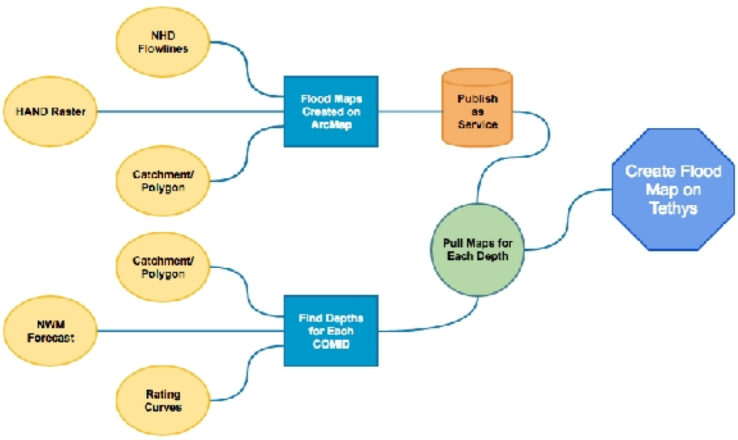

Figure 2. Workflow of creating a dynamic flood map for an area in Tuscaloosa.

In ArcMap, a library of flood maps was populated for a HUC12 watershed in Tuscaloosa. An ArcMap tool, as seen in Figure 4, was written to generate these maps at each stream reach in the selected area. This app takes requested data from the NWM and uses SPRNT rating curves to interpolate the streamflow data into depths. The app then takes those depth values and parses through the inundation library to find the correlating flood maps. Then it displays the flood maps on the app for each time step of the NWM forecast. The user can move a slider bar to step through the different time steps of the forecasted flood maps.

5. Results

5.1. ArcMap Preprocessing and Python Scripting

An ArcGIS toolbox has been developed for the Tethys-HAND project, shown below in Figure 3.

Figure 3. ArcGIS toolbox for creating a Tethys-HAND project.

For the first tool, once the inputs are set, as below in Figure 4, an inundation map library will be generated for each reach in the study area. The model allows the user to choose the desired area, the beginning depth and ending depth, and the increment steps of the flood maps.

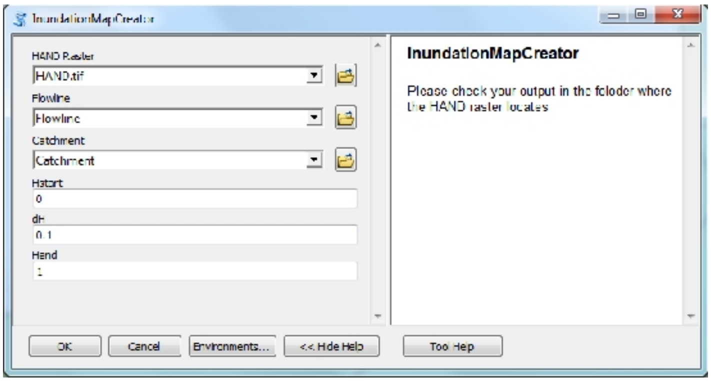

Figure 4. Inputs for the ArcGIS toolbox for creating a Tethys-HAND project.

The second tool takes a National Water Model output netCDF file from another Tethys web application named National Water Model Filesystem Explorer, in Figure 5 (https://apps.hydroshare.org/apps/nwm-data-explorer/files_explorer/).

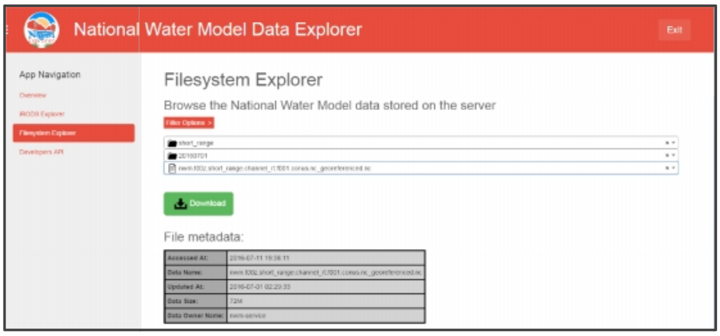

Figure 5. National Water Model Data Explorer App for retrieving netCDF files.

The real time inundation tool script has specific inputs as seen in Figure 6.

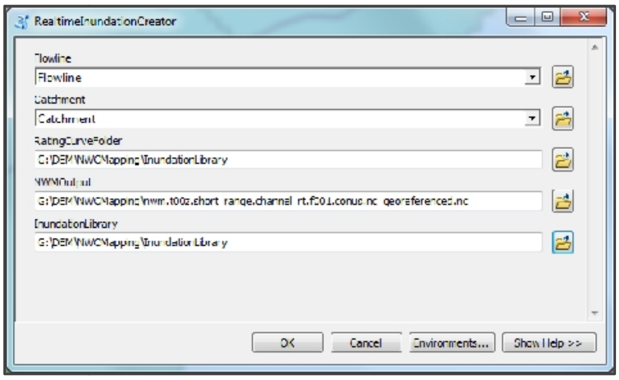

Figure 6. Inputs for real time inundation creator.

After the tool is completed, a csv table named as the forecast time-step is created with the COMID, discharge and stage height for each reach stored inside, as shown in Table 1.

Also, an inundation map folder for that time-step is created with the separate inundation map for each reach stored inside.

Table 1. Outputs of the csv file for the forecasted time step.

COMID	Discharge	StageHeight
18228791	6.24	0.31
18228803	0.92	0.21
18228847	0.92	0.23

5.2. Tethys HAND Flood Map Applications

The two Tethys apps that were created are available to view online at appsdev.hydroshare.org. The Hand Flood Map apps provide visualization of the potential flooding in the areas of Tuscaloosa County, AL and Greenbrier County, WV. Below in Figure 7 are shown the different parts of the app interface. The user interface is divided in five parts:

1) Toggle the layers to display the flood map, developed areas, and address points (address points only for Tuscaloosa County)
2) Click the "View Flood Animation" button to manually view a flood as it progresses with depth
3) Choose a forecast range, date, and time, then click "View Flood Forecast" to view the flood prediction by referencing the NWM
4) Slide the "Forecast Slider" bar to change time or depth
5) View the flood map

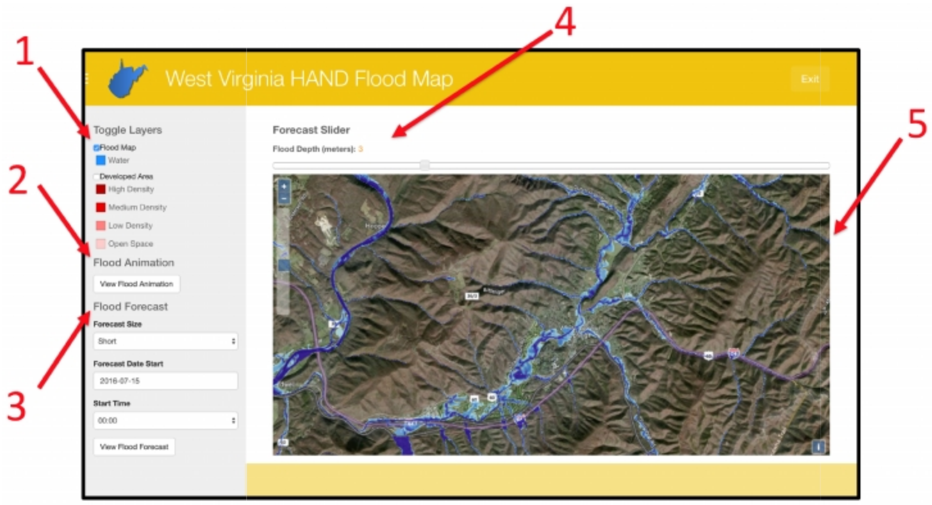

Figure 7. Components of the Tethys West Virginia HAND Flood Map.

5.3. App Development

This app is available to view online at appsdev.hydroshare.org. It provides visualization of potential flooding that is predicted by the NWM. The web app interface is shown in Figure 8. It has been successfully completed for a HUC12 watershed study area in Tuscaloosa. The watershed contains 48 COMID's. The Inundation Map Creator tool, found in figure 4, was successfully used on the watershed to populate a flood map library. For the study area, flood maps were created from 0-14.7 meters high of flooding in 0.3 meter increments. These flood maps were archived inside the app for the code to parse through when data is called.

Layers were pulled in to show the study area. On the left navigation bar, a user can turn these layers on and off. For later production, these layers can be used for a user to select a watershed that they would like to analyze. The navigation bar is also where the user can select what forecast they would like to analyze. A slider bar appears above the map and the user can move through the time steps of the forecast.

This app allows a user to view a dynamic map of a potential flood that is predicted by the NWM. It analyzes by each COMID, so the maps can have improved accuracy. The app was set up using this study area but everything was coded so that it can easily have usability for other areas as well. The preprocessing to input a new study area is populating a flood inundation library and generating rating curves by the SPRNT method. The functionality of the code is set up so that the app can easily be used for more areas than just Tuscaloosa. Further production of the app will be setting up other pages for an admin user to upload new data for different areas. A selection tool can be added so that the user could select a watershed area or draw a polygon around the desired area.

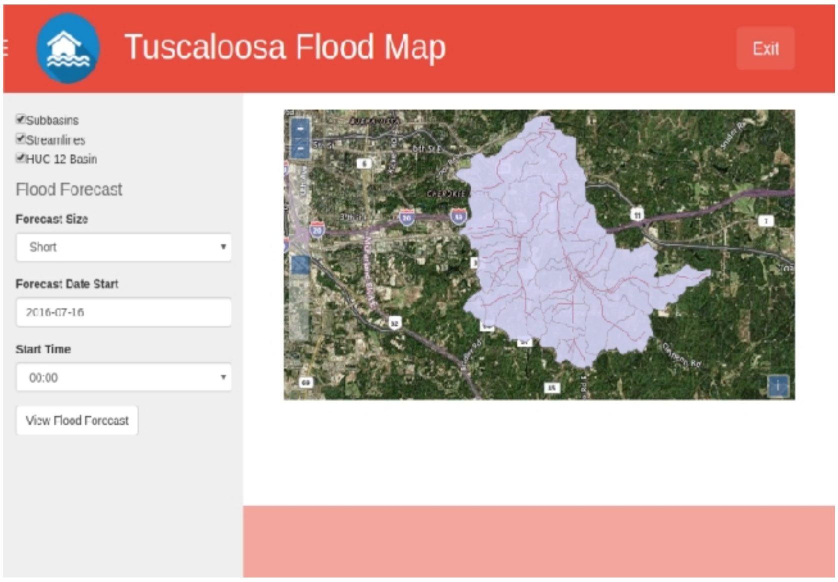

Figure 8. Tuscaloosa Study Area Web App Interface.

6. Conclusion

With the framework we establish and validate in this project, we have successfully realized the transformation from the National Water Model real-time forecast discharge to real-time forecast stage height, and eventually real-time forecast inundation maps, and show in a usable way. Emergency responders get an easy access to the water information provided by the National Weather Services without no requirement for engineering and GIS backgrounds. The workflow we implement and the tools we develop during our project are applicable and portable for the same application for a larger scale.

The Tethys app structure allows for easy use to view possible floods and flood forecasts. The app is a good source for emergency preparedness personnel to prepare the first responders for flood events. Currently, there is a process to create a flood map app for a given area. In the future, hopefully a flood map app similar to this can be created to give live updates for floods anywhere in the world.

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Chapter 11

Reimagining Disaster Warning Systems

OPERA: Operational Platform for Emergency Response and Awareness

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Abstract: Modern disaster alerts are primitive in comparison to the geospatial intelligence and forecasting capabilities of modern science. Alerts are often spatially vague and lag temporally, resulting in warnings that are confusing and often ignored. This research aims to bridge the gap between science and emergency alerts with a system that operates across the full life of an event including preparedness, warning, and response. The OPERA portal showcases a suite of systems and relevant functionalities for fire, flood, and chemical spill emergencies, which can be easily translated to other disasters representable as polygons. Ultimately the goal is not to create a final solution for emergency response, but rather to reimagine emergency alert systems, demonstrate potential improvements, and inspire relevant institutions and researchers to believe in their viability.

1. Motivation

In 2000, the National Science and Technology Council's Effective Disaster Warnings Report noted that "people at risk from disasters, whether natural or human in origin, can take actions that save lives, reduce losses, speed responses, and reduce human suffering when they receive accurate warnings in a timely manner" [1]. Specifically, this highlights the ability individuals have to help themselves when provided disaster information in a way they understand. Weather related disasters such as tornados, floods, and wildfires have benefited hugely from the impact of numerical weather prediction, and though some emergency situations can never be predicted, there is still a fundamental need for immediate and accurate information dissemination [2].

Though "accurate forecasts save lives, support emergency management and mitigation of impacts and prevent economic losses from high-impact weather…"[2], there have been limited efforts on bringing these forecasts to the average citizen. An example of this conflict is exemplified by the National Water Center (NWC) in Tuscaloosa, Alabama: the NWC is currently working towards providing "real-time dynamic flood inundation mapping portraying the extent, depth, and impacts of flood waters" for each of the 2.67 million river reaches within the contiguous United States [3, 4]. Despite this breakthrough in scientific capabilities, attempts at sharing this knowledge with the public and emergency response communities is still evolving [5].

2. Objectives and Scope

Current warning systems are text-based, geographically broad, and imprecise, resulting in warnings that are vague and desensitizing due to their frequency [6]. Disaster response is flirting with the same concern that faced meteorology more than a decade ago: too many false alarms leading to warnings that are being ignored [7]. In an attempt to bridge the gap between scientists and non-scientists, this paper offers a prototype system, the Operational Platform for Emergency Response and Awareness (OPERA), aimed at providing awareness, alerts, and specific functionalities to individual citizens. The need for this system is reinforced by the continued requests of organizations such as the California Department of Transportation, Travis County, Texas, and Tuscaloosa County, Alabama for simplified, accurate and timely information [8]. The implementation of OPERA progresses beyond traditional warnings to an integrated platform disseminated along social networks, focused on providing three essential services: pre-disaster awareness; real-time, spatially explicit alerts; and personalized actionable intelligence.

These principles are demonstrated by three OPERA case studies each containing unique, context-specific functionalities. These functionalities are not exhaustive, rather they serve to demonstrate the potential in a centralized operational platform for emergency response and awareness. To aid individuals with remembering the OPERA system, each prototype within the system has been given a memorable name. The OPERA system then becomes the Disaster Zoo containing the FloodHippo, FireBadger, and ChemicalSpillPenguin.

3. Goals

Prior to the development of the OPERA system, four needs were identified as critical for effective and improved disaster warnings:

1. **Actionable Intelligence**: Alerts and information must be relevant at the individual level, received only when directly applicable, and intuitively understood.
2. **Real-time, accurate information delivery**: Alerts must be easily disseminated through a wide variety of communication outlets and be grounded in well-documented, easy-to-remember terminology. The information provided must also be spatially and temporally accurate.
3. **Easy access**: All functionality must be simple and utilize an intuitive Graphical User Interface while mirroring or integrating with well-established, universal platforms. Alerts must be consistent across all software devices, and translatable across demographic and economic boundaries.
4. **Social dissemination**: The system must integrate with social networks to enable disaster alerts to take advantage of the interconnected nature of the modern world, allowing users to more easily share, recognize, and heed disasters.

To accomplish these goals, each OPERA system is composed of two facets: awareness and response. The awareness portion includes an educational web page with a variety of sources useful for educating individuals about emergencies. The response focuses on a web app which can be shared as a hyperlink, and uses current forecasts and a user's location to aid in stepping them through an emergency safely.

4. Awareness and Results

4.1. Awareness

Providing simple and memorable information before an event occurs is critical for guiding how people respond during an emergency [7]. Formal education can increase disaster preparedness and reduce vulnerability, and while incorporating disaster education into formal education is ideal, other routes must be explored to create a disaster ready nation [9-13]. As a more immediate solution, OPERA is designed to better communicate the impacts of disasters by integrating crowdsourced photos, news, and information of disasters around the country while improving understanding of how translated science can increase general awareness and survivability. Each disaster application within the OPERA suite provides different functionality within the same common operating framework: FloodHippo focuses on navigating citizens to predefined shelters; FireBadger showcases the ability to buffer existing dangers and provide immediate feedback; and ChemicalSpillPenguin demonstrates how networks can be used to track hazard paths and communities impacted by them.

Each OPERA account includes a number of applications constructed utilizing the Twitter and ESRI application programming interfaces (API). Within these applications, information is pulled from across the country, covering the spectrum of news sources which including individuals, news stations, and federal agencies. The web based format creates the potential for these web apps to be easily updated, providing additional disaster information on the day of an event and enabling future collaboration with formal educational systems as well. Furthermore, a web application is superior to a mobile application for a number of reasons. Web applications are functionally cross-platform (can be accessed on iOS, Android, Windows, etc.) without requiring separate development teams. They also allow for the rapid updating of information on the response side of the system, which ensures that users are constantly receiving the most up to date information possible. Finally, mobile apps require downloading prior to use, whereas a web application automatically integrates with internet capable device without requiring an individual to anticipate a disaster. In order to meet these goals, the website interface focuses on increasing preparedness through four web services.

4.1.1. Georeferenced Twitter feeds

This web map application (Figure 1a) pulls all tweets from across the country that contain the disaster specific words within the text string such as "flood" or "fire". The primary purpose of this app is to quickly and effectively highlight where disasters are being discussed by allowing users to easily access a large warehouse of real-time information: tweets returned by the filter are mostly warnings or similar notifications. The current weakness of this application is the reliance on geotagged (geo-referenced) tweets; currently only 1% of tweets are geotagged. An additional wall feed (Figure 1b) pulls tweets with the tags relating to disasters, allowing images, news hyperlinks, and more subjective content to be displayed, providing a more tangible and visual representation of disasters at the personal level. The benefits of this are two-fold: the wall feed provides additional reinforcement for the georeferenced Twitter map while also having the potential to affect individual perceptions of disasters through visual exposure to disaster damage.

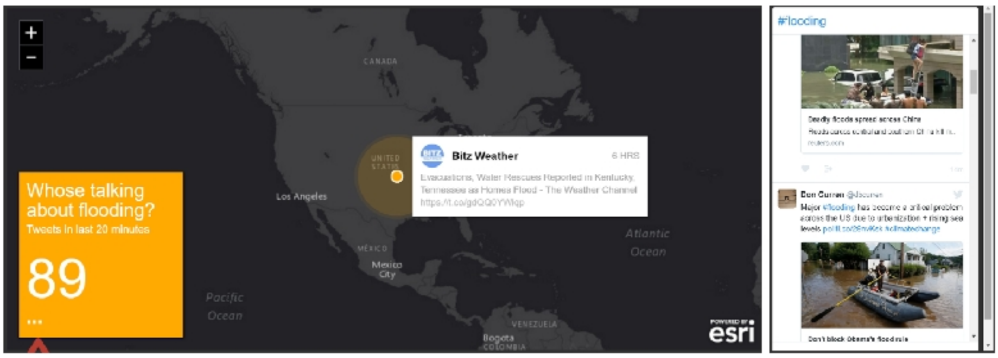

Figure 10. Georeferenced Twitter map application (left); Twitter '#Flooding' wall application (right).

4.1.2. Searchable map of static information and dynamic warnings

This web application allows an individual to search and visualize an area of interest such as their home, the address of a friend or relative, or even statewide warning extents. As an example, FloodHippo shows real-time, short-term National Oceanic and Atmospheric Association (NOAA) warnings along with a static map of the 100-year flood extent for the United States (100-year flood is defined as a flood that has a 1-percent chance of occurring in any given year[14]). Both of these datasets are hosted on ESRI ArcGIS online. While these datasets are informative for understanding potential flood extents and danger zones, the end goal of this application is to integrate real-time flood inundation maps generated by the NWC. At this point, the ability to read in the 100-year flood extent map and the dynamic NOAA warnings proves a conceptual framework.

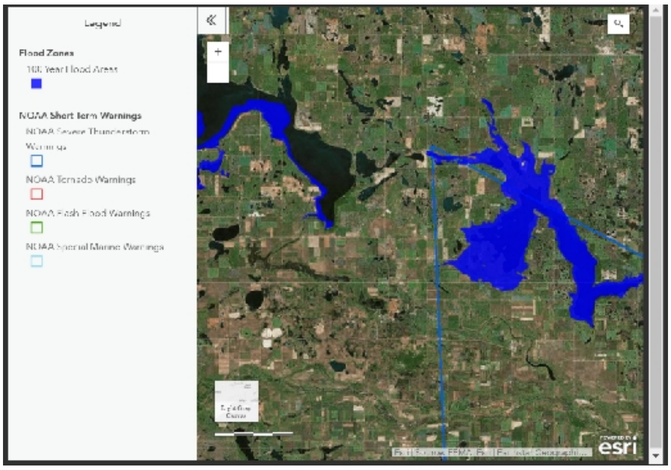

Figure 11. Short-term NOAA warnings with static map of 100-year flood extents.

4.1.3. A call to follow OPERA accounts on Twitter

Information dissemination is a vital part of any emergency situation. While it is desirable that the response facet of the platform be integrated into the wireless emergency alert network, OPERA requires additional means for alerts if it is to be widely adopted. Twitter was selected as a dissemination platform because it provides a powerful, low cost, and already existing solution. Currently, Twitter is used by 15% of United States, its integration with SMS, email, Facebook, and other forms of communications has the potential to let users customize their experience. 83% of current Twitter users utilize mobile devices [15]. Further, the ability for citizens to tweet and retweet real time information adds additional value in the form of understanding, validation, and cognition.

This duality is vital because, while the wireless emergency alerts reach a large audience, individuals will more readily pay attention to their social media accounts because they personally elected to receive information from them.

4.1.4. Disaster specific functionalities

While OPERA is designed to be a holistic platform for disasters of all types, each disaster requires unique approaches in response. Within the three accounts, unique disaster specific functionalites are highlighted that work to broad cast individualized actionable information and showcase the potential directions for this platform, shown below in Figure 3.

a. **Buffer**: Disaster extents are easily identified, however to preventively act, people need to know where the disaster is moving. The buffer capacity allows for future scenarios to be shown to users in regard to their location, allowing them to act in an appropriate manner. Buffer distance can be determined from forecasts, probabilities, or else defined. FireBadger employs a buffer to show individuals how a fire might spread using the fire perimeter from a 1990 fire in Santa Barbra CA. Future applications could exist for nuclear accidents, tornadoes, and other disasters.
b. **Routing**: Often times the most dangerous component of a disaster is trying to get away, through or around it. As such, embedding representations of a disaster in traditional routing platforms is a huge step forward in helping people help themselves. FloodHippo has the ability to route individuals from their location to either a destination of choice or to their nearest shelter. It is anticipated that a shelter database will be controlled by the Red Cross and/or other NGOs, who will be able to toggle location availability during an emergency based on local knowledge.
c. **Network**: In some cases disaster paths are dominated by topography or other predefined networks. In ChemicalSpillPenguin, disaster origin points can be entered to produce a deterministic travel path based on the network, and users are alerted as to the current and future location of the contaminant. This functionality may be expanded to include landslides, avalanches, etc if efforts to identify and single out areas of increased risk are undertaken.

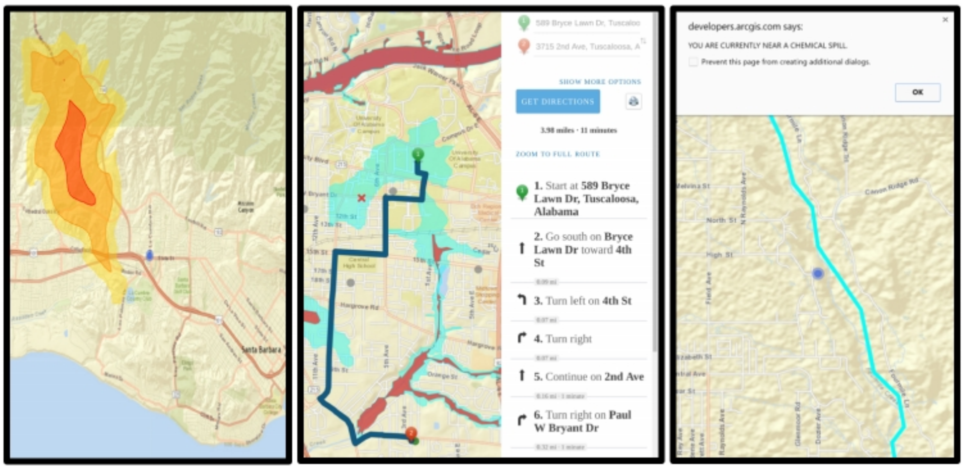

Figure 3. FireBadger (left), FloodHippo (center), and ChemicalSpillPenguin (right).

4.2. Response

Use of the OPERA platform aims to demonstrate the potential for a centralized disaster awareness and preparedness platform. The combination of web based maps and crowd sourced data aims to make disaster awareness, easier, more visual, and personally relevant. During an event, however, many individuals will not be aware of the impending event, and once alerted will not have the time needed to look through the main portal previously described. In this case, the combination of wireless emergency alerts and Twitter alerts will be sent out. An example of the existing NWS alert system compared with the proposed OPERA emergency alert system can be seen in Figure 4. In order to provide actionable intelligence, the disaster alerts will include a hyperlink to the appropriate disaster alert page. Though all disasters will differ, an example of the hyperlinked page for FloodHippo is shown.

Figure 4. Current NWC flood alert (left) vs. proposed OPERA FloodHippo alert progression (right).

The "Evacuate" application, intended for individuals within the current or forecasted danger area, will route a user from their current location to the nearest shelter while avoiding current flood extents. Similarly, the "Navigate" application will route a user around flood extents but will further allow the user to select their starting location and destination; this tool is intended for individuals outside of the flood extent who, though not in immediate danger, would benefit from a safe routing application to direct them home or to their destination of choice. Both of these applications were constructed using ESRI's ArcGIS API for JavaScript v. 3.17, and rely on the ESRI routing services [16]. A modeled flood for the Black Warrior River, generated by the NWC, serves as an input to the polygon barrier parameter, restricting routing within the flood polygon extents. Both the real-time (red) and three-hour forecasted (blue) polygons are included, and the routing tasks are parameterized such that all shelters within the flood polygon are off-limits and routing is disabled within 100 meters of the real-time flood extent.

In both the "Navigate" and "Evacuate" applications, careful attention was paid to the mobile compatibility and visual impact of the colors and layouts used. Red was chosen as the real-time flood color because its natural association with danger, while blue was selected for future flood extents due to the human understanding of blue as representing water. While this color scheme may appear obvious, many current alert systems, including the NOAA flash flood warnings, are not intuitively colored. In this way FloodHippo attempts to be the most intuitive and practical flood alert system for aiding individuals during flood events in the simplest way possible.

5. Conclusion

By combining awareness and actionable response, the OPERA system meets the above goals with a generalized prototype proof of concept. The limitations withholding this case study from national application is ESRI's size limitations on polygon extents and production level specific science outcomes. The only reason for the localized scope of the case study areas is the institutional lack of support for the functionalities required by this framework. Fortunately, assuming these case studies inspire action by relevant actors in the field, these conflicts will be resolvable in the near future.

As a new form of alert system, OPERA is more than a sum of its parts; instead, it offers a way to graphically interact at a personal level throughout an emergency event's life history. The strength of this system is demonstrated by its ability to unite citizens, first responders, and NGOs to work together towards a common goal, while allowing each interest group to focus on their own concerns. OPERA not only offers an improved means of intelligently reacting to an emergency, it also demonstrates how complicated science may be presented in a simple and straightforward manner at the individual level. Further, while it is ultimately desired that relevant warning agencies adopt this form of alert system for all disaster types, social media, particularly Twitter, is highly encouraged as a supplemental platform for education and warning dissemination. The reason this is considered a "disaster life history system" is a combination of the improved information delivered, the way it is delivered, and the flexibility offered for reaching the vast majority of Americans [17]. Finally, a summary of the key features previously identified as being critical for reimagining a new alert system, and how OPERA meets each criterion:

1. **Actionable Intelligence**: Through this system, individuals receive actionable intelligence describing how to navigate a disaster event. These applications show individuals how they will be impacted during an event, making a disaster more understandable and relatable, and ultimately helping convey the gravity of disasters to prompt more appropriate disaster response behavior.
2. **Real-time, accurate information delivery**: A partnership with NOAA, the EPA, and other central agencies provides accurate intelligence at the street scale, and the proposed partnership with ESRI allows for alerts to be delivered in real time using their navigation services. OPERA and the underlying systems together create Disaster Zoo "brands" that are easy to remember during emergencies, allowing individuals to seek out the routing capabilities even in the absence of a pushed warning. Further, the central location and interface can integrate with current social media outlets, federal warnings, and any other means of communication that occur over the internet without requiring premeditated action by the end user, and all web applications function across any internet capable devices.
3. **Easy access**: OPERA and the associated services all mimic existing applications and aim for simplicity and intelligent design. The routing applications mirror similar applications such as Google Maps, and the use of web applications allows for consistent use across all mobile and desktop devices. The intent of this cross-platform integration is to provide a sense of familiarity and clarity for users which, in times of emergency, is critical for impacting behavior.
4. **Social dissemination**: The ability to share a hyperlink across social networks, government push notifications, and web pages provides an additional means of education and awareness over the current federally pushed warnings. Allowing individuals to aid with alert dissemination is

similar to integrating local knowledge of a disaster: when individuals see an impacted area on the map they can quickly and easily notify their contacts of the potential risks. The OPERA platforms also all operate on the same backbone, making alert systems consistent and simple while offering different ways to reach people.

Ultimately, OPERA is an event-specific, integrated, community-based response system prototype that improves on existing disaster alerts by integrating the power of existing - yet underutilized - technologies and tapping into a robust social network of communication. The OPERA system was designed to be translatable across all form of disasters generalizable as polygons, including chemical spills, wildfires, nuclear accidents, infrastructure failures, and man-made disasters. The system also has the ability to scale up from the community to the national level, and has potential to be integrated in current navigation systems as well as within the existing emergency response infrastructure.

Supplementary Materials: QR Code to main OPERA webpage (http://disasterzoo.wixsite.com/main).

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Chapter 12 Section A

Translator TTX – Bridging the Communication Gap between Researchers and Emergency Responders

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Abstract: This study focuses specifically on what emergency management agencies at all hierarchical levels consider to be a "gap" between the critical needs of first responders and the deliverables offered by advancing science. For this study, we posit that this gap is in fact not an engineering science problem but rather a communication problem. Social norms and human behavior hold the key to better understanding and reducing loss of life from flood events. The objective of this study is to develop a conceptual model to translate and interconnect the "science domain" (i.e., weather information sources) with the "social domain" (i.e. emergency managers, first responders and those affected by an event). To address communication problems between the science domain and the social domain, we adopt a "Rosetta Stone" metaphor as a model paradigm. We refer to this "translation" concept as "Translator-TTX". The study has the potential to make a contribution through maximizing the applied value of disaster science and management research and technology. Our investigation supports the notion that with simplification and efficient delivery of the knowledge contained in the science domain, using just-in-time techniques, and state-of-the-art algorithms, the needs of first responder practitioners met and exceeded. Finally the first responders engaged in this study were eager to close the communication gap between researchers and practitioners. The main findings suggest further research opportunities exist in implementing ESRI Story Maps for pre-planning tabletop exercises (TTX); reverse look-up inundation mapping updates through first responder windshield survey methods and spatial-temporal locational 3D object analytics to provide emergency personnel at different hierarchical levels with enhanced visual perceptions and situational awareness. In conclusion, an expert decision support system utilizing an evolving knowledge warehouse repository of events, scenarios, standard operating procedures (SOPs), and best practices appears possible and meriting of further research. Also the feasibility of implementing such approaches in a serious game software platform is supported by the literature. Finally, helping connect the efforts of engineering science with the needs of first responders, serving the public safety interest, is the primary motivation behind this study.

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1. Motivation

According to NOAA, in 2015, water related events alone affected 7 million citizens in 15 states across the country for an estimated cost exceeding $1 billion. Many lives at risk were saved, but too many were unnecessarily lost. Persistent lack of knowledge and respect for the dangers associated with the physical forces of flooding by the general population likely contribute to the loss of life. First responders are also not immune to these risks. After-action reviews (AARs) from past incidents cite "lack of effective communication" as a primary issue in responding to incidents. This issue must be overcome in order to significantly reduce current loss of life due to flooding. In weather related events, any opportunity to strengthen the capabilities of the interface between the science domain and the social domain is an opportunity to strengthen and enhance the efficiency and effectiveness of operations, further reducing loss of life and property.

The National Water Model can now be utilized to predict flood timing, heights, flow rates and other parameters, but the only way it can be useful in a flood event to first responders and the public is if this information is delivered in a timely and simplified manner. The specific weather hazard investigated in this study is inundation flooding (e.g. watershed downstream flooding, simplified dam and levee breach).

The translator is also distinguished from other efforts through the use of an expert system, a logic engine and a data repository with a robust maintenance module that will provide a knowledge warehouse capability that is scalable three-dimensionally. Additional models can be added to include an all hazards approach. As of now, the model can be used to execute pre-planning training, but eventually will be available for live situational awareness enhancement to emergency managers facing real events. It will also be developed as a post analysis tool collecting and storing standard operating procedures and modifications as well as best practices for individual jurisdictions. Finally, Translator-TTX can be tailored and delivered to address the different hierarchical training needs of various levels of emergency management.

2. Objectives and Scope

The purpose of the study is to explore the potential for new National Water Model scientific prediction capabilities and initiatives to be implemented as useful enhancements to first responder preparedness at all hierarchical levels of emergency response and management (i.e., EOC's, Police & Fire & Rescue Chiefs, and actual on-scene crews).

Our goal is to save lives and property.

- Objective – Provide enhanced predictive anticipatory information and instruction to ensure whole community flood resiliency
    - Strategy #1 – Provide tabletop exercises as a service to meet the needs of first responders in protecting vulnerable population groups
        - Tactic #1 – Real-time pre-planning simulations (Translator-TTX, serious game software)
    - Strategy #2 – Create innovative utilizations of geospatial information and informatics to improve situational awareness and improve opportunities positive impacts on flood evacuation and rescue
        - Tactic #1 – Reverse look-up to improve first responders' situational awareness (using windshield survey methodologies)
        - Tactic #2 – Provide deliverable preventable actions, education, planning and training programs

Translator-TTX has specifically addressed each tactic through its knowledge warehouse and expert decision support system software platform (Figure 1). A website proof of concept is provided in supplementary materials to demonstrate the flow and logic of such a model.

Finally, an innovative three-dimensional object was incorporated into the model as a potential emergency management decision making tool called "Avatar" to allow visual semaphore object representation of the unfolding events for various emergency management roles.

3. Previous Studies

There is a strong movement to adopt serious game software approaches to meet the needs of first responders [1]. One of the most popular applications of a software “role playing” approach is in a development referred to as RimSim [2]. A leading author of “Emergency Response and Training“has written extensively about the subject and has gained acceptance for his scholarship from the Department of Homeland Security and USGS [3]. Further justifications and rationale for “Adapting Simulation Environments for Emergency Response Planning” can be found in good measure in this doctoral thesis [4]. The literature not only talks about the potential for weather hazard simulation but also the applicability to emergency processes like hospital evacuation [5]. Further possibilities for analytic solutions to the problems faced by first responders appear in the work associated with GIS network analyst using Capacity Aware Shortest Path Evacuation Routing (CASPER) algorithms [6] discussed briefly in our study as one potential adoption of an integration of mapping demographics and CASPER.

The architecture and conceptual structure of our Translator-TTX approach is supported in the literature discussing “...game architecture centered on a modeling and simulation infrastructure” [7]. The best of computerized intentions cannot ignore human cognitive visual limitations. This literature provides discussion of the analytics appropriate for human cognitive capacities [8]. Funding and interest for a “translator” approach to the communication problem presented in our study can be found in literature describing the Department of Homeland Security involvement with this initiative [9]. “Realistic evaluation” of an emergency management organization’s disaster preparedness is another role a computerized infrastructure may be able to provide in combination with a knowledge warehouse as discussed from an IT management perspective [10]. We explore the future of visualization and analytics with our suggestion for a three-way factor analysis, using our “Avatar” semaphore, 3D printed object or software model to visualize situational awareness. This literature supports such a discussion and development through “3D Crisis Mapping for Disaster Simulation training” from an information systems perspective [11, 12]. Finally, a report on simulation by the Department of Homeland Security and a case study from New Zealand with live call data provide guidance from previous studies.

4. Methodology

We utilized a mixed method of inquiry combining qualitative and exploratory research designs in a phenomenological approach. We conducted primary research in the form of face-to-face, open-ended interviews with scientists and first responders in selected using a convenience-sampling frame. In support of the study, we conducted a thorough review of the literature in our secondary research within the emergency management science domain.

We conducted three informal, face-to-face interviews. The first was with Tuscaloosa County Fire and Rescue Deputy Chief Chris Williamson and staff, the second with Northport Fire and Rescue Chief Bart Marshall and staff, and the third with Tuscaloosa County EMA Director Rob Robertson. After conducting these interviews, it was clear that communication gaps existed between the science community and first responder community. This feedback was used to develop the Translator – TTX software platform. Due to time and resource constraints, we developed a small proof of concept to test the capabilities of Translator – TTX.

This proof of concept included a number of approaches:

- Provide first responders and emergency managers access to a user friendly website (powered by WIX) that is broken down by organization (NGO’s, Police, EMA, and Fire and Rescue) [see Supplementary Details for more information]
- Develop online tabletop exercise templates (powered by ESRI Story Maps) that can be tailored to a community’s needs.
- Develop a knowledge warehouse that categorizes information using an if-then logic system.

- For example, IF a dam breaches, THEN certain actions must be taken. These actions are taken from best practices and lessons learned from After Action Reports (AARs)

5. Discussion

5.1. Description of Results **-** The investigation to date has identified two main results (1) what is needed and (2) by whom.

5.1.1. Result #1 **– "What is needed?"** More pre-planning opportunities for integrating the engineering science advances exemplified by the National Water Model.

5.1.2. Result #2 **– "Who needs what?"** The hierarchical structure of emergency management organizations (from on-the-ground first responders to chiefs and directors) dictates the delivery of different pre-planning services for different roles within each organizational job function.

5.2. Interpretations

5.2.1. Interpretation of Result #1 "What is needed?"– Based on our investigations, we believe an intelligent transfer mechanism is needed to facilitate the "translation" of scientific data and derive results into usable information, knowledge and actionable understandings in the language of first responders. That language typically consists of "visual" maps such as flood inundation maps. In addition, since the National Water Model covers all of the contiguous United States, any first responder within that area utilizing the Translator-TTX Tabletop Exercises as a Service will be able to work with their local and familiar real data.

Our conceptual model (called Translator-TTX) has provided the theoretical framework to address the communications gap between researchers and practitioners. We believe such a mechanism could also be scaled to address all hazard scenarios across time and in formats to address of the hierarchical needs of emergency management and first responders. Translator-TTX is conceptually like an integrated "switchboard". Such a software platform would connect a robust knowledge warehouse to provide the training needs of first responders with data for realistic simulations in familiar geographic settings provided by the National Water Model (Figure 2).

In preparing for an event, emergency managers and responders participate in various exercises to clarify roles and responsibilities. Tabletop exercises (TTX), for instance, are meetings to discuss a simulated emergency situation. Members of the group review and discuss the actions they would take in a particular emergency, testing their emergency plan in an informal, low-stress environment [15]. Tabletop exercises have recently taken on a new, modern approach and such as a software emulation referred to as "RimSim". This is a simulation-based software platform designed specifically for countries around the Pacific Rim and their emergency management organizations for pre-planning exercises associated with hazards that affect the area, such as earthquakes. Their approach, however, does not have the advantage of using real data and thus adopts fictitious place names, events and scenarios. We have developed a series of tabletop exercises (TTX) using ESRI's ArcGIS Online Story Maps to describe flood scenarios based on a community's needs (Figure 3). These tabletop exercises use real data and events in order to better prepare first responders.

Due to time and resource constraints, we have chosen to demonstrate our approach by delimiting it to a proof-of-concept visualization (through the use of an innovative web design cloud host called WIX.com). The WIX proof-of-concept site [see Supplementary Details for more information] offers a tour of the essential components envisaged in the Translator-TTX (Figure 4).

5.2.2. Interpretation of Result #2 "Who needs what?"– There is a need for a comprehensive "intelligent transfer" mechanism to take the detailed data, information and interpretations derived from the "science cloud" so as to filter that content into improved knowledge and meaningful understandings to the hierarchical structure of the first responder/emergency management community. Specifically, by improving the detail and awareness of the geocoded property at risk and its demographics, this platform can shorten lead times and ultimately save lives.

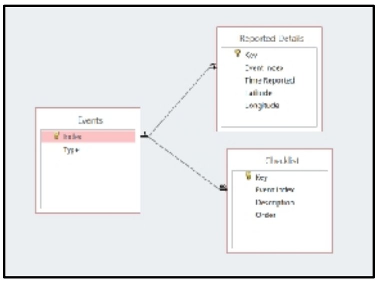

Figure 1: Knowledge Warehouse Level 1 Entity Relationships

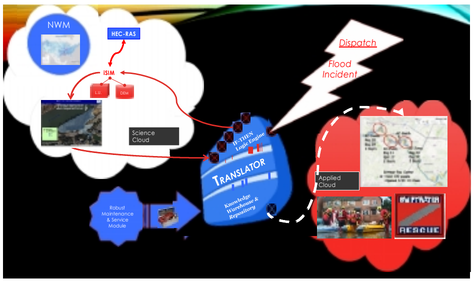

Figure 2: Sample of Translator – TTX "switchboard"

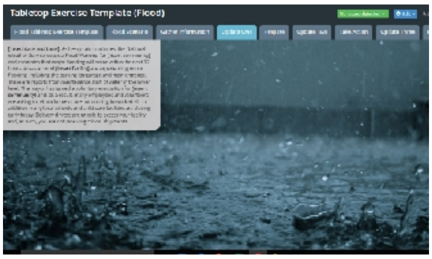

Figure 3: Sample of Tabletop Exercise Story Map

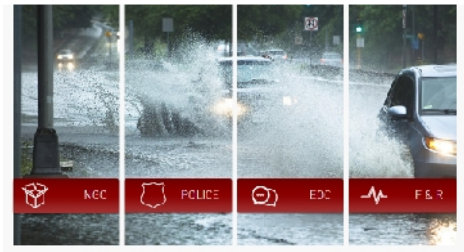

Figure 4: Translator – TTX Software Platform

6. Conclusion

The Summer Institute environment has allowed us the privilege and opportunity to explore, investigate and examine our intellectual curiosities using a rapid prototyping methodology on new topics and to tease out potential solutions that might offer innovative breakthroughs to tough unsolved-to-date problems. We have taken the opportunity to explore and experiment with a wide range of investigations, without fear.

This has in turn spawned new opportunities to address the "communication problem" discussed earlier. The communication problem refers to the translation of scientific information into knowledge that is useable and adaptable for first responders. These improvement opportunities are derivative of significant recent scientific developments. For example, the National Water Model dramatically strengthens the geographic coverage, predictability and advanced warning time intervals for flood inundation effects mitigation.

Other promising research directions for further investigation

- **Reverse-Lookup** shows how flood conditions verified as ground truth by first responder crews (using standard Windshield Surveys) in real time could play an important role in recasting the geographic event scene and potentially uncovering upcoming weakness while identifying just-in-time opportunistic recover and rescue efforts as dynamic conditions unfold.
- **Distant Learning** implementations for classrooms could be applied to pre-planning tabletop exercises as a service.
- **Real Time -** With appropriate resources, the Translator-TTX platform need not be limited to flooding or pre-planning only and could effectively organize and manage simultaneous numbers of unexpected hazards either as a simulator or eventually through development real-time events and eventual post-event analysis
- **Avatar –** Space-time three-way factor analysis

- **iMDE –** Integrated Mapping Demography and Evacuation
- **iSIM –** Integrated Simplified Inundation Mapping
- **Costs –** Flood Damage Estimator
- **Site Locator –** A siting approach that looks not only at population density and drive time for siting new Rescue Service facilities, but also weights using GIS buffered layers for flood and other hazards

This information would be housed in a knowledge warehouse to accumulate as a repository of best practices and lessons learned. It would be envisaged as a three-dimensional conceptual platform horizontally scaling to all hazards; vertically addressing the various needs of the traditional hierarchical emergency management governmental structures over the third axis of time (pre-event, event and post-event).

Supplementary Materials: More information on Figures 3 and 4 are available online at http://liamgesahc.wix.com/translator-ttx; ESRI Story Maps Tabletop Exercises are available at http://arcg.is/29sE921 and http://arcg.is/29sFRAc

Special Thanks to CUAHSI, NOAA's National Water Center, Northport Fire and Rescue Station #2, Tuscaloosa Fire and Rescue Station #2, and Tuscaloosa County Emergency Management Agency

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Chapter 12 Section B

Increasing Citizen Awareness of Floodwater Risks: An Effort at Reducing Flood-related Fatalities

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Abstract: Flood-related fatalities are often avoidable, but the number of total annual deaths from flooding events has been resistant to governments' efforts at reduction (e.g., flood emergency alerts, "Turn around, don't drown" signage, website-based education, etc.). A more effective flood hazard reduction/education program needs to be developed. In order to better tailor and target education, flood fatality data from 1996 to 2015 was analyzed to determine the basic demographics of which people were dying and where they were dying. Also determined were average minimum floodwater depths at which fatality risks are significant. It was found that across the adult population, men made up ~63% of the fatalities, while women accounted for ~37%. It has also been reported that fatality risks are significant at floodwater depths as low as 7.9 inches for people in vehicles [1] and as low as 12 inches for people on foot [2]. A possible factor in the persistence of flood-related deaths is the relatively low perception of the risks of crossing floodwaters [3-7]. An improved education program would include thoroughly communicating flood risks to all ages, not just to the proactive adults who research websites and heed flood emergency alerts.

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1. Motivation

Flooding is a significant cause of deaths due to weather hazards, and unlike other hazard-related deaths, there has not been a declining trend [3] (Figure 1). The top two locations of where these fatalities occur are in vehicles (e.g., driving into flooded areas of roads) and in water (e.g., trying to cross flooded areas on foot or by swimming) (Figure 2). Both of these risks are highly avoidable. It has been proposed in numerous studies that, among other factors, risk perception plays a significant role in whether people take these risks [3-7]. Therefore, various education methods, targeted to different audiences, have the potential to reduce flood-related fatalities.

2. Objectives and Scope

The development of targeted education materials is the objective of the author's Summer Institute project. Assessment of which groups of people were dying, and where it was occurring, was accomplished by analyzing the most recent 20 years of data obtained from the National Weather Service (NWS) [8]. Also determined were the average minimum floodwater depths at which fatality risks are significant [1, 2]. From these, Citizen Maps which include some flood hazard avoidance facts, will be generated.

3. Previous Studies

Although there has some research on flood fatalities [3-7], most of it is not recent (e.g., data only up to 2005 was analyzed). The author analyzed more recent, and a longer period of data; 1996-2015.

4. Methodology

Flood fatality data for the United States and its territories (U.S.) was obtained from the NWS website [8] for the period of 1996-2015. This data included a break-down of deaths by year, state, gender, 10-year age group, and location. Analyses conducted included: Total flood-related fatalities by year (1940-2015), totals and percentages by gender (ages 20 and higher; children 0-19 were excluded due to the author's assumption that they were passengers and not decision-making drivers), totals and percentages by age group and gender (ages 20 and higher; 0-19 ages were excluded, as previously noted), totals and percentages by location, totals and percentages by state (including average number of fatalities per year in which flood deaths occur), and totals and percentages by location and state. Data has not been normalized by population, yet. Research was also conducted to determine what the average minimum floodwater depths at which fatality risk becomes significant for both the vehicle [1] and the in water locations [2].

As part of communicating risk, a Citizen's Map was developed using Esri's ArcMap 10.3. The map uses a street basemap, a 10-meter by 10-meter resolution National Elevation Dataset [9] digital elevation model (DEM), and a house location. The symbology of the DEM was then adjusted to reflect elevation groupings; red ("don't go" zone) for elevations at and below the house level, orange ("slightly better" zone) for elevations up to 10 feet over the house elevation, yellow ("better" zone) for elevations of 10 to 30 feet over the house elevation, and green ("much better" zone) for elevations at least 30 feet over the house elevation. Two versions of the map were created; one for people evacuating on foot (1 to 4,000 scale, Figure 3) and one for people that may be able to evacuate by vehicle (1 to 10,000 scale, Figure 4). Also included with the map printout are some flood hazard avoidance facts.

5. Results

5.1. Fatality Research

5.1.1. Data Analysis

Basic demographics of the people who are dying and where are they dying in the U.S., from 1996 to 2015:

1) The total annual flood-related deaths were highly variable and there was no significant trend (Note that this data is for the period of 1940 to 2015, Figure 1).
2) Gender: Of the people aged 20 and higher, men were ~63% of fatalities, while women were ~37% of fatalities, which is a rate of ~1.73 to 1 (men to women) (Figure 5). Since males are only ~49.2% of the population [10], this may indicate that significant sociological factors are driving the higher mortality rate for men. Breaking this down by 10-year age group, men die at a rate of 1.5 to 2.1 times more often than women (this excludes the anomalous rate of 5 to 1 men to women in the 90+ age group) (Figure 6).
3) Location: Approximately 52% of deaths occurred in vehicles or towed trailers and ~25% of deaths occurred in water, making these, by far, the most common locations for flood-related fatalities (Figure 2).
4) Of the 52 states and territories with flood fatalities, 21 had deaths in at least 50% of the years analyzed. Those states, in descending order of percentage of years with flood deaths are: Texas (95%), Missouri (95%), Kentucky (90%), Ohio (90%), California (85%), Arizona (80%), Indiana (75%), Virginia (75%), Washington (75%), Illinois (70%), New York (70%), Arkansas (65%), Oklahoma (65%), Puerto Rico (60%), Tennessee (60%), West Virginia (60%), Mississippi (55%), Pennsylvania (55%), Kansas (50%), New Mexico (50%), and Utah (50%).
5) The highest average number of flood fatalities per year, in years with flood fatalities, varied by state. The top 12 averages by state: Texas = 14.16, Pennsylvania = 6.91, North Carolina = 5.67, Arkansas = 5.54, Missouri = 5.37, Tennessee = 5.25, Colorado = 4.80, Oklahoma = 4.46, Arizona = 4.38, Kentucky = 4.22, California = 4.12, American Samoa = 4.00.

6) In the top 4 states (by number of years with flood deaths) ~65% to ~89% of the deaths occurred in vehicles or in water (Figure 7). In the top 6 states (by number of deaths per year with flood deaths) ~54% to ~92% of the deaths occurred in vehicles or in water.

5.1.2. Flood Hazard Statistics

Dangers of driving into floodwaters: Vehicles can float when water depth reaches the car floor.

1) Sub-compact cars (weighing a little over 2,300 pounds) can become unstable and difficult to maneuver in water as shallow as 7.9 inches and moving as slowly as 2.25 miles per hour (mph) (average walking speed is approximately 3 miles per hour) [1].
2) Large trucks/SUVs (weighing approximately 5,500 pounds) can become unstable and difficult to maneuver in water as shallow as 17.7 inches and moving as slowly as 3 mph (average walking speed) [1].

Dangers of walking into floodwaters: Water that is as shallow as 3 feet deep and moving as slowly as 2.6 mph can knock down an adult male. The same can happen at a depth of 2 feet at 4 mph, and at 1-foot-deep at 6.7 mph [2]. It is presumed that the depths and speeds that are hazardous for women would be lower because, on average, women are shorter and weigh less.

5.2. Figures

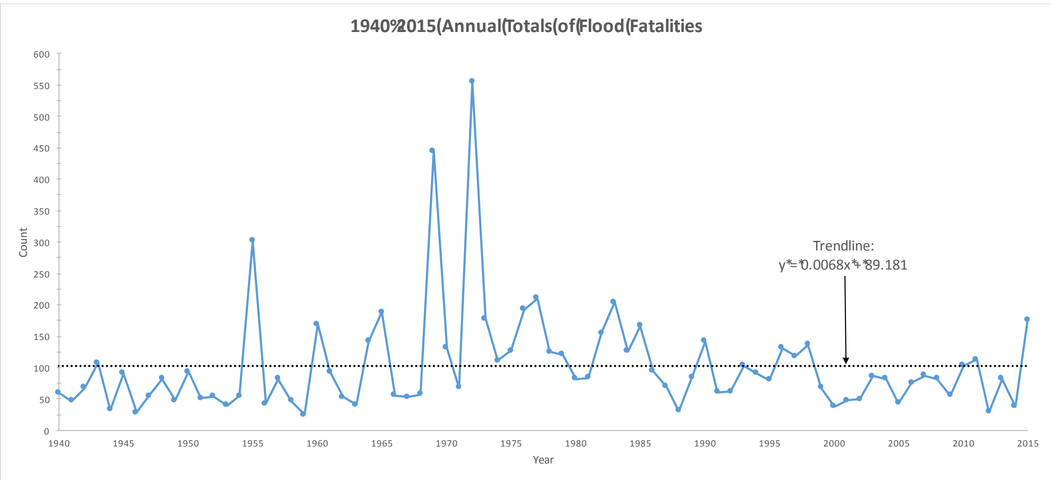

Figure 1. This graph depicts the total number of flood fatalities by year, for the period of 1940 to 2015. The Excel-computed trendline indicates that the number of deaths per year is neither declining nor increasing (the author believes that the 0.0068 positive slope value is not significant).

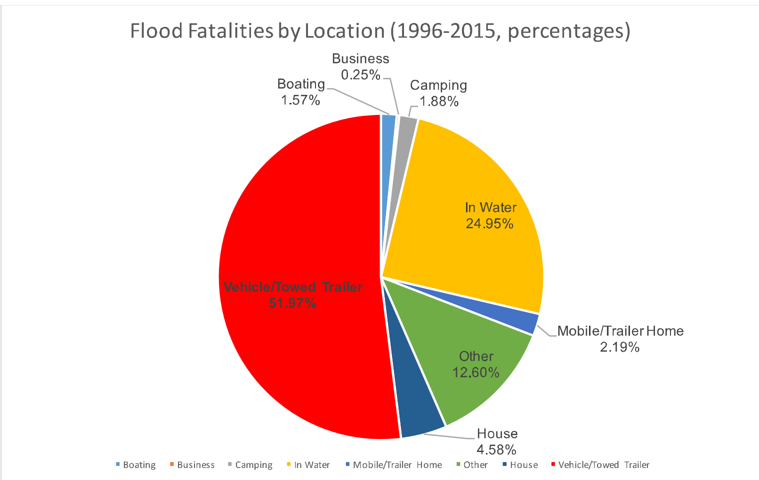

Figure 2. This chart shows the percentages of flood-related fatalities in the U.S., by location, for the period of 1996-2015.

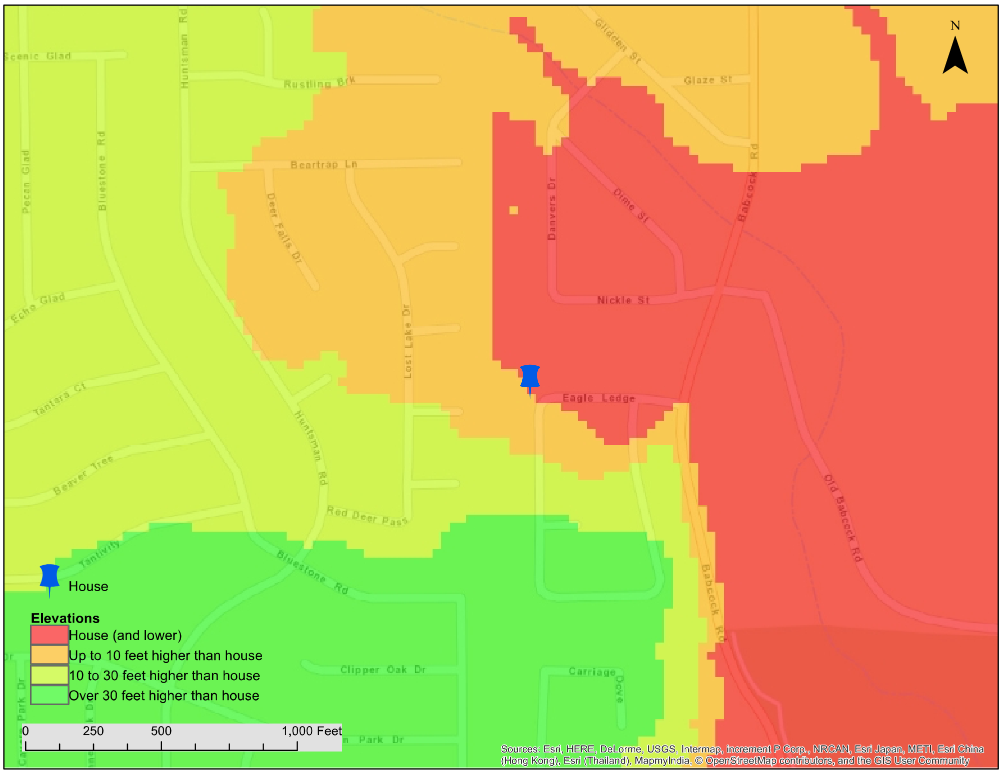

Figure 3. Elevation map showing roads and elevation ranges in relation to a house at 1 to 4,000 scale (in order to aid in on-foot evacuation).

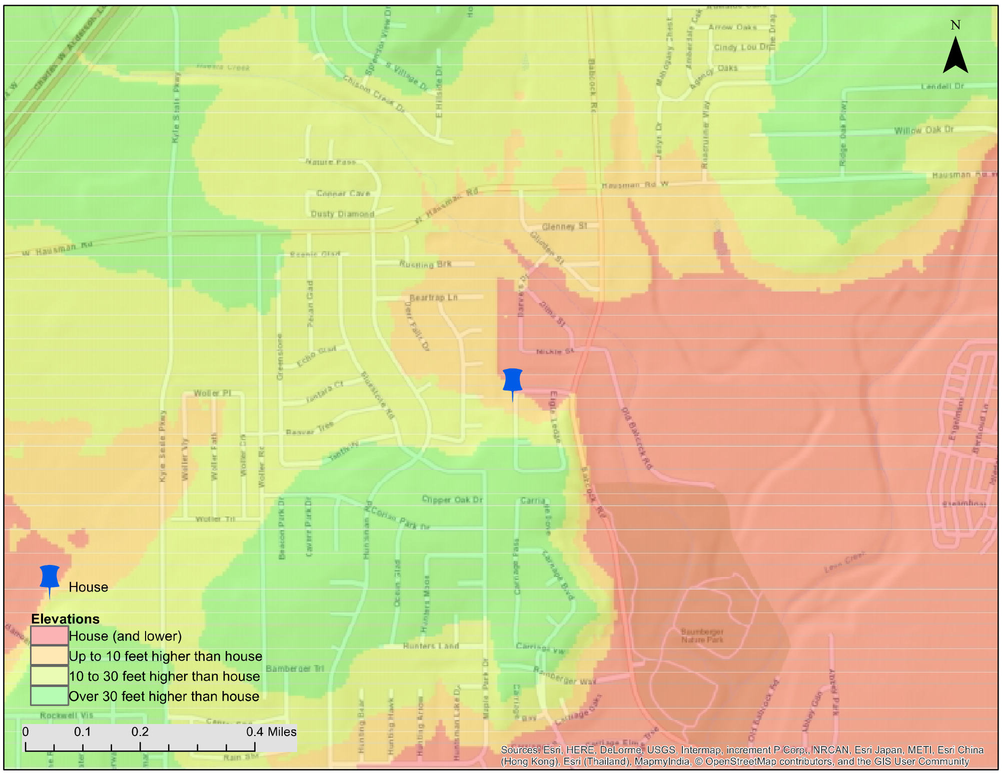

Figure 4. Elevation map showing roads and elevation ranges in relation to a house at 1 to 10,000 scale (in order to aid in in-vehicle evacuation, if possible).

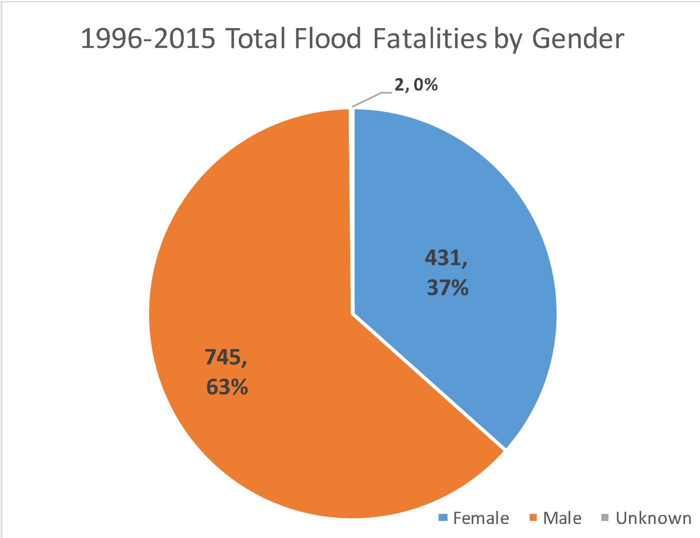

Figure 5. This chart depicts flood-related fatalities, by gender, of adults aged 20 and higher, in the U.S. from 1996-2015. Men were ~63% of fatalities, while women were ~36% of fatalities.

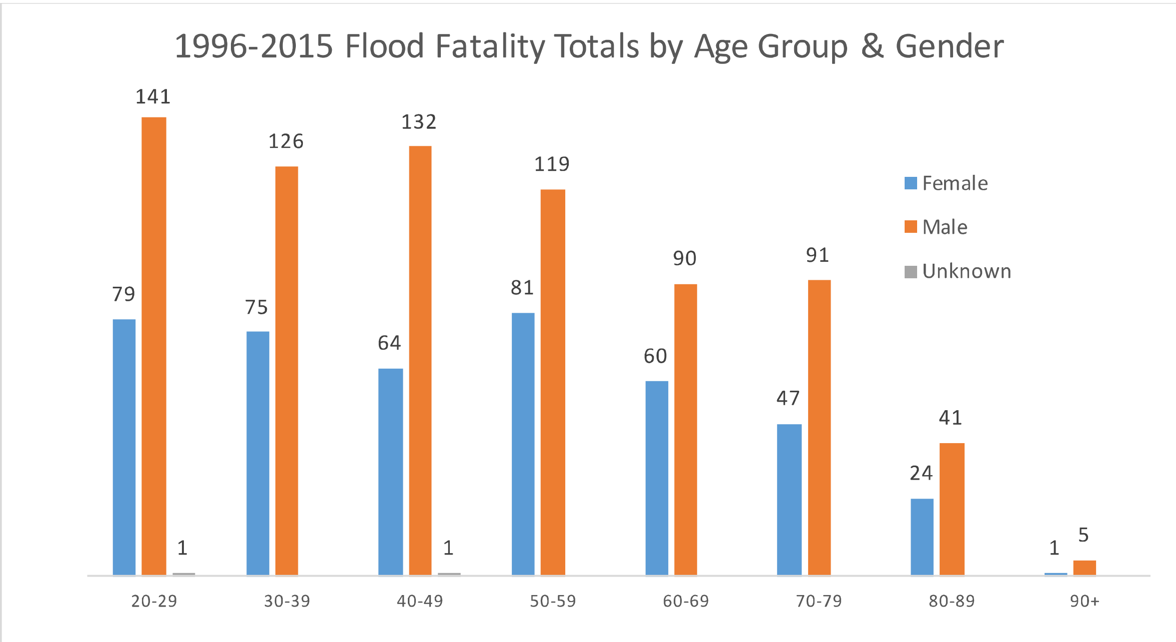

Figure 6. Chart depicting flood-related fatalities, by gender and age group, in the U.S. from 1996-2015. Men die at a rate of 1.5 to 2.1 times more often than women (this excludes the anomalous rate of 5 to 1 men to women in the 90+ age group).

6. Conclusion

Flood-related fatalities are a persistent problem with numbers that vary by year and is not exhibiting a declining trend as other weather-related hazards have [3]. A possible large factor in this persistence is a relatively low perception of the risk of driving or walking into flooded areas [3-7].

A common and often effective method of changing perceptions is through education. Flood hazard education should be conducted at all ages.

- For the school-aged children (i.e., pre-driving and newly-driving ages), "Safety Week" programs should include a unit on flood hazards. Included could be the slogans "If it's flowing, don't be going" (to avoid vehicle deaths) and "Don't drown, get to higher ground" (to avoid in water deaths). Depending on the age group, the statistics would be explained at various levels of detail. Also included in the program would be a printout of the Citizen's Maps (laminated, if possible) for each child to give to their parents or guardians for keeping in the car and/or posting on the back of their house's front door. People in driver education programs should receive education along the same lines. Other methods of distribution for the maps might include churches, retail businesses, and social service agencies.

- For adults, the primary education methods could include public service announcements that include floating vehicle video with a voice-over of floodwater risks and the slogans "Turn around, don't drown" (to tie in the message with signage many drivers already see during their commutes), "If it's flowing, don't be going" (to avoid vehicle deaths) and "Don't drown, get to higher ground" (to avoid in water deaths).

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Appendix

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Chapter 1: Radar Measurement and Flow Modeling: Methods

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Chapter 2: Delineating Stream Flowlines and Watershed Boundaries in the Lower Rio Grande Valley using High Resolution LiDAR Derived Digital Elevation Models

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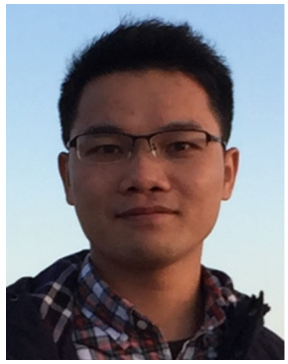

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Chapter 5: Object-based Flood Inundation Mapping

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Chapter 6: Comparison of Flood Inundation Mapping Techniques between Different Modeling Approaches and Satellite Imagery

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Chapter 7: Real Time Postprocessor Towards Improving Flood Inundation Mapping

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Chapter 8: Quantifying Uncertainty in Flood Inundation Mapping using Streamflow Ensembles and Multiple Hydraulic Modeling Techniques

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Chapter 9: Assimilation of Water Level Observations in River Models to Update Flood Inundation Maps

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Chapter 10: HAND Flood Inundation Mapping through the Tethys Platform

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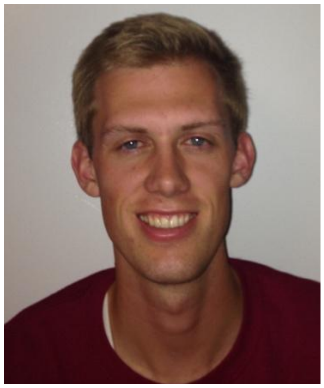

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Chapter 11: Reimagining Disaster Warning System
OPERA: Operational Platform for Emergency Response and Awareness

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Chapter 12:

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B. Increasing Citizen Awareness of Floodwater Risks: An Effort at Reducing Flood-related Fatalities

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