The Thesis Committee for Cassandra Fagan
Certifies that this is the approved version of the following thesis:

Improving Flood Preparedness in South-Central Texas

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor:

David Maidment

Daene McKinney

Improving Flood Preparedness in South-Central Texas

by

Cassandra Fagan, B.S.

Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

May 2016

Acknowledgements

I would like to thank my advisor, Dr. David R. Maidment, for the support and mentoring he has provided to me over the past two years. Dr. Maidment's enthusiasm for water resources and determination to make a change is inspiring. I would also like to thank our wonderful research team at the Center for Research in Water Resources (CRWR), who was very supportive of my research and always willing to provide guidance. I am grateful for my NFIE Summer Institute teammates Caleb Buahin, Nikhil Sangwan, and Curtis Rea for their dedication and support in this research. Lastly, I would like the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) for funding the 2015 National Flood Interoperability Experiment (NFIE) Summer Institute where much of this research was performed.

Abstract

Improving Flood Preparedness in South-Central Texas

Cassandra Fagan, M.S.E.
The University of Texas at Austin, 2016

Supervisor: David Maidment

In order to prevent future tragedies, improvements in flood preparedness at the local level must be a priority. The emergency response community needs accurate and timely information to effectively protect lives, property, infrastructure, and the environment. This thesis investigates improving the level of flood emergency response at the local level by 1) using downscaled ensemble forecasts to extend forecast lead teams and incorporate uncertainty, and 2) by creating a flood map plan for high priority reaches using Austin, Texas as the case-study area.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Motivation

According to statistics from the National Weather Service (NWS), floods were the leading cause of death from weather related fatalities in 2015, claiming 155 lives in total (NWS 2016). The frequency, and magnitude of these flooding events is expected to increase in the Southeastern portion of the United States due to urbanization and anthropogenic climate change (U.S. Global Change Research Group 2016). Texas leads the nation in flood related fatalities, followed by Pennsylvania and South Dakota (Ashley and Ashley 2008).

The City of Austin, Texas is located in one of the most flash flood prone areas in the country known as “Flash Flood Alley”. The National Weather Service Glossary defines a flash flood as a rapid and extreme flow of high water into a normally dry area, or a rapid water level rise in a stream about a predetermined flood level beginning within six hours of the causative event (NWS 2012). The climate and terrain of the region are the driving factors of the chronic flash flood occurrences in South-Central Texas (Baker 1975). Thin, rocky soil, in combination with steep slopes, and intense precipitation events transforms dry creeks in raging rivers in little time, with urbanization also being a contributor to flash flooding (U.S. Global Change Research Group 2016).

The Balcones Escarpment, separating the eastern Edwards Plateau from the western Coastal Plains, is often blamed for enhancing the areas ability to produce exceptionally high flows. Tropical storms and hurricanes moving inland can become stalled at the escarpment where there is a rise in elevation. Warm, moisture laden air moving from east to west from the Gulf of Mexico rises when it converges upon the Balcones Escarpment. Air masses may undergo orographic cooling which leads to extremely intense precipitation events lasting hours to days. The orographic cooling effect along the Balcones Escarpment has been accredited with many record breaking rainstorms (Caran and Baker 1986).

In addition to climate effects, the Balcones escarpment contributes to drainage properties that maximize runoff. Steep gradient and rocky, thin soil reduce the ability of runoff to infiltrate the soil. A 2004 study from the United States Geological Survey (USGS) states that the greatest concentration of peak unit discharges, the peak discharge per unit area per depth of runoff, in the United States is at the Balcones Escarpment of central Texas. Maximum U.S. rainfall amounts combined with basin characteristics produce some of the largest measured floods in the United States, leading to Texas having nearly twice the average annual flood-related fatalities of any other state (O'Connor and Costa 2004).

The NWS is responsible for providing streamflow forecasts and issuing warnings in the United States to protect life and property. The NWS Advanced Hydrologic Prediction Service (AHPS) produces short-term to seasonal streamflow forecasts at 3600 locations in the United States (NWS 2015). The low density of streamflow forecast points forces the NWS to issue county wide flash flood warnings. These wide-area warnings may cause numbness in communities to warnings if they repeatedly receive flash flood warnings and are not affected by these events (Kapucu 2008).

Recent events have shown that the current NWS operational forecasting network is inadequate. The 2016 Memorial Day in Wimberley, Texas is an example of this. The Blanco River, at Wimberley, TX is the forecast point for Wimberley, TX. Unable to afford a gaging network to support a local flood forecasting system, Wimberley, TX relies on the NWS and an informal flood warning system, the "old-timers" network, made up of ranchers living in the upper basin of the Blanco Basin. The NWS was not able to forecast the Memorial Day flooding event with significant lead time. However, a rancher in living upstream in the Basin notified Hays County officials of the record setting water stage, which triggered an evacuation of residents living close to the Blanco River bank shortly before the peak flows arrived in Wimberley, TX and saved many lives. To prevent future situations such as this, improvements in flood forecasting and preparedness are necessary.

The National Flood Interoperability Experiment (NFIE) proposed forecasting streamflow on a densified stream network to connect flood forecasts to the local level (Maidment 2015). This stream network consists of 2.7 million stream reaches and catchments in the continental United States. The NFIE framework is broken into five categories: Geo, Hydro, River, Response, and Services, seen in Figure 1. Improving flood forecasts supports the emergency response community by providing them with higher resolution streamflow forecasts more frequently. However, there is work that must be done to translate streamflow forecasts into actionable information for emergency responders. The information they receive must be easily understood and interpreted due to the compressed time frames available during emergencies. The work presented in this thesis focuses on NFIE-Response, presents tools to improve flood forecasts, and connect flood forecasting data to the emergency response community.

1.2 Objectives

The purpose of this work is to understand and assess the following:

a) Can an ensemble prediction system be used to forecast flooding extent and depth while extending forecast lead time and incorporating uncertainty?

b) Is it computationally feasible to use a hydrologic ensemble prediction system (EPS) in forecast mode? If so, are the results comparable to the conventional floodplain mapping software?

c) How can maps be created prior to flood events to improve the level of emergency response during flood emergencies?

1.3 Chapter Outline

This thesis is divided into two related study focuses: 1) Improving flood forecasts, and 2) Connecting flood data to the emergency response community. Chapter 2 introduces the background information for these study area. Chapter 3 presents the methods involved in translating ECMWF-RAPID forecasts to inundation extent and depth forecasts. Chapter 4 describes the Flood Map book that was developed for Central Texas. Chapter 5 provides a conclusion and recommendations for future work.

Chapter 2: Background

2.1 Ensemble Prediction Systems

In recent years there has been an effort to extend uncertainties in hydrologic and hydraulic models to flood inundation maps (Merwade et al. 2008; Smemoe 2004; Beven 2009). Ensemble predictions systems (EPS) which are widely used in meteorological forecasting are now being used with increasing frequency for flood forecasting to help mitigate the impacts of flooding (Demeritt et al. 2007; Cloke and Pappenberger 2009). The main benefit using a Hydrologic Ensemble Prediction System (HEPS) is the extended lead time the forecasts provide to the emergency response community, and the incorporation of uncertainty in the forecasting framework (Cloke and Pappenberger 2009; Thielen et al. 2009).

Hydrological ensemble predictions systems (HEPS) forecasts are based on ensembles of numerical weather prediction (NWP) models, rather than observation networks. This allows the models to increase the forecasting lead time beyond the basin's time of concentration (Cloke and Pappenberger 2009; Demeritt et al. 2007). In addition, NWP systems may be more dependable, because they do no rely on observation networks, including streamflow and precipitation gages. NWP are able to produce forecasts in basins where streamflow data or other observations are not available (Cloke and Pappenberger 2009). In addition, observation networks are vulnerable to failures during extreme events, such as streamflow gages which are located near river beds. Without these data, deterministic models are not able to accurately forecast flood events. An example of this was in the 2013 Halloween Flood, when USGS Gage 08158827 Onion Creek at Twin Creek Bridge near Manchaca failed. The floodwaters continued travelling downstream and surprised residents and emergency responders by cresting at a record setting 40 ft. Another benefit of HEPS, is the increased number of forecasts which provide indicators of the uncertainty associated with flood forecasting. Conventional deterministic forecasts outputs result in single-extent inundation boundaries that do not convey the inherent uncertainty in precipitation, streamflow, and topographic parameters (Merwade et al. 2008; Demeritt et al. 2007). However, the computational intensity of producing the forecasts in HEPS has been one of the main challenges in implementing HEPS operationally. In addition to high computational intensity, the mismatch of meteorological and hydrological spatial and temporal scales, and the interpretation of forecasts have all been cited as challenges preventing HEPS from being implemented operationally (Thielen et al. 2009; Cloke and Pappenberger 2009).

2.2 European Centre For Medium Range Weather Forecasts

The European Center for Medium Range Weather Forecasts (ECMWF) is an independent intergovernmental organization supported that was formed by 34 European countries within the World Meteorological Organization's Region V. The ECMWF acts as a research institute as well as an operational forecasting service by producing a variety of oceanography, meteorology, and hydrology forecasting products. The forecast product of interest for this study is the ECMWF EPS global gridded runoff forecasts.

The EPS forecasts are comprised of two component forecasts, the high-resolution forecast and the ensemble forecasts, together totaling 52 forecasts. The high resolution forecast, HRES, is produced twice daily for up to ten days at a ~ 0.14-degree grid cell resolution and a varying time step for ten days out. The HRES forecast has a 1-hour time-step for hours 0 to 90, a 3-hour time step from hour 90 to hour 150, and a 6-hour time step from hour 150 to hour 240.

The ECMWF ensemble forecasts consist of one control forecast whose initial conditions are slightly perturbed and produce 50 ensemble forecasts. These forecasts are produced twice daily for up to fifteen days ahead, at a ~0.28 degree grid cell resolution. Similar to the HRES forecast, the time step for the ENS forecasts varies temporally. The ENS forecasts have a 3-hour time step until hour 96, and have a 6 hour time-step from hour 96 until day 15.

2.3 RATING CURVES

A rating curve describes the unique relationship between discharge and water stage at a specific cross-section along a river and may be represented by a table, graphic, or equation. Rating curves are routinely used to interpolate discharge from water stage, because this is more straightforward than measuring discharge. The information provided by rating curves guide stakeholders determining water resources allocations, design of infrastructure and flood thresholds during extreme events. Many of the modern methods for developing rating curves based on discharge and water stage measurements were led by studies from the United States Geological Survey (USGS) (Corbett 1943; Mitchell 1954; Dawdy 1961; Bailey and Ray 1966; Sauer 2002). Rating curves are developed through repeated, simultaneous measurements of discharge and stage across low and high discharge values. The most common rating curves assume a unique relationship between stage and discharge, and fit the measured values to a power equation (Braca and Grafiche Futura 2008):

$$Q = a(b + y)^{\alpha} \tag{1}$$

where Q is streamflow, y is the water depth, and α, a, and b are constants. Equation 1 is based on the Manning's (2) used to estimate average flow in an open-channel:

$$Q = \frac{1}{n} A R^{\frac{2}{3}} S_0^{\frac{1}{2}} \tag{2}$$

where n is Manning's roughness coefficient, A is the cross sectional area of flow, R is the hydraulic radius, and S_o is the channel bottom slope. The unsteady gradually varied flow equation for the S_f is as follows:

$$S_f = S_o - \left[\frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{1}{gA}\frac{\partial\left(\frac{Q^2}{A}\right)}{\partial x} + \frac{\partial y}{\partial x}\right] \tag{3}$$

where S_o is the channel bottom slope, g is the gravitational constant, t is time, and x is the longitudinal location along the channel.

The development of the discharge and water stage relationships along rivers is not a trivial matter. Rivers are complex, dynamic systems that are changing constantly, however in order to have a valid rating curve there must be a unique relationship between discharge and stage. Equations (2) and (3) have two criteria that must be met in order to satisfy the unique discharge-stage relationship. The first criterion required is a constant relationship between stage and cross-section. Streams may be subject to scour and deposition, seasonal variation of aquatic vegetation, variable backwater effects, and ice (Braca and Grafiche Futura 2008). If these processes are present in a river system, the rating curve may need to be shifted, or divided into separate parts for low and high flow in order to have a valid rating (Colby 1960; Braca and Grafiche Futura 2008).

The second condition required for a valid rating curve is steady flow, where the depth, water area, velocity, and discharge along the river section remain constant (Chow 1953). Variations in the energy slope can cause hysteresis, or looping of the rating curve where multiple discharge values are associated with a single stage measurement (Braca and Grafiche Futura 2008). This is common when the water levels in a channel rise or fall rapidly. During the rising limb, the water surface slope is much steeper than during steady-flow conditions resulting in a higher flow than is predicted by the rating curve.

Conversely, on the falling limb the water surface slope is less steep than predicted by the rating curve resulting in lower flows than predicted by the steady flow rating curve.

2.4 GEOGRAPHIC INFORMATION SYSTEM

Geographic information systems (GIS) are used for studying spatial or geographic information in digital form. The primary abilities include data visualization, pre-processing and post-processing data for modelling purposes, and analysis. GIS allows users to integrate many forms of data to form a more complete, and integrated model of environmental systems. Information contained in the geospatial features is stored in tables related to the features, and these tables contain the feature's attributes.

The development of ArcHydro as a toolbox in ESRI's ArcGIS software was a milestone for hydrologic and hydraulic modeling. ArcHydro is a set of tools that support water quality modelling, water supply quantification, and flood modeling (Maidment 2002). The ArcHydro toolbox allows users to model the physical elements of water resources features using polygons, lines, and arc objects. For example, modelling a river basin may represent a river reach using a line, a reservoir by use of a polygon, and a stream gage as a point. These representations are linked to tables containing the attributes of the modeled object (McKinney and Cai 2002). These features may be extracted from a DEM by automated procedures using GIS tools.

GIS also supports the use of terrain data, such as the National Elevation Dataset (NED) Digital Terrain Model (DEM) or Light Detecting and Ranging (LiDAR). ArcGIS has a LAS toolbox that may be used to convert LAS files to a DEM and also allows the user to specify DEM resolution. The ArcHydro toolbox offers terrain analyses which are essential in watershed analysis (Maidment 2002).The results of the terrain analysis, drainage network, area, and hydrologic parameters, may be used as input to a hydraulic model. HEC-GeoRAS is an ArcGIS toolbox for processing simulation results from HEC-RAS. The HEC-GeoRAS toolbox may be used to model water surface profiles, and inundation depth and extent maps from various flood scenarios.

GIS provides a way to acquire, and synthesize various types of spatial data, which may be useful to emergency responders Various data relevant to emergency response may be incorporated and viewed together in GIS, such as inundation maps, address points, the transportation network and Census data. Doing so allows emergency responders to view the spatial scope of wide-area flooding events. A simple procedure such as intersecting address points with a flood plain provides an estimate of the number of people that may be affected by an event. This information may be used to determine the resources that are needed to support that event.

The transportation network is particularly vulnerable during flooding events, especially in South-Central Texas. Low water crossings may be flooded very quickly, and catch drivers off guard. Approximately 75% of people who die in flash floods in Austin, TX die in their car. This prompted the NWS campaign “Turn around, don’t drown”, advising people to avoid driving or walking on flooded roadways. Understanding how the transportation network will be affected during a flooding event is very important for reducing the public’s exposure to flood hazards. Intersecting the floodplain with the roadway, and DEMs can be used to determine roadways are at risk of being flooded. Unconventional data, such social media posts that are geotagged, may also be viewed in GIS and provide real-time updates on an event. Social media was used extensively by the public during the 2015 Memorial Day Flood in Austin, TX. Users posted videos and pictures of the flood in different areas around the city, and using the #ATXFloods hashtag. This thesis proposes to use GIS as a platform to transfer flood information to the emergency response community.

2.5 Emergency Flood Preparedness

The societal response to disasters is broken down into four elements: mitigation; preparedness; response; and recovery (Kapucu 2008; Cutter 2006). This cycle begins with preparation for an event and proceeds into the direct response, such as rescue and relief. Once the immediate dangers are removed, communities transition into the recovery and mitigation stages of disaster response. Preparation, which refers to planning actions taken before the flood impact, is a key step in effectively managing a wide-spread disaster (Kapucu 2008). Due to the difficulty in forecasting flash flooding events with significant lead time, preparation is especially important for areas at risk of flash flooding, such as communities in South- Central Texas (Borga et al. 2011).

Flooding is a wide-area event having substantial social and economic impacts on communities affected. Understanding where, when, and the magnitude of a flooding event can help emergency responders reduce the public's exposure to a flood (Looper and Vieux 2012). GIS is increasingly being used by the emergency response community to visualize, manage and analyze events in all phases of emergency response (Wicks et al. 2014; Wang, Wen, and Zhong 2010; Cutter 2006). Its ability to perform processing tasks, model, and visualize and integrate spatial data make it an ideal platform for disaster response. Geospatial information is critical to understanding the effects that flooding will have on communities and the transportation network, which are particular vulnerable in these events.

An issue that is emphasized by (Cutter 2006), is that many emergency responders are not trained to use GIS, and rely on GIS specialists to develop their mapping products. During emergencies, when timeframes are compressed it can be difficult and stressful to develop these mapping products. In order to address this issue, a flood map book was developed using GIS as the platform. This thesis describes the process of developing the pre-planning and operational maps in the flood map book to increase the level of emergency response.

Chapter 3: Translating Ensemble Streamflow Forecasts to Inundation Extent and Depth Forecasts

3.1 Overview

The work performed in this study was done at the National Flood Interoperability Experiment (NFIE) Summer Institute. The NFIE Summer Institute was a seven week research program hosted at the National Water Center in Tuscaloosa, AL from June 1st – July 17th, 2015. Forty-five students from 19 different academic institutions participated in this event, and were involved in research addressing the nation's flood forecasting challenges. The NFIE is divided into five components, seen in Figure 1, and each component was a research theme in the NFIE summer institute. The research described herein was done by the NFIE-Response team, which included me, Caleb Buahin, Nikhil Sanghwan, and Curtis Rae.

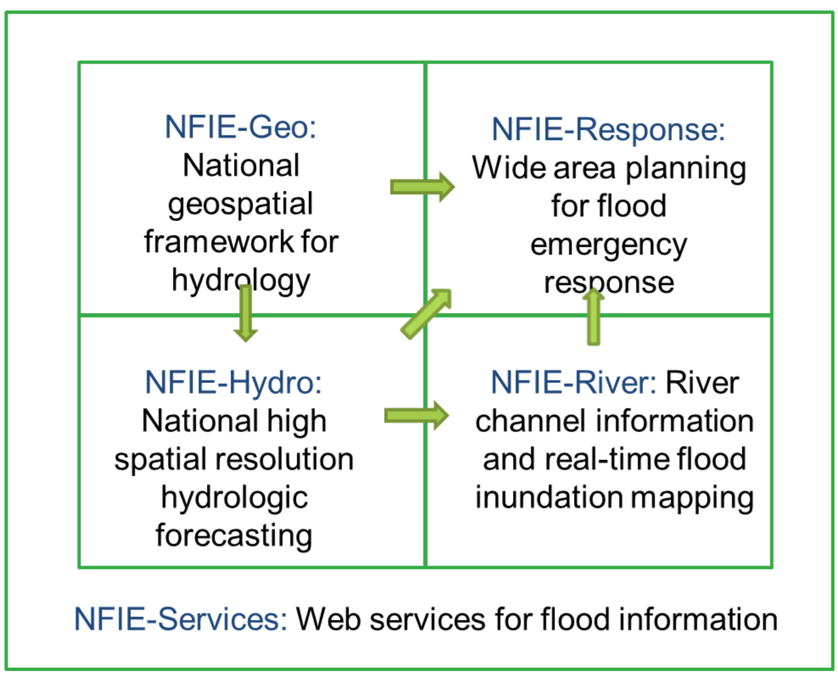


Figure 1: Components of the National Flood Interoperability Experiment (NFIE)

In recent years there has been an emphasis on incorporating uncertainty in operational flood forecasting frameworks. A number of forecasting systems have done so using EPS with various atmospheric conceptualizations, parameters, and initial and boundary conditions in model predictions. Due to the large number of forecasts associated with EPS, it is very computationally expense to use operationally for flood forecasting over large spatial domains at hydrologically relevant spatial resolutions. This thesis describes a rating curve approach that was developed to reduce the computational intensity of the EPS and produce inundation extent and depth forecasts.

The rating curve approach entails pre-running a hydraulic model for various flow scenarios, extracting rating curves, which prescribe a unique relationship between streamflow and water surface elevation, and storing those rating curves in a look-up library format. The rating curve library is referenced when a new streamflow forecast is received, to interpolate water surface elevation and develop inundation depth and extent forecasts. A Rating Curve Based Automated Flood Forecasting (RCAFF) Tool was developed to automate this workflow. The rating curve library approach reduces the computation intensity of the EPS by eliminating the hydraulic model from the operational workflow. The usefulness of this modeling framework is investigated herein for the Onion and Shoal Creeks in Austin, Texas.

3.2 Study Area

To evaluate the usefulness of the RCAFF workflow coupled with the downscaled ECMWF-RAPID runoff forecasts, the 33.7 km^2 Shoal Creek and 546.5 km^2 Onion Creek watersheds were used in this case study (Figure 2). These creeks were selected because of the availability of high resolution LiDAR data, high quality hydraulic models, as well as the high frequency of flooding events experienced on these creeks. LiDAR data from a

2012 survey covering 2810 km^2 of Austin, TX was obtained from Capital Area Council of Governments (CAPCOG). The LiDAR data were used to create 0.3 and 1.5 meter resolution digital elevation models (DEM) for the Shoal Creek and Onion Creek watersheds respectively. The hydraulic models were developed using the Hydraulic Engineering Center-River Analysis Model (HEC-RAS) program by the City of Austin's Watershed Protection Department. Both Shoal Creek and Onion Creek were affected by the 2015 Memorial Day Flood event on May 24-25th.

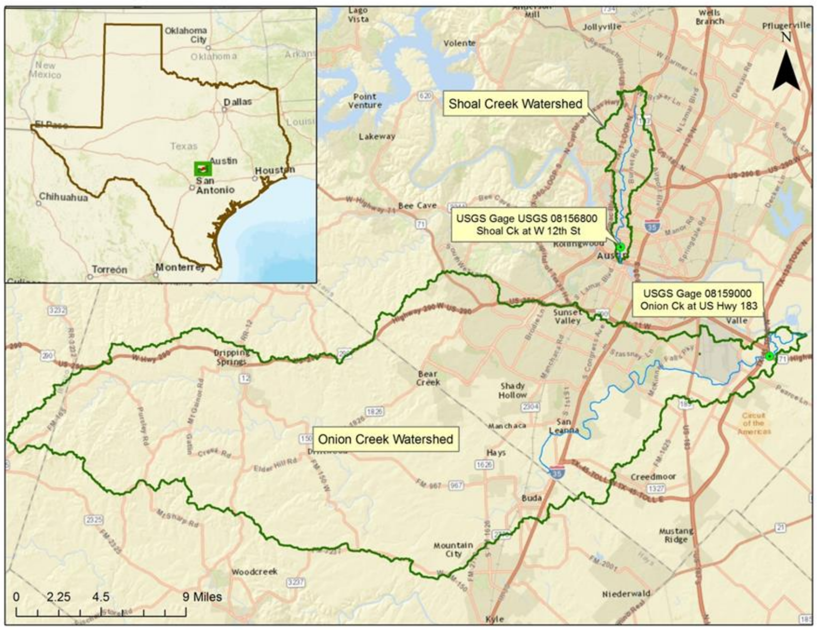


Figure 2: Shoal and Onion Creek Watersheds

3.3 DATA ACCESS

The National Hydrography Dataset PlusV2 (NHDPlus) dataset was released in June 2012 and contains digitation of the watershed features in the United States. The NHD dataset is an integrated dataset containing the most useful features of the National Hydrography Dataset (NHD), the National Elevation Dataset (NED), and the Watershed Boundary Dataset (WBD) represents rivers, streams, reservoirs, damns, and streamgages in a shapefile format compatible with ArcGIS (Mckay et al. 2012). An important aspect of this dataset is the network connectivity. Each reach has a unique common identifier (COMID) linking each reach to a catchment. The reaches also have ToNODE and FromNODE attributes identifying the reaches upstream and downstream (Mckay et al. 2012).

A method was developed for downscaling ECMWF runoff forecasts onto the NHDPlus reach network to produce ensemble streamflow forecasts (Snow 2007). A spatial mismatch is often encountered when assimilating atmospheric and hydrologic data. There is a fundamental difference in the spatial scales used to model atmospheric and hydrologic processes (Liston and Elder 2006). Atmospheric processes are modeled using a regular grid system ranging from 1- 1000 km grid resolution. In contrast, hydrologic processes are modeled using irregularly shaped drainage areas as the “grid elements”, with grid resolution ranging from 1m to 30 m. In order to connect atmospheric and hydrologic modelling processes, the regular grid must be downscaled to the watershed grid. These significant spatial mismatches of the atmospheric and hydrologic modeling framework require the downscaling procedure described below.

Geoprocessing tools were developed to calculate the weighted area of the ECMWF grids overlapping the Catchments. Each time a forecast was received, this weighting table was referenced to compute the incremental runoff volume produced in each catchment (Snow 2007). The cumulative runoff volume forecasts are applied as lateral inflow to the NHDPlus reach network and routed using the Routing for Parallel computation of Discharge (RAPID). The RAPID model routes lateral inflow through the reach network using the Muskingum routing method which has two parameters k, the storage constant, and x, the lag constant.

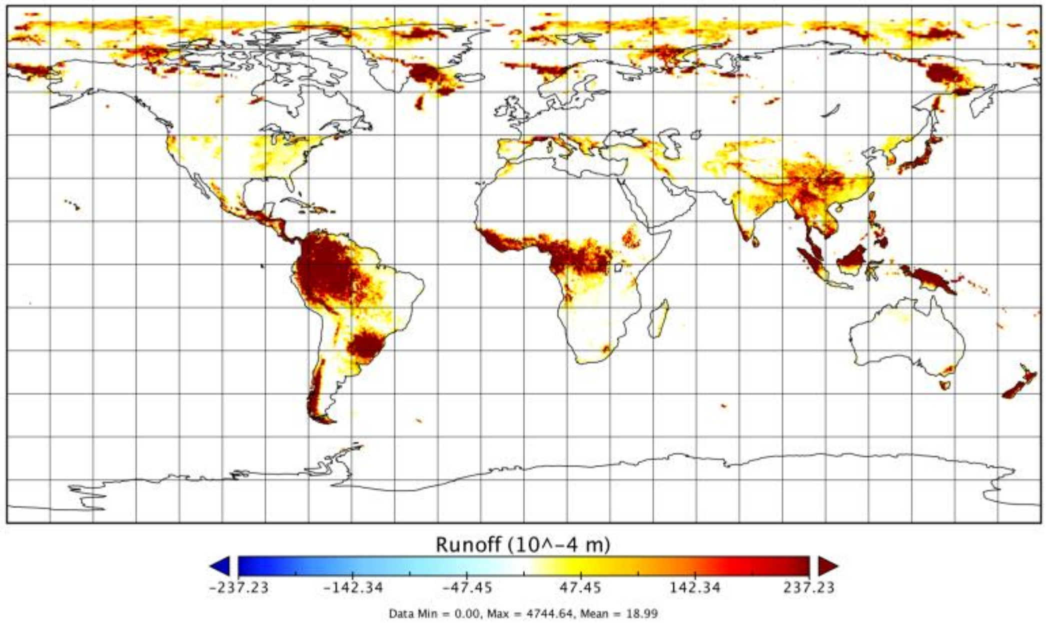


Figure 3: Example ECMWF Runoff Forecast

ECMWF-RAPID outputs for the forecast period May 1, 2015 – July 1, 2015 were used in this study. The forecasts were made available through an integrated Rule-Oriented Data System (iRODS) server at twelve-hour spatial resolution in the NetCDF4 data format. iRODS is an open-source data management software developed by the Renaissance Computing Institute (RENCI) and provides users easy access to large amounts of geographic data.

3.3 Synthesis of ECMWF and City of Austin Hydraulic Models

A Rating Curve Based Automated Flood Forecasting Tool (RCAFF) was developed to translate the ECMWF-RAPID streamflow forecasts into inundation depths and extent forecasts. The RCAFF tool uses open-source software in its workflow, Figure 4, to ensure it is open to all users, and was developed in the C# and python programming environments. The tasks involved in developing this workflow were divided amongst the emergency response team at the NFIE Summer Institute. Caleb Buahin developed the code for the RCAFF tool. Nikhil Sangwan and I were responsible for preparing the models and creating the necessary files for using the RCAFF tool. Curtis Rae built a web application in Tethys, a platform for developing and hosting water resources we applications.

The initial step in the RCAFF workflow involves extracting the rating curves from the HEC-RAS models. However, before this step could take place we needed rating curves at the cross-sections in our Shoal Creek and Onion Creek HEC-RAS models. Nikhil and I led the effort of developing rating curves using a series of steady-state flow simulations that span the expected flows on the modeled reaches. Running the flow scenarios produces rating curves at the 299 and 266 cross-sections in the Shoal Creek and Onion Creek hydraulic models respectively. Following the development of the rating curves, the RCAFF tool could proceed to extract the rating curves and store them in a library look-up table.

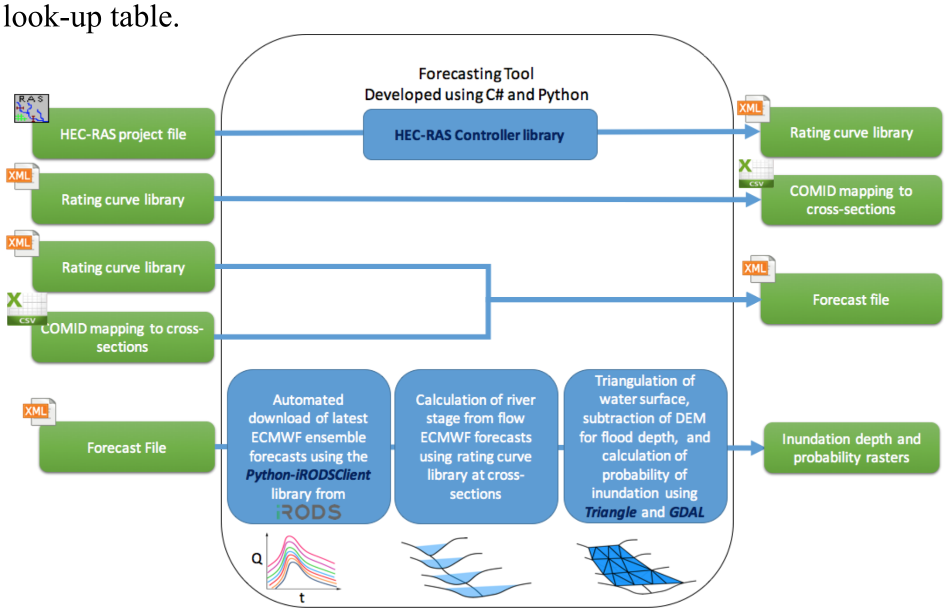


Figure 4: RCAFF workflow

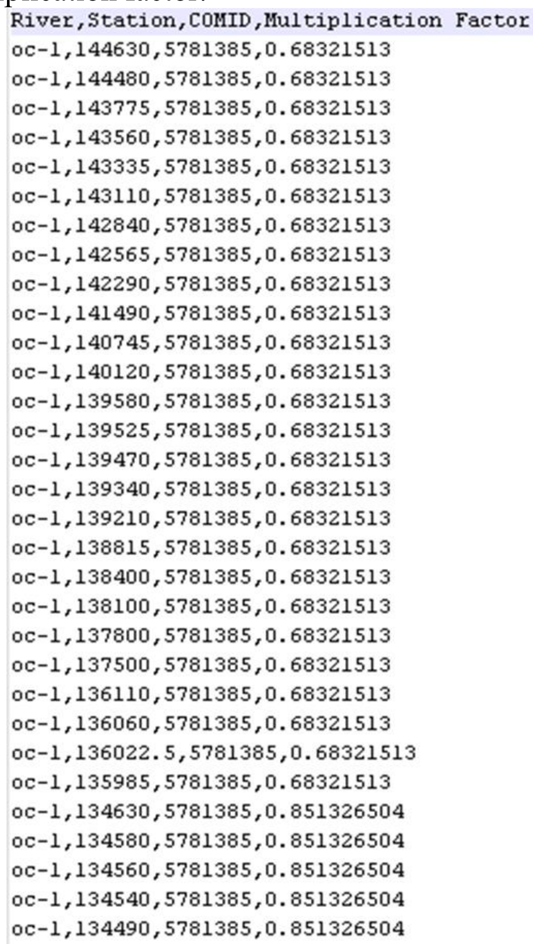
The rating curves from the HEC-RAS model are extracted using the Component Object Model (COM) HECRASController library, a component of the HEC-RAS installation package. Caleb was the lead in this portion of the workflow. Caleb learned how to extract rating curves from the HECRASController library using the application programming interface (API) instructions for the HECRASController library provided by Goodell (2014). RCAFF creates a rating curve library in an eXtensible Markup Language (XML) file format storing the rating curves. By extracting and storing the reach rating curves, the hydraulic model may be removed from the RCAFF operational workflow, reducing the computing power of the workflow. XML format was chosen for the rating curve library, because it is human-readable and thus very convenient to work with. An excerpt from the Onion Creek XML rating curve file is seen in Figure 5.


```
<?xml version="1.0" encoding="utf-8"?>
<HECRASRatingCurve xmlns:xsd="http://www.w3.org/2001/XMLSchema" xmlns:xsi="http://www.w3.org/2001/XMLSchema-
    instance" ProjectFile="Z:\Documents\Projects\NFIE\Modeling\HEC_RAS_Models\Onion_Creek\OnionCreekNFIE.prj">
  <Rivers ItemAlias="RiverReachDictionaryItem" KeyAlias="Key" ValueAlias="Value">
    <RiverReachDictionaryItem>
      <Key>
        <string>onion</string>
      </Key>
      <Value>
        <River Name="onion">
          <Reaches ItemAlias="XSectionDictionaryItem" KeyAlias="Key" ValueAlias="Value">
            <XSectionDictionaryItem>
              <Key>
                <string>oc-1</string>
              </Key>
              <Value>
                <Reach Name="oc-1">
                  <XSections ItemAlias="XSectionDictionaryItem" KeyAlias="Key" ValueAlias="Value">
                    <XSectionDictionaryItem>
                      <Key>
                        <string>144630</string>
                      </Key>
                      <Value>
                        <XSection StationName="144630">
                          <RatingCurve>
                            <FlowStagePair>
                              <Flow>3210.12</Flow>
                              <Stage>621.1117</Stage>
                            </FlowStagePair>
                            <FlowStagePair>
                              <Flow>3611.385</Flow>
                              <Stage>621.4486</Stage>
                            </FlowStagePair>
                            <FlowStagePair>
                              <Flow>4012.65</Flow>
                              <Stage>621.7772</Stage>
                            </FlowStagePair>
```


Figure 5: Excerpt from the XML Rating curve library

Following the creation of the rating curve library, the next step in the workflow is linking the ECMWF-RAPID streamflow network to the reach network used in the rating curve library. The ECMWF-RAPID forecasts produce single value streamflow forecasts on the NHDPlus network, therefore in order to use the rating curve library the flow must be mapped and distributed along the hydraulic model reach. The RCAFF tool creates a comma separated values (CSV) mapping file, seen in Figure 6, which allows the user to specify the COMID of the NHDPlus reach that corresponds to each cross-section in the hydraulic model. The CSV file also contains a multiplier column, where the user specifies the multiplier at each cross-section in order to account for increased runoff as the river accumulates flow moving downstream.

Flow accumulation points were determined by the hydrologic and hydraulic model developers at the City of Austin's (COA) Watershed Protection Department. The hydrologic models for Shoal Creek and Onion Creek divide the respective watersheds into multiple smaller drainage areas called subbasins. The subbasins are selected based on confluence points in the watershed. The COA modelers overlaid the spatial attributes, subbasins and cross-sections, of the hydrologic and hydraulic models to determine the appropriate cross-sections to designate as flow change locations. Typically, the cross-section closest to the centroid of the subbasin is selected, but it is at the modeler's discretion to select the flow change location. The Shoal Creek model has 33 flow change locations, and the Onion Creek model has 30 flow change locations. The peak flows at the subbasin junctions in the hydrologic model are allocated to the appropriate flow change location. The subbasin peak flow is reduced based on the fractional drainage area associate with that flow change location. The specific multiplication factor is calculated by dividing the peak flow at the flow change location by the peak flow at the most downstream location of the watershed. Each time an ECMWF-RAPID forecast is received, the RCAFF tool maps the forecast to the specified model reach and distributes the flow based the multiplication factor.



```
River,Station,COMID,Multiplication Factor
oc-1,144630,5781385,0.68321513
oc-1,144480,5781385,0.68321513
oc-1,143775,5781385,0.68321513
oc-1,143560,5781385,0.68321513
oc-1,143335,5781385,0.68321513
oc-1,143110,5781385,0.68321513
oc-1,142840,5781385,0.68321513
oc-1,142565,5781385,0.68321513
oc-1,142290,5781385,0.68321513
oc-1,141490,5781385,0.68321513
oc-1,140745,5781385,0.68321513
oc-1,140120,5781385,0.68321513
oc-1,139580,5781385,0.68321513
oc-1,139525,5781385,0.68321513
oc-1,139470,5781385,0.68321513
oc-1,139340,5781385,0.68321513
oc-1,139210,5781385,0.68321513
oc-1,138815,5781385,0.68321513
oc-1,138400,5781385,0.68321513
oc-1,138100,5781385,0.68321513
oc-1,137800,5781385,0.68321513
oc-1,137500,5781385,0.68321513
oc-1,136110,5781385,0.68321513
oc-1,136060,5781385,0.68321513
oc-1,136022.5,5781385,0.68321513
oc-1,135985,5781385,0.68321513
oc-1,134630,5781385,0.851326504
oc-1,134580,5781385,0.851326504
oc-1,134560,5781385,0.851326504
oc-1,134540,5781385,0.851326504
oc-1,134490,5781385,0.851326504
```

Figure 6: Excerpt from the COMID Mapping File

Finally, the last step in the RCAFF workflow combines the rating curve library and the COMID mapping file to produce an XML forecast configuration file. The forecast configuration file allows the user to specify the DEM, the COMID mapping file, and the rating curve library that should be used. Additionally, the forecast configuration file is where the user specifies the location of the forecasts and which forecasts should be used. The RCAFF tool automatically downloads the ECMWF-RAPID forecasts from the iRODS server. The streamflow forecasts are connected to the modeled reaches using the COMID mapping file. The streamflow is distributed along the reach, and the rating curve library is used to interpolate the water surface elevation at each cross-section.

The RCAFF tool uses the Geospatial Data Abstraction Library (GDAL) as the geospatial processor to perform the inundation mapping along the modelled reaches. GDAL interpolates, and triangulates the water surface along the reach using the Triangle library. The DEM is subtracted from the triangulated water surface, and where the difference is positive that number is taken to be the water depth. This is depicted in Figure 7. In addition to inundation extent, the RCAFF also produces an output raster displaying the fraction of forecasts prediction inundation for each pixel along the modeled reach. This raster may be interpreted as the probability of inundation, because the ECMWF forecasts are equally likely and come from a distribution representing all possible atmospheric conditions.

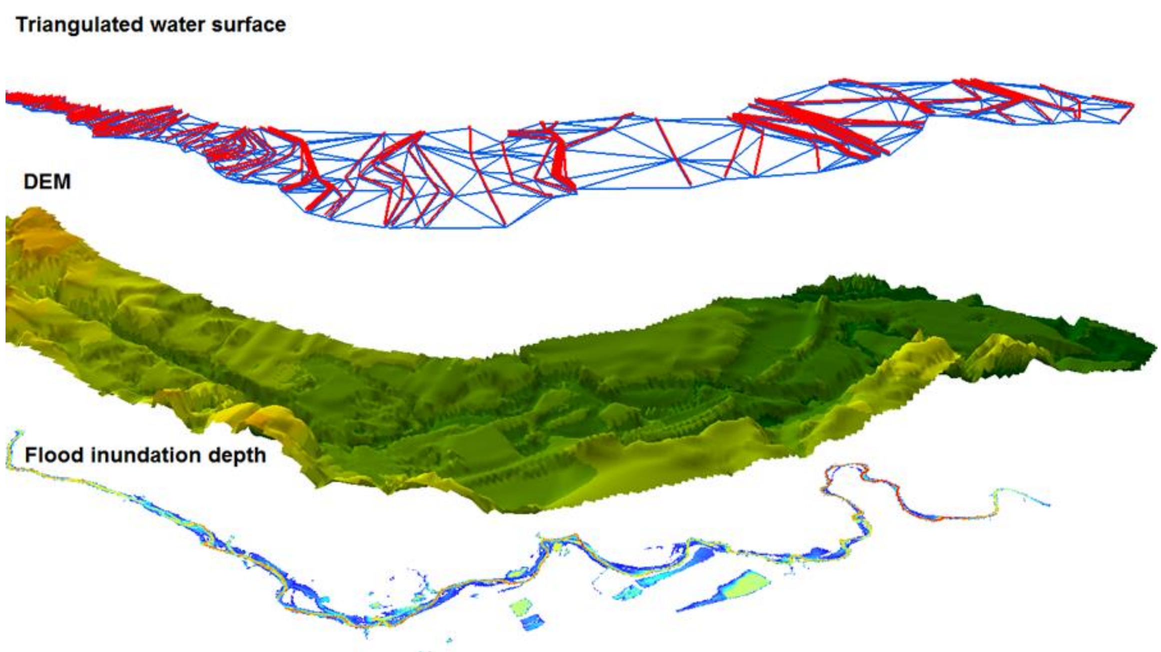


Figure 7: GDAL inundation delineation procedure

A test case was performed for Shoal Creek and Onion Creek in Austin, Texas using the RCAFF tool. The 2015 Memorial Day Flooding event occurring on May 24-25, 2016 in Austin, TX was selected as the test case event. The timing and magnitude of this event took many by surprise, and resulted in significant flood damages and swift water rescues. This test case strived to prove whether the ECMWF-RAPID forecasts coupled with the RCAFF tool could improve flood forecasts by providing accurate forecasts at extended lead times. I lead the effort to prepare the Shoal Creek and Onion Creek models for the RCAFF tool. After obtaining the Shoal Creek and Onion Creek models from the COA, the models were calibrated to peak events using USGS gaged streamflow data. Following this, flow scenarios were developed in each model with flows ranging from 20 m^3/s to the flow associated with their 1% annual chance storm, totaling approximately 50 flow scenarios per model. These flow scenarios were run in a steady-state simulation to develop the rating curves at each cross-section along the modeled reaches. The rating curves produced from these scenarios are such that the stage between each discharge value does not exceed 0.5 m. When a streamflow forecast is received, the RCAFF tool references the rating curve library to interpolate the water surface elevation at each cross-section along the modeled reach. The DEMs used were produced from CAPCOG 2013 LiDAR data, and were 0.3 m and 1.5 m for the Shoal Creek and Onion Creek watersheds respectively.

3.4 Ensemble Forecasts Evaluation Methodology

An assessment was performed to understand the feasibility and usefulness of the EMCWF-RAPID ensemble forecasts coupled with the RCAFF tool. The May 24-25, 2015 Memorial Day flood on Shoal Creek and Onion Creek was selected as the case study event for this assessment. Flash flooding in this event caused significant damage along Shoal Creek and Onion Creek, and caught many people by surprise. The advantage of the ECMWF-RAPID forecasts combined with the RCAFF tool is the extended lead time which has the potential increase the time available to disseminate flood warnings. Three assessments were performed in this study to evaluate the usefulness of this workflow. The first evaluation tests the ability of the forecasts to accurately predict the hydrograph on Shoal Creek and Onion Creek. The second evaluation compares the RCAFF inundation results with the conventional inundation mapping tool. Lastly, a rating curve used in the RCAFF tool is compared with a USGS Gage rating curve to assess the agreement and check for hysteresis.

The first test compared the ECMWF-RAPID streamflow forecasts to the measured flow at the most downstream USGS gage on Shoal Creek and Onion Creek, seen in Figure 8 and Figure 9. Statistics on the ECMWF-RAPID streamflow forecasts are shown in these graphs, rather than all 52 ensembles for simplicity. The ECMWF-RAPID forecasts under predicted the magnitude of flooding on Shoal Creek and Onion Creek. The forecasts were able to predict the timing of the event on Onion Creek, but not on Shoal Creek. In addition to the errors resulting from atmospheric initial/boundary conditions, and model structure, the discrepancies between the USGS measured gage flow and forecasted streamflow may be attributed to the course temporal and spatial resolution of the ECMWF runoff forecasts, and in the downscaling of the runoff forecasts to the NHDPlus Catchments.

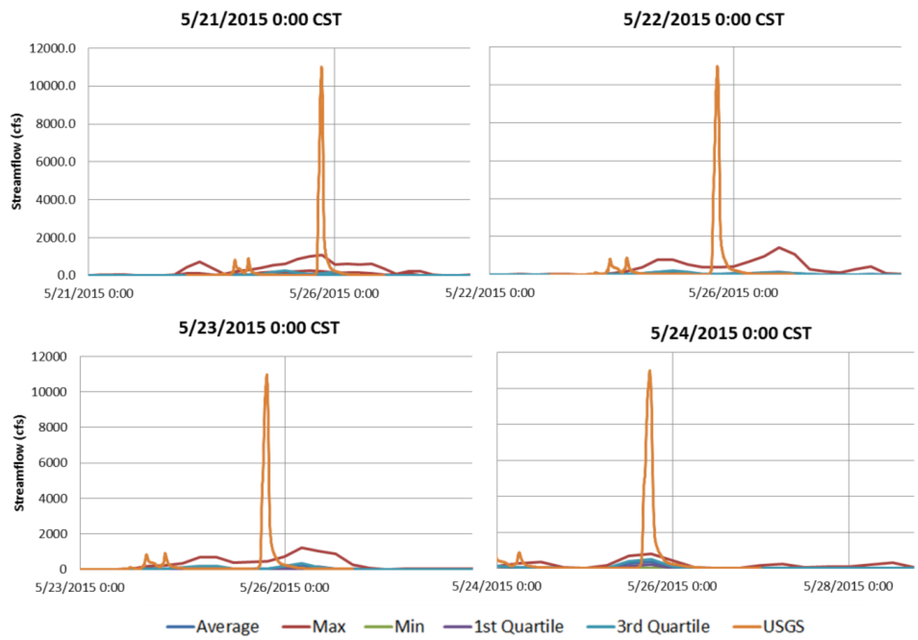


Figure 8: Time series plot of EMCWF-RAPID forecasts versus USGS Gage 08156800 Shoal Creek at 12th Street, Austin. TX

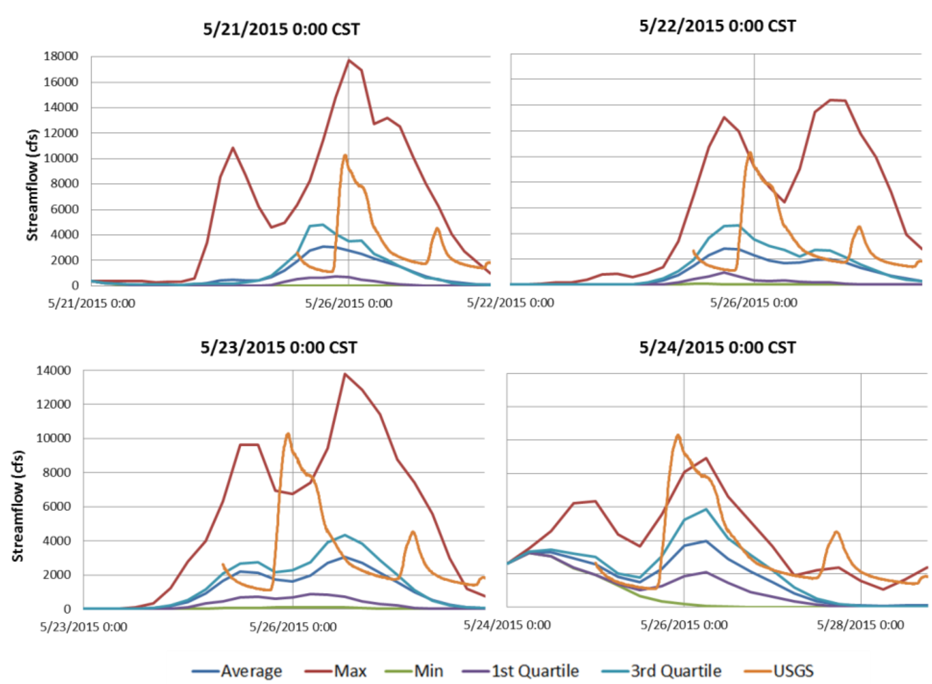


Figure 9: Time series plot of EMCWF-RAPID ensemble streamflow forecasts versus USGS Gage 08159000 Onion Creek at US HWY 183, Austin, TX

The ECMWF-RAPID forecasts were not able to capture the local weather phenomenon occurring in the Shoal Creek watershed. Therefore, for the two remaining portions of the assessment Onion Creek results will only discussed. The second test in the compares the RCAFF inundation results to the results using the conventional HEC-RAS inundation mapping method. The RCAFF and HEC-RAS inundation mapping workflows are very similar; both workflows extract water surface elevation using the cross-section rating curves, triangulate the water surface elevation, and subtract the DEM from the water surface to derive the inundation depth and extent maps. The rating curves and DEM used in the RCAFF and HEC-RAS workflow were identical. Given this, we were expecting the two workflows to produce very similar inundation depth and extent maps. Fitness index was used to compare the agreement between the inundation extents produced by the two methods. A fitness index is defined as the ratio of inundation area commonly predicted by both maps to the union of inundation area predicted by them (Equation 4), and is illustrated in Figure 10. The fitness index, accounts for overestimation of the inundation area, as well as the agreement (Bates and De Roo 2000).

$$Fit(\%) = \frac{FA_a \cap A_b}{FA_a \cap A_b} \times 100 = \frac{A_{ab}}{(A_a + A_b - A_{ab})} \times 100 \quad (4)$$

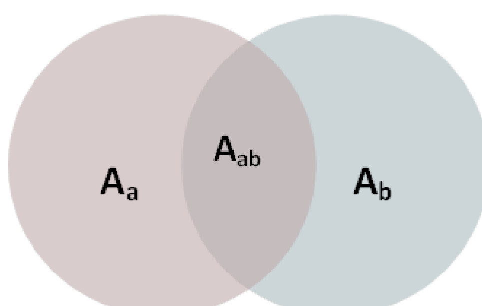


Figure 10: Representation of Fitness Index

The FIT results comparing the inundation extents produced by the RCAFF tool, and HEC-RAS for Onion Creek are presented in Figure 11. The RCAFF has produced an inundation extent that is very similar to the HEC-RAS extent for the peak flow on Onion Creek during the 2015 Memorial Day event. The RCAFF tool was able to produce these results in ~10 minutes, compared to ~130 minutes for the HEC-RAS manual execution. In addition to being slower than the RCAFF tool, it also took multiple attempts successfully complete the inundation map without crashing mid-way through. The final portion of the assessment was the inspection of the rating curves. Figure 12 compares the rating curve produced by the USGS Gage 08159000 and the rating curve derived from the HEC-RAS model. This figure shows agreement between the rating curves for streamflows greater than ~9,000 cfs, which is smaller than the peak streamflow of ~10,000 which was observed for the case study event. The RCAFF rating curve shows no signs of hysteresis.

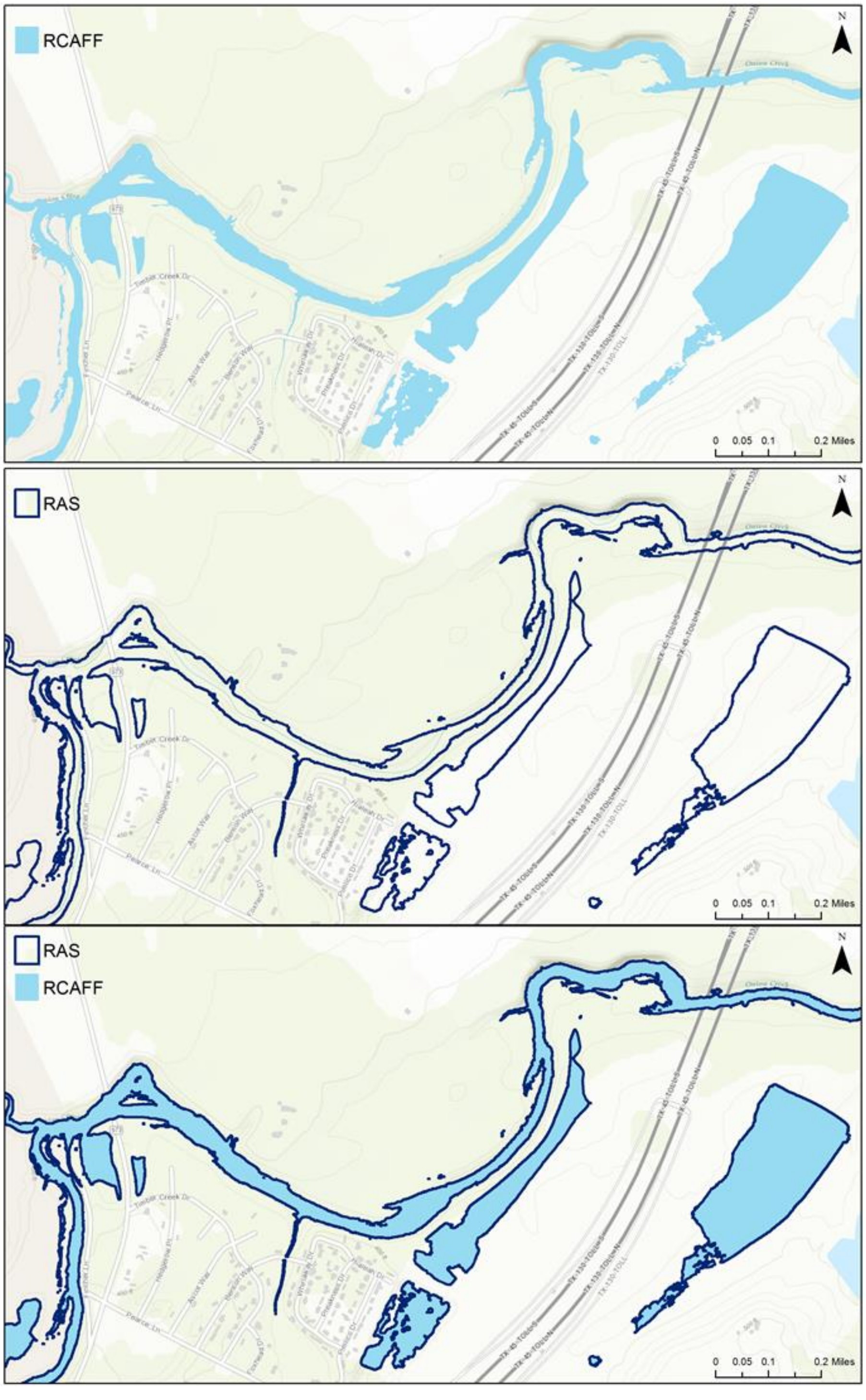


Figure 11: Comparison of Inundation Extents produced for the 2015 Memorial Day Peak Flow on Onion Creek Using the RCAFF tool and HEC-RAS methods

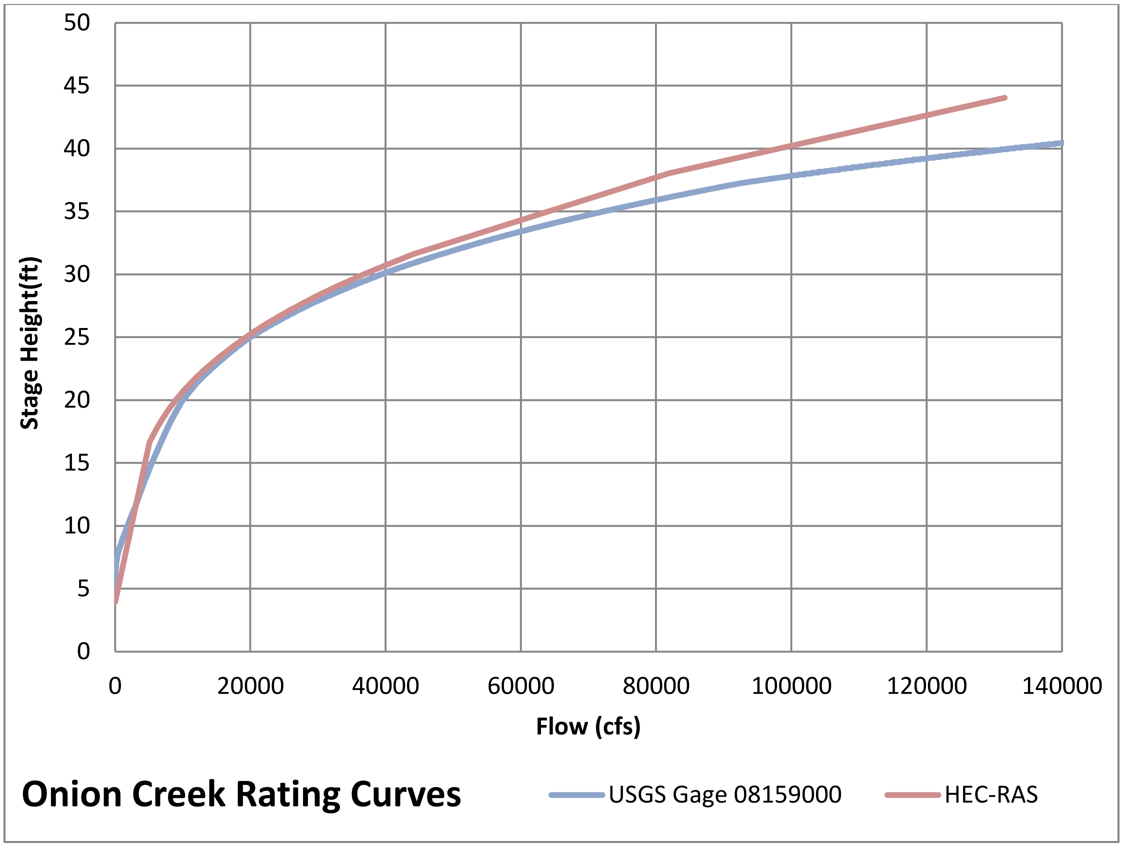


Figure 12: Onion Creek Rating Curve Comparison

Figure 13 shows inundation extent and depth map produced with the RCAFF tool from the EMWF-RAPID ensemble member 47, which predicted the highest streamflow for the 5/26/2015 6:00 A.M. forecast. The probabilistic inundation map for the ECMWF-RAPID 5/26/2015 6:00 A.M. forecast is seen in Figure 14. The RCAFF tool under predicted the water surface elevation, and extent of flooding for this case study event, because the ECMWF-RCAFF forecasts were not able to capture the peak streamflow for Onion Creek.

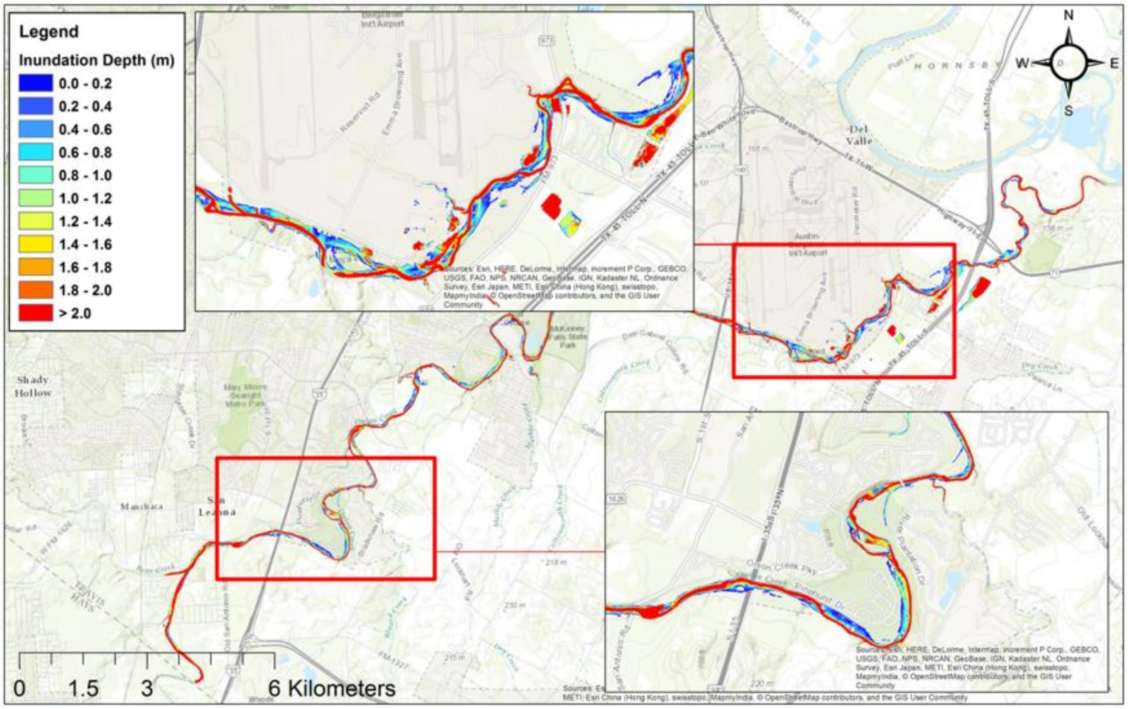


Figure 13: RCAFF inundation depth map for Ensemble 47 for Onion Creek at 5/26/2015 6:00 A.M.

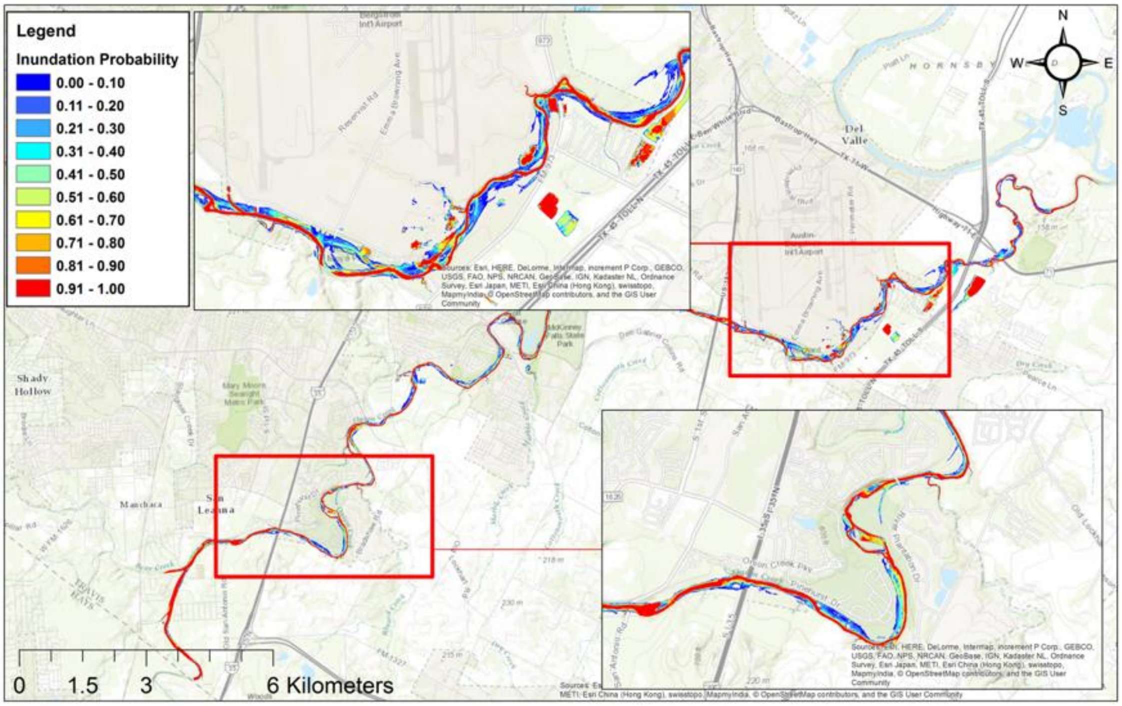


Figure 14: RCAFF inundation probability map for Onion Creek at 5/26/2015 6:00 A.M

Chapter 4: South-Central Texas Flood Map Book

4.1 Overview

The climate and terrain in South-Central Texas make the region susceptible to flash flooding. Urban areas in this region, such as the City of Austin, are even more vulnerable due to the high population density where impervious land cover, and increased runoff rate elevate the flood damages (Looper and Vieux 2012). In order to minimize the public's exposure to flooding hazards, the emergency response community needs factual information regarding the severity of events as well as when and where the event will occur. With this information, the public's exposure to the flood event may be minimized.

NFIE-Response is one of the five components of the NFIE, and focuses on providing emergency responders with tools for wide-area flood planning and response. In a joint effort between The University of Texas at Austin, the City of Austin's Watershed Protection Department, and the Austin Fire Department a flood map book has been developed, with emergency responders being the design user. The map book contains pre-planning and operational flood maps for high priority reaches in Travis County and Williamson County, TX. A schematic of the types of maps included in the flood map book may be seen in Figure 15. These maps are meant to support the planning and operation phases of emergency response. Travis and Williamson County, TX were selected in this study because they are both susceptible to flooding events, have detailed models and high quality terrain data, and are diverse communities. Two counties were included study to ensure a broad spectrum of stakeholders was involved in the development and vetting phases of the flood map book. The overarching goal of this study is to provide a refined flood map template that may be used as a guide for other municipalities to develop their own flood map book.

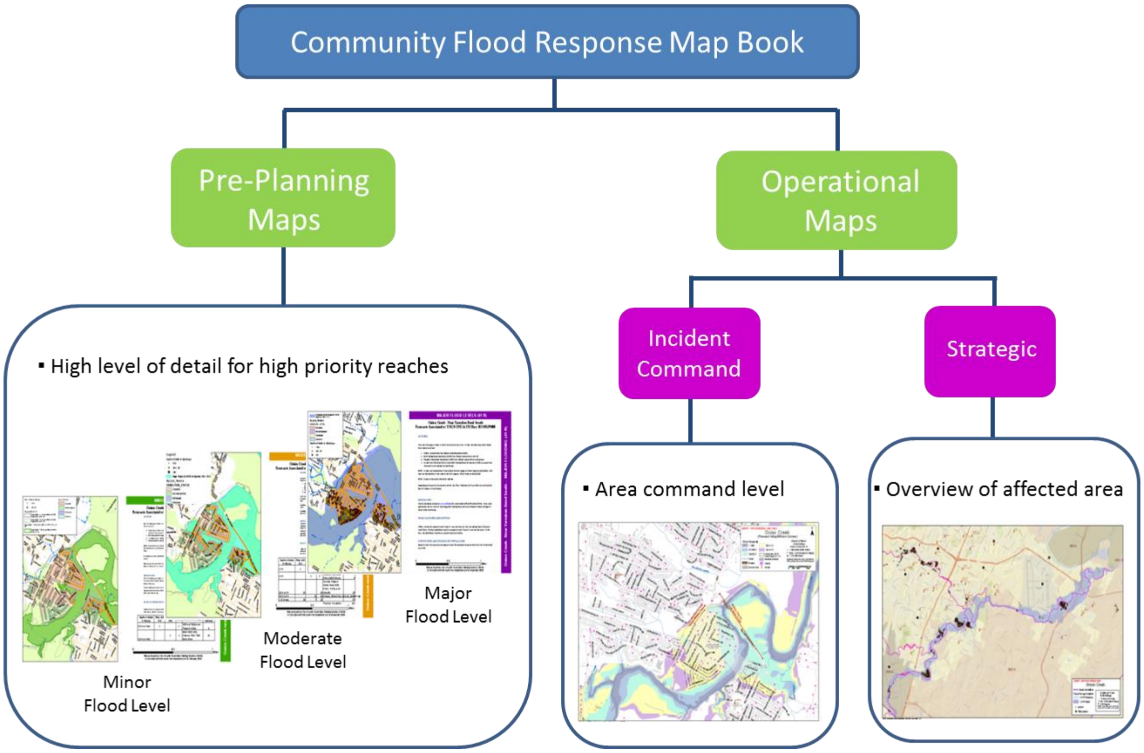


Figure 15: Community Flood Map Book

4.2 Pre-Planning Maps

Prior to a flooding event, it is vital for the emergency response community to understand the rivers that pose significant flood risks to the public. More specifically, emergency responders need to know the communities and roadways that will be affected. When provided this information, emergency responders can be more strategic about allocating resources, deciding between sheltering in place or ordering an evacuation, and prioritizing rescues. Pre-planning maps have been developed for four high priority reaches in Travis County, TX, and for one high priority reach in Williamson County, TX. The high priority reaches are divided into various sections that are featured in the pre-planning maps. The maps are zoomed into these sections to provide a high level of detail regarding the structures and roadways that may flood.

Figure 16 is the index page for Middle Williamson Creek. This map is a layout showing the three featured section along Middle Williamson Creek in Travis County. Each section of reach contains three maps with layers corresponding to the minor, moderate, and major flood levels at the representative gage. The National Weather Service uses the minor, moderate, and major flood level terms to describe the severity of flood impacts along a particular reach (NWS 2012). As defined by the NWS, minor flood levels corresponds to minimal or no property damage, but is possibly threatening to the public (NWS 2012). Moderate flood levels cause some inundation of property and structures that are in close proximity to the river, and may require evacuations. Major flood levels cause extensive damage of structures, property, and roadways, and significant evacuations may be necessary. The minor, moderate, and major flood inundation extents are linked to water stage at a representative gage along the river. The reaches featured in the flood map book contain at least one USGS or COA Flood Early Warning System (FEWS) water level gage with established NWS flood categories that are used as indicators of flood levels. The minor, moderate, and major flood maps for Middle Williamson Creek near Heartwood Drive are seen in Figures 17- 19 respectively.

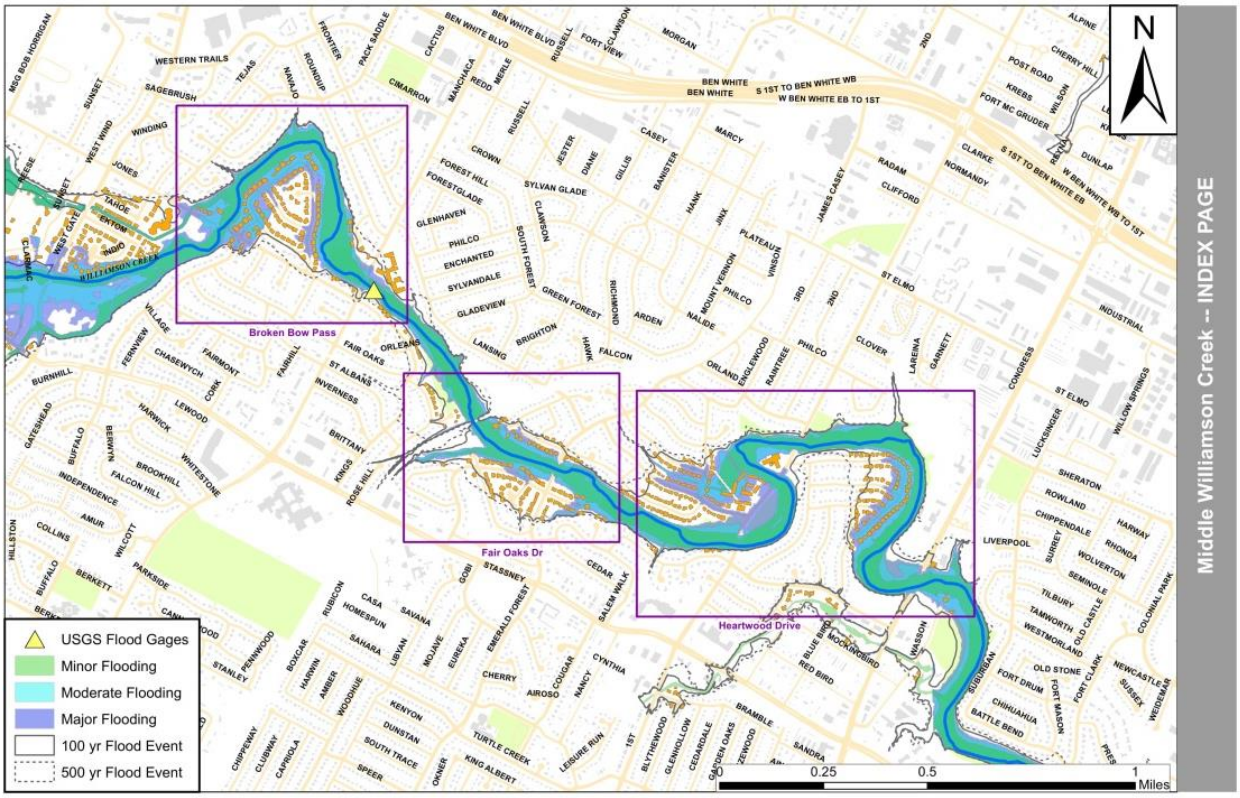


Figure 16: Middle Williamson Creek Flood Map Index Page

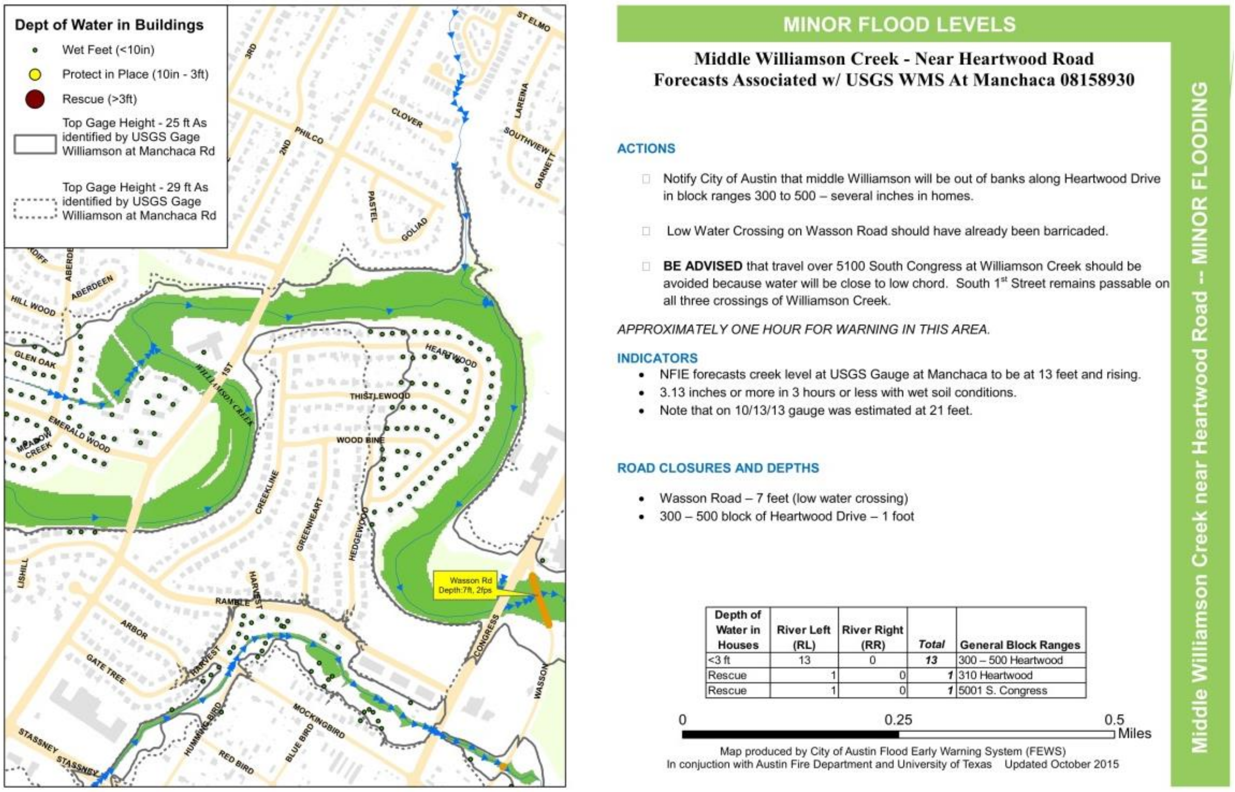


Figure 17: Minor Flood Level map for Onion Creek near William Cannon Drive

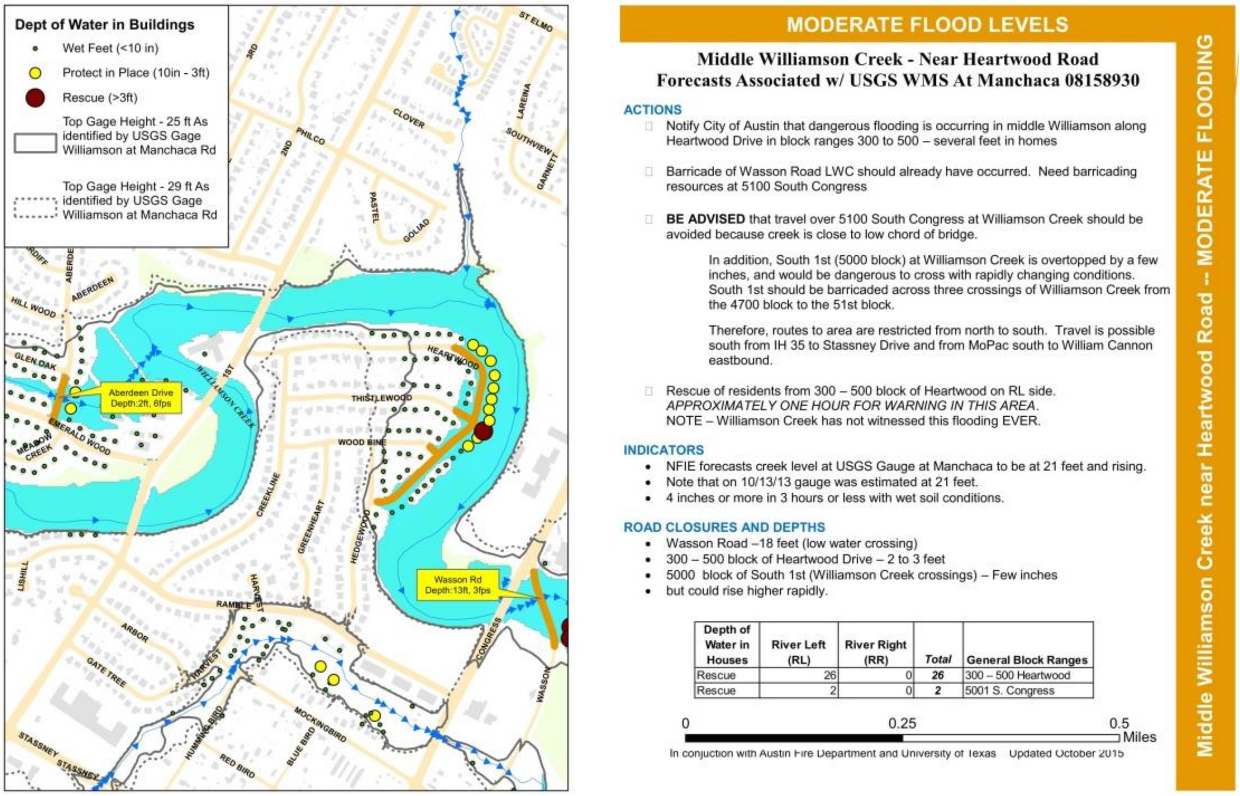


Figure 18: Moderate Flood Level map for Onion Creek near William Cannon Drive

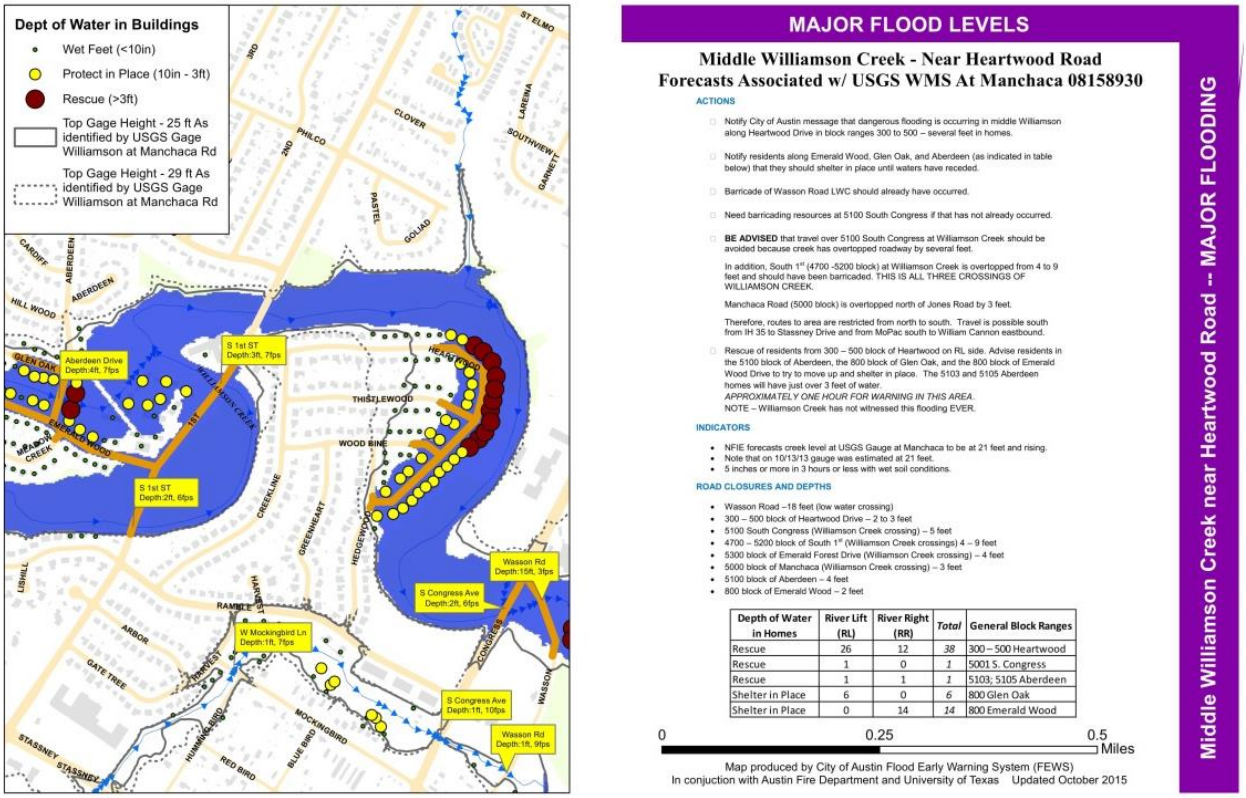


Figure 19: Major Flood Level map for Onion Creek near William Cannon Drive

The minor, moderate, and major pre-planning flood maps contain a mapping component and text component. The map displays the spatial extent of inundation, the depth of flooding in structures, depth and velocity of flooding on roadways, as well as historic inundation extent markers. Much of the data included in the maps came from highly detailed HEC-RAS models developed by the COA's Watershed Protection Department. Flow scenarios were created in the hydraulic model to estimate the water surface elevation resulting from the minor, moderate and major flood levels. Bridges, culverts, and low water crossings are included as cross-sections in the hydraulic model. The water depth and velocity of the roadway at these locations was extracted from the model for the minor, moderate and major flood levels.

The inundation extents for these flood levels were developed using very detailed HEC-RAS hydraulic models. The COA performed a survey to collect the base elevations of structures in the city. This elevation was compared to the water surface elevation for the three flood levels. At structures where the water surface elevation was found to be greater than the base elevation, the difference was calculated. This difference is the depth of structure flooding resulting from the minor, moderate, or major flood levels.

The text component in these maps is divided into four sections: actions, indicators, road closures and depths, and depth of water in homes. Descriptions of these components are found below in Table 1. The actions section of the pre-planning maps provides emergency responders with the task list of specific sections of roadways that will need to be closed. This information is derived from the hydraulic model and is confirmed from local knowledge. The flood map book has provided a means of communication between two communities that may only meet during flooding emergencies.

The indicators section describe the gage water stage, or forecasts that will produce the minor, moderate, or major flood levels on the specific reach segment. Local high water marks used as indicators by emergency responders were also included in some of the maps. The depth and extent of flooding on roadways is described in the road closures and water depth section. This sections lists the address blocks where roadways flood, helping emergency responders to decide where barricades should be placed prior to flooding. Additionally, this informs emergency responders about for ingress and egress transportation routes for evacuations and rescue operations. A table provides a summary of the depth of water in address blocks, the number of affected homes located river left and river right, as well as an estimate of the population in the homes.

Term	Definition	Example for a Minor Flood Level on Williamson Creek - Near Heartwood Road
Action	A task that should be completed once a minor, moderate or major flood level has been reached	Notify City of Austin that middle Williamson will be out of banks along Heartwood Drive in block ranges 300 to 500- several inches of water in homes.
Indicator	An established benchmark that is used to determine flood severity	National Water Model forecasts stage at USGS Gage 08158930 at Manchaca to be at 13 feet and rising.
Road Closure and Depth	Recommended locations for barricading roadways, and the depth of water associated with the closed road for a minor, moderate, or major flood level	Blocks 300 to 500 of Heartwood Drive should be closed - 1 ft of water on road.
Depth of Water in Home	Modeled water depths in homes home as a result of a minor, moderate, or major flood level	Greater than 3ft of water at 5001 S. Congress, located river left. Rescue may be necessary.

Table 1: Description of the Pre-planning map text components

These pre-planning maps are meant to be studied prior to a flooding event. Emergency responders may study these maps to familiarize themselves with high risk areas, and perhaps even drive the streets included in the map. These maps would be especially useful for emergency responders who are unfamiliar with the high risk flooding areas in Travis or Williamson County. These maps may also be used for routine training purposes or tabletop exercises where emergency responders review emergency operations. The minor, moderate and major flood levels may be used in progression, as a flood increases in severity.

Here I will step through a use case scenario using the Pre-planning flood maps for Middle Williamson Creek near Heartwood Road. During a training session, emergency responders may be told to use these maps to run through a flood scenario on Williamson Creek. The flood scenario on Williamson Creek will progress from minor to moderate to major flood level, and emergency responders will simulate their response efforts. The indicator or representative gage for this location is the USGS Gage 08158930 Williamson Creek at Manchaca Road, Austin, TX.

Once the minor flood level is predicted or has been reached, emergency responders follow the prescribed list of actions on the minor flood level map, seen in Figure 17. For the minor flood level on Middle Williamson Creek near Heartwood Road, these actions include a notifying the COA of that the minor flood level has been reached and the barricading of Wasson Road. The map display, and text describe the location of the structures and roadways that may be affected by minor flood levels. Based on this map 15 homes will be affected by minor flood levels on Williamson Creek, and two roadways will be impassible. This information supports emergency responders in deciding where to allocate resources, and how many resources are necessary.

In the scenario, the flooding worsens reaching moderate flood level based on the representative gage. At this point emergency responders move switch to the moderate flood level map. At this flood level additional actions will need to be carried out. This includes notifying the COA that the structures in block ranges 300-500 on Heartwood Drive have several feet of water in them, and will need to be rescued. As seen in Figure 18, a total of 26 structures will be severely affected by the moderate flood levels. Emergency responders will use this to estimate the resources needed to support this event. If they decided their resources are not adequate to support the event, emergency responders will brainstorm neighboring emergency response communities they may contact to borrow resources such as rescue personnel, and swift water rescue equipment.

The flood level transitions from moderate to major when the river stage reaches or is forecasted to reach 21ft at the representative gage. This is the most severe level of flooding that is included in the flood map book. As seen in Figure 19, a large population, approximately 60 structures, will be impacted by this event. The map symbology displays the depth of water in buildings ranging from less than 10in to greater than 3ft. This information may be used by emergency responders to prioritize rescues, by first rescuing residents in homes that have greater than 3ft of flooding. At the major flood level there is a long list of road closures. The map provides water depth and velocity at major intersections in the area. Water depth and velocity are useful for determining whether a high clearance response vehicle will be able to navigate through. Proactively developing alternate routes of ingress and egress to facilitate rescues will reduce the response time during a real flooding emergency. Understanding the impacts of a wide-area flooding emergency is a key component to providing effective emergency response. The pre-planning maps outline these impacts, and provide actions that may reduce the public's exposure to the flood hazard.

4.3 Operational Maps

In addition to the pre-planning maps, operational maps intended for use during a flood emergency have been developed as a part of the flood map book. These maps are at a lower resolution than the pre-planning maps to display a larger scope of the flooding event. Two types of operational maps have been developed in the flood map book: Incident Command and Strategic Planning maps. The Incident command map displays the flooding events at an area command level, seen in Figure 20. There are several area commands per reach, and each is responsible for assigning units and allocating resources during a flooding emergency. These maps are a scale that will allow area commanders to understand the scope of the emergency and log where resources are being assigned, where rescue personal are needed, and future areas of focus. The incident command map displays various data, including flooding extents, building footprints, depth of water in structures, and shelters. The data included in these maps are derived from hydraulic models, survey data, and local knowledge from emergency responders.

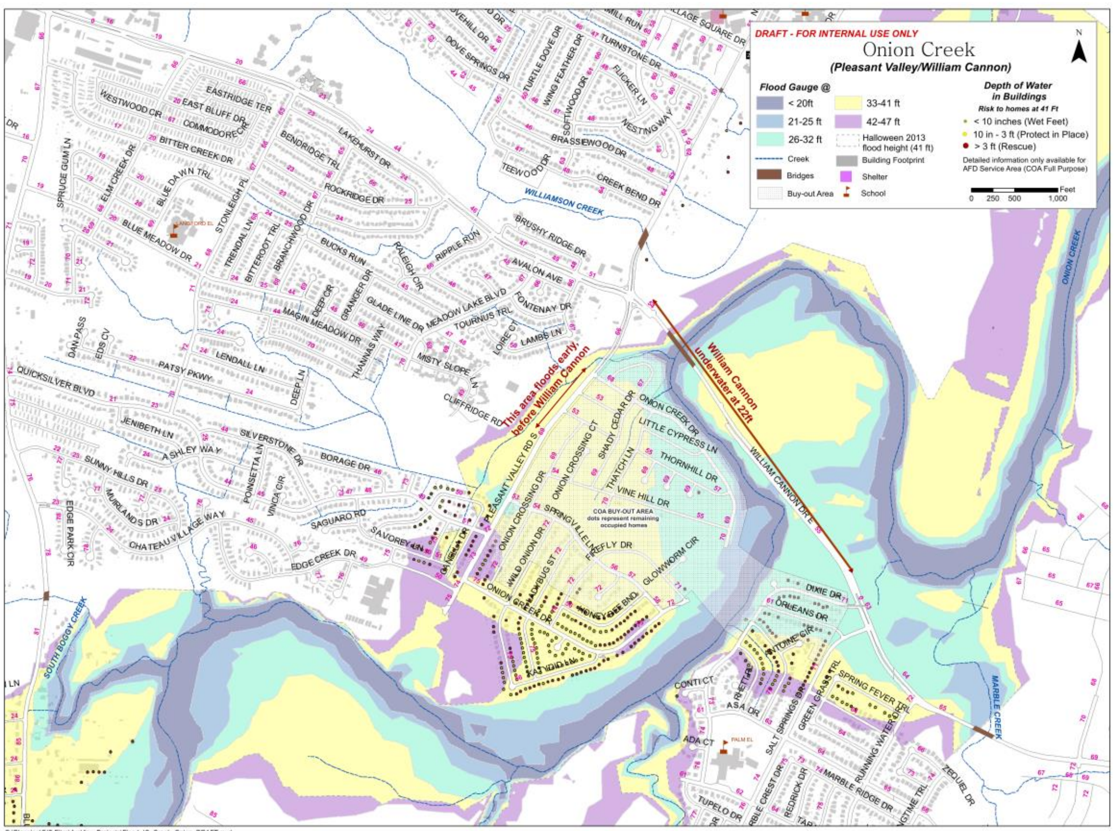


Figure 20: Incident Command Map for Onion Creek near Pleasant Valley and William Cannon

The strategic map, seen in Figure 21, provides an over view of the entire area affected by the flooding event. This map will be used at the Emergency Operations Center (EOC) to organize several area commands and groups of resources. Although at a larger scale and less detailed than the pre-planning and incident command maps, the strategic maps are a key piece in understanding the scope of the flooding event. The strategic maps include inundation extents, structure flood depths, and shelters. These data have also been obtained through surveys and from hydraulic models. A cluster of structures on the map indicate that many structures may be affected by flooding, and will need to be supported during an event. The number of structure clusters will help emergency responders determine the resources that will be necessary during a flooding emergency.

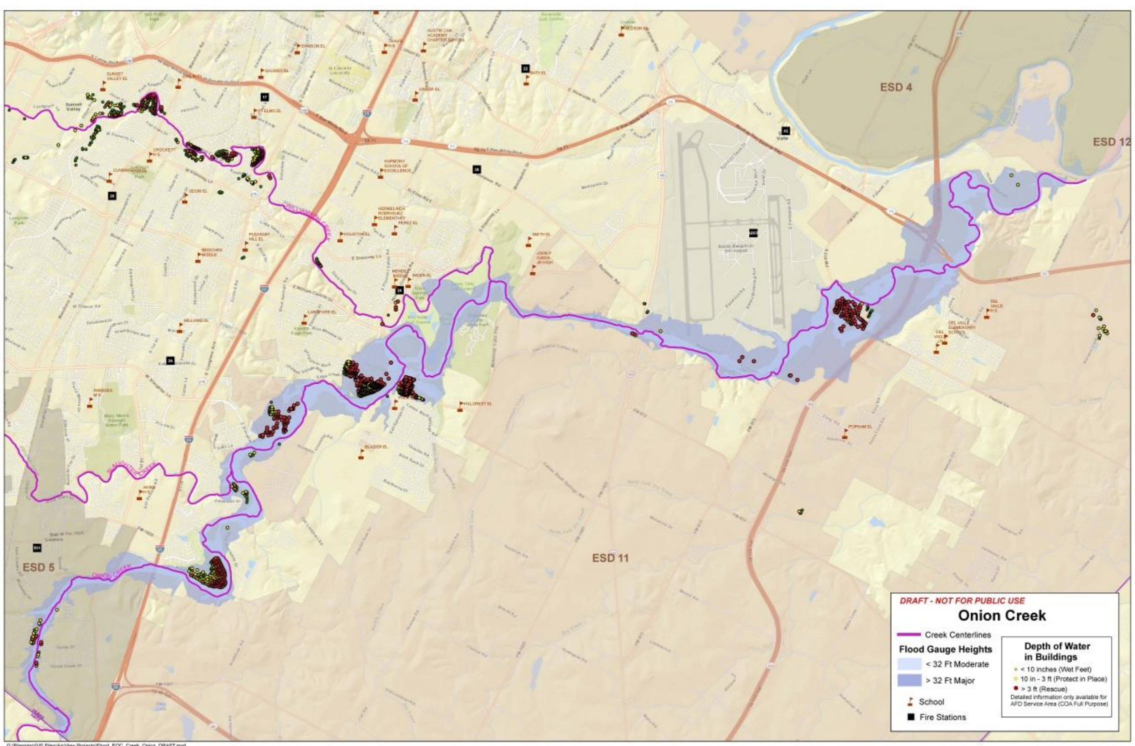


Figure 21: Strategic Planning Map for Onion Creek

4.4 Flood Map Book Results

A significant effort has been made to develop the flood map book for high priority reaches in Travis County and Williamson County. The flood maps for these counties are meant to be used as a template for other counties to use to develop their own flood map books. In order for the map book to be a successful template, it must be a useful and informative product for any emergency response community. To ensure this, a multitude of emergency response experts have been included in the evolution of the flood map book. The project was divided into three phases: development, revision, and implementation phases. As we moved through the steps, additional members of the emergency response community were incorporated in the review process.

During the flood map book development phase, the University of Texas at Austin, COA Watershed Protection Department and the Austin Fire Department (AFD) were the main stakeholders involved. This initial phase focused determining the type of maps that should be included and the map layout. Out of this phase came the decision to include pre-planning and strategic maps for the flood map book. The pre-planning maps are used by the emergency response community for "sunny day" training sessions. Emergency responders may study the maps to understand the possible effects of a flooding event. It is encouraged that they also drive to the areas included in the map book to also visualize the roads and communities that are at risk. The operational maps are designed to be used during flooding events. The flood map book presents two types of operational maps: incident command and strategic. The incident command maps display data at the area command level, and provide situational awareness to emergency responders. The strategic maps display an overview of the entire affected area, and are used at the EOC to keep track of several area commands and groups of units.

As the maps evolved we transitioned into the review phase and began including more stakeholders. The goal of the review phase was to refine the data included in the maps to ensure it was useful and informative for emergency responders. The review phase consisted of meetings with stakeholders, a flood symposium, and a table top exercise. Members of the emergency response community were invited to the 2016 Flood Symposium, hosted at the 2016 ESRI Austin Water Conference. Emergency managers, fire firefighters, police officers, and hydrologists from Travis and Williamson County reviewed the flood map book and provided feedback on the data and layout of the maps. The flood symposium provided a way for various agencies to interact, communicate, and infuse local knowledge into the flood map book. During the map critique a police chief pointed out that our pre-planning maps were not capturing the flooding occurring on a tributary to Onion Creek. The tributary was not included in the COA's hydraulic model that was used to create the inundation extents and depths found on the maps. The police chief also described a high-water mark that is used on a highway along Onion Creek that is used as a flooding indicator. The flood symposium provided an opportunity for local knowledge and unconventional data sources to be incorporated into the maps, and also for feedback on the map presentation. These local pieces of knowledge brought forward in the symposium were later incorporated into the pre-planning flood maps.

In the final step in the review phase, a table-top exercise was executed to simulate the usefulness of the maps in a flooding emergency. Members of the COA Fire Department were the main participants, and the table top exercise simulated a flooding event along Onion Creek, in Austin, TX. Similar to in a real-world flooding event, participants were gradually given updates and information on the progression of the event. As the water levels along Onion Creek rose in the simulation, participants were asked to make decisions about where/when to allocated resources and begin rescues using the operational flood maps. The participants found the flood maps useful for understanding the communities at risk, and for organizing units and other resources.

The flood map book has proved successful in bridging the gap between the flood data and emergency response. Emergency responders have been involved in every step of this project to ensure the maps are useful and informative to them during flooding emergencies. In addition to bridging the information gap, the flood map book collaboration has strengthened the relationship between the COA Watershed Protection Department, and AFD. Prior to this flood map book project, the COA Watershed Protection Department and AFD met rarely outside of emergency situations. These agencies are responsible for coordination flood emergency response in the City of Austin. The flood map book provided a way for these agencies to collaborate, and build trust outside of a flooding emergency. Maintaining these strong cross-agency relationship is a key step in building resilient communities (Cutter 2006). Another positive outcome of this project is that is provided an inlet for local knowledge to be included. This local knowledge is data that the emergency response community has gained through flood experiences, and may not be reflected in the data obtained from the hydraulic models. This includes flooding on tributaries that are not modeled, as well as high water marks that are used as indicators.

Chapter 5: Conclusions

Progress has been made in recent years in flood forecasting. With the release of the National Water Model in June 2016, the NWS will switch from forecasting at 3600 locations to producing hourly forecasts at 2.7 million locations across the CONUS on the NHDPlus Network. In addition to increasing forecasting spatial and temporal density, flood forecasting systems are moving towards the use of ensemble prediction systems to increase forecast lead time and incorporate uncertainty into the forecasts. These forecasting systems will provide more information to emergency responders in the wake of flooding events. However, in order to be useful for emergency responders the data must be conveyed in a clear and informative way. This thesis presents methods of connecting flood data to fill the gap between continental flood forecasting and local emergency response.

This study evaluated the benefits and feasibility of using ECMWF-RAPID ensemble streamflow forecasts for predicting the 2015 Memorial Day Floods on Shoal and Onion Creek, in Austin, TX. The 2015 Memorial Day flood was still very fresh in the public's mind while this work was being done at the 2015 NFIE Summer Institute, which is why it was selected as the case study event. The availability of highly detailed hydraulic models and high resolution terrain data, and frequency of flooding in these watersheds made Shoal Creek and Onion Creek an ideal location for a case study. The Rating Curve Based Automated Flood Forecasting (RCAFF) tool developed herein provides a methodology for connecting EPS to flood forecasting, addressing the computational intensity and scale issues associated with EPS.

By limiting the spatial and temporal domain of the forecasts, the RCAFF tool was able to efficiently produce inundation extent and depth forecasts for the 51 ECMWF ensembles. The rating curve approach and use of an open-source geospatial mapping library contributed to the RCAFF tool efficiency. The inundation extent and depth rasters produced using the RCAFF tool and the conventional HEC-RAS mapping for the peak flow along Onion Creek were compared using the fitness index. The results of the comparison were a 96% fitness index, and a 0.06m average inundation depth difference between the two methods. These findings show that these two workflows produce very similar results.

Based on our results it is clear that the EPS runoff forecasts, the downscaling process translating runoff from the coarse grid to the catchment network, and the RAPID routing scheme have the largest impact on the RCAFF tool results. The majority of the ECMWF-RAPID ensemble forecasts under predicted the streamflow for the Memorial Day Flood event on Shoal Creek and Onion Creek, which is believed to be the main reason the RCAFF tool under predicted the inundation depth for this event. Atmospheric uncertainty is considered the largest contributor to uncertainty for streamflow forecasting (Cloke and Pappenberger 2009), and is included in the ECMWF runoff forecasts. However, there are additional uncertainties not accounted for in this workflow including the downscaling of the runoff forecasts, RAPID routing parameters, hydraulic model parameters, and the interpolation methods used to transform streamflow forecasts into inundation extents and depths. Accounting for uncertainties in the areas discussed above, may improve the accuracy of the RCADD tool results.

The goal of the flood map book project is to connect flood forecasting data to actionable information for emergency responders. This project is collaboration between the University of Texas at Austin, the City of Austin's Watershed Protection Department, and the Austin Fire Department. Pre-planning and Operational flood maps were developed in this project. The flood maps contain a great deal of data obtained from highly detailed hydraulic models, surveys, and local knowledge. The process of distilling this data into concise and easily interpreted information took many rounds of revisions. The project was divided into three phases: development, review, and implementation. The types of maps to be included in the flood map book as well as the map layouts were selected in the development phase. The pre-planning maps are at a very high resolution, and convey very detailed structure and roadway information. The operational maps include both incident command, and strategic maps. These maps convey pertinent flood information while displaying a larger portion of the affected area. The review phase involved meetings, a symposium, and a table-top exercise in an effort to include as many stakeholders into the project. The maps are meant to include a great deal of information; however we wanted to strike a balance and ensure they are easily understood and interpreted especially during stressful circumstances. By including a large group of stakeholders we obtained a spectrum of ideas and critiques that have improved the map template.

Currently, the flood map book is ready for the implementation phase. The implantation phase will trial the flood map book in the Emergency Operations Center (EOC), at Fire houses, and on Fire Trucks in Travis County. There, emergency responders will have the opportunity to use the flood maps in routine training exercises, and during real flooding emergencies. Following this trial period, the emergency responders will provide feedback on the usefulness of the maps and improvements that could be made. Once this implementation phase is complete, the flood map book template will be available to other municipalities to develop their own local flood map book. Based on the interactions with the emergency response community in Austin, TX these maps are going to be very useful for improving flood response. The flood map is readily available in times of emergency, and also prior to emergencies. The emergency response community is encouraged to become familiar with the maps, but the maps are also meant be useful for first time users. The benefit of developing these maps prior to a flooding event is that the GIS staff will not be forced to develop response maps during an emergency. In addition to being readily available, the flood map book has gone through rounds of revisions to ensure the data presented in the maps is informative, concise, and easily interpreted.

With the release of the National Water Model in June 2016, hourly streamflow forecasts will be available at 2.7million locations in the CONUS. This is a major densification of forecasting locations, with the current NWS model is produces forecasts at 3600 locations across the CONUS. The National Water Model forecasts will significantly increase the amount of streamflow forecasts available to local emergency response communities. However, these streamflow data will not tell emergency responders all the information they will need to respond to flooding emergencies. The emergency response community will also need tools to tell them where the water will go, and the communities and roadways that will be affected. The two studies presented in this thesis work together to connect large-scale streamflow forecasts to local emergency response communities. The first study presented, translates streamflow forecasts into inundation extent and depths maps. These maps show emergency responders the areas that will be affected by a flood. An ensemble forecasting system was used in this study which allowed us assign probabilities to the forecasts, and produce probabilistic inundation maps. The products of the RCAFF tool are the building blocks for the flood map book operational and pre-planning maps discussed in this thesis. The pre-planning maps use inundation and extent maps, coupled with address points, and the transportation network to provide emergency responders with comprehensive view of the flooding emergency.

Appendix: List of Acronyms

AFD	Austin Fire Department
AHPS	Advanced Hydrologic Prediction System
COA	City of Austin
COMID	Common Identifier
CONUS	Continental United States
CSV	Comma Separated Values
CUAHSI	Consortium of Universities for the Advancement of Hydrologic Science, Inc.
DEM	Digital Elevation Model
ECMWF	European Centre for Medium-Range Weather Forecasts
EOC	Emergency Operations Center
EPS	Ensemble Prediction System
GDAL	Geospatial Data Abstraction Library
GIS	Geographic Information System
HEC-RAS	Hydrologic Engineering Centers River Analysis System
HEPS	Hydrologic Ensemble Prediction System
iRODS	integrated Rule-Oriented Data System
LiDAR	Light Detecting and Ranging
NED	National Elevation Dataset
NFIE	National Flood Interoperability Experiment
NHD	National Hydrography Dataset

NHDPlus	National Hydrography Dataset PlusV2
NWP	Numerical Weather Prediction
NWS	National Weather Service
RAPID	Routing for Parallel computatIon of Discharge
RCAFF	Rating Curve Based Automated Flood Forecasting
RENCI	Renaissance Computing Institute
USGS	United States Geological Survey
WBD	Watershed Boundary Dataset
XML	eXtensible Markup Language

Bibliography

Ashley, Sharon T., and Walker S. Ashley. 2008. "Flood Fatalities in the United States." *Journal of Applied Meteorology and Climatology* 47 (3): 805–18. doi:10.1175/2007JAMC1611.1.

Bailey, James F., and Herman A. Ray. 1966. *Definition of Stage-Discharge Relation in Natural Channels by Step-Backwater Analysis*. US Government Printing Office. http://pubs.usgs.gov/wsp/1869a/report.pdf.

Baker, Victor. 1975. "BalconesFault.pdf." Bureau of Economic Geology.

Bates, Paul D., and A. P. J. De Roo. 2000. "A Simple Raster-Based Model for Flood Inundation Simulation." *Journal of Hydrology* 236 (1): 54–77.

Beven, K. 2009. *Environmental Modelling : An Uncertain Future?* London ; New York: Routledge.

Borga, M., E.N. Anagnostou, G. Blöschl, and J.-D. Creutin. 2011. "Flash Flood Forecasting, Warning and Risk Management: The HYDRATE Project." *Environmental Science & Policy* 14 (7): 834–44. doi:10.1016/j.envsci.2011.05.017.

Braca, Giovanni, and Grafiche Futura. 2008. *Stage-Discharge Relationships in Open Channels: Practices and Problems*. Trento: Università di Trento. Dipartimento di ingegneria civile e ambientale.

Caran, Christopher, and Victor Baker. 1986. *Flooding Along the Balcones Escarpment, Central Texas: Geological Society of America*, 1–14.

Chow, Ven. 1953. *Open-Channel Hydraulics*. Civil Engineering Series. The University of Michigan: McGraw-Hill.

Cloke, H.L., and F. Pappenberger. 2009. "Ensemble Flood Forecasting: A Review." *Journal of Hydrology* 375 (3-4): 613–26. doi:10.1016/j.jhydrol.2009.06.005.

Colby, B. 1960. "Discontinuous Rating Curves for Pigeon Roost and Cuffawa Creeks in Northern Mississippi." *U.S. Department of Agriculture, Agr. Research Service* ARS 41-36 (April). http://agris.fao.org/agris-search/search.do?recordID=US201300011564.

Corbett, Don. 1943. "Stream-Gaging Procedure, a Manual Describing Methods and Practices of the Geological Survey." USGS Numbered Series 888. Water Supply Paper. U. S. Govt. Print. Off.,. https://pubs.er.usgs.gov/publication/wsp888.

Cutter, Susan L. 2006. "GI Science, Disasters and Emergency Management." *Hazards, Vulnerability and Environmental Justice*, 399–406.

Dawdy, D. 1961. "Depth-Discharge Relations of Alluvial Streams --Discontinuous Rating Curves." USGS Numbered Series. https://pubs.er.usgs.gov/publication/wsp1498C.

Demeritt, D, H Cloke, F Pappenberger, J Thielen, J Bartholmes, and M Ramos. 2007. "Ensemble Predictions and Perceptions of Risk, Uncertainty, and Error in Flood Forecasting." *Environmental Hazards* 7 (2): 115–27. doi:10.1016/j.envhaz.2007.05.001.

Goodell, Christopher. 2014. *Breaking the HEC-RAS Code*.
Kapucu, Naim. 2008. “Collaborative Emergency Management: Better Community Organising, Better Public Preparedness and Response.” *Disasters* 32 (2): 239–62.
Liston, Glen E., and Kelly Elder. 2006. “A Meteorological Distribution System for High-Resolution Terrestrial Modeling (MicroMet).” *Journal of Hydrometeorology* 7 (2): 217–34.
Looper, Jonathan P., and Baxter E. Vieux. 2012. “An Assessment of Distributed Flash Flood Forecasting Accuracy Using Radar and Rain Gauge Input for a Physics-Based Distributed Hydrologic Model.” *Journal of Hydrology* 412-413 (January): 114–32. doi:10.1016/j.jhydrol.2011.05.046.
Maidment, David. 2002. *Arc Hydro: GIS for Water Resources*. Vol. 1. Esri Press.
———. 2015. “A Conceptual Framework for the National Flood Interoperability Experiment.” *NFIE Conceptual Framework Pap*.
Mckay, L., T Bondelid, T Dewald, J Johnston, R Moore, and A Rea. 2012. “NHDPlus Version 2: User Guide.” Horizon Systems Corporation.
McKinney, Daene C., and Ximing Cai. 2002. “Linking GIS and Water Resources Management Models: An Object-Oriented Method.” *Environmental Modelling & Software* 17 (5): 413–25.
Merwade, Venkatesh, Francisco Olivera, Mazdak Arabi, and Scott Edleman. 2008. “Uncertainty in Flood Inundation Mapping: Current Issues and Future Directions.” *Journal of Hydrologic Engineering* 13 (7): 608–20.
Mitchell, William. 1954. “Stage-Fall-Discharge Relations for Steady Flow in Prismatic Channels.” USGS Numbered Series 1164. Water Supply Paper. https://pubs.er.usgs.gov/publication/wsp1164.
NWS. 2012. “National Weather Service Glossary.” http://w1.weather.gov/glossary.
———. 2015. “AHPS.” http://www.nws.noaa.gov/ohd/ahps/index.html.
———. 2016. “Summary of Natural Hazard Statistics for 2015 in the United States.” National Weather Service. http://www.nws.noaa.gov/os/hazstats.shtml.
O’Connor, Jim E., and John E. Costa. 2004. “Spatial Distribution of the Largest Rainfall-Runoff Floods from Basins between 2.6 and 26,000 Km^2 in the United States and Puerto Rico: DISTRIBUTION OF LARGEST U.S. FLOODS.” *Water Resources Research* 40 (1): n/a – n/a. doi:10.1029/2003WR002247.
Sauer, Vernon. 2002. “Standards for the Analysis and Processing of Surface-Water Data and Information Using Electronic Methods.” USGS Numbered Series 2001-4044. https://pubs.er.usgs.gov/publication/wri20014044.
Smemoe, Christopher M. 2004. “Floodplain Risk Analysis Using Flood Probability and Annual Exceedance Probability Maps.” http://scholarsarchive.byu.edu/etd/19/.
Snow, Alan. 2007. “A New Global Forecasting Model to Produce High-Resolution Stream Forecasts.” Provo, Utah: Brigham Young University. http://scholarsarchive.byu.edu/cgi/viewcontent.cgi?article=6271&context=etd.
Thielen, J., K. Bogner, F. Pappenberger, M. Kalas, M. del Medico, and A. de Roo. 2009. “Monthly-, Medium-, and Short-Range Flood Warning: Testing the Limits of Predictability.” *Meteorological Applications* 16 (1): 77–90. doi:10.1002/met.140.

U.S. Global Change Research Group. 2016. "Heavy Downpours Increasing | National Climate Assessment." Accessed February 9. http://nca2014.globalchange.gov/report/our-changing-climate/heavy-downpours-increasing.

Wang, Fei, Renqiang Wen, and Shaobo Zhong. 2010. "Key Issues in Mapping Technologies for Disaster Management." In *Information Engineering and Computer Science (ICIECS), 2010 2nd International Conference on*, 1–4. IEEE. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5677703.

Wicks, Jon, Joseph Clarke, John Davis, Dawei Han, and Luke Lovell. 2014. "Keep It Simple: User-Focused Flood Risk Visualisation." *Proceedings of the ICE - Civil Engineering* 167 (5): 41–48. doi:10.1680/cien.13.00016.

Vita

Cassandra Fagan grew up in North Andover, Massachusetts, where she attended North Andover High School. She earned her Bachelor of Science degree in Civil and Environmental Engineering from the University of Massachusetts at Amherst. Cassandra is now completing her Master of Science degree in Environmental and Water Resources Engineering at the University of Texas at Austin. Following graduation, Cassandra plans to move to the San Francisco area where she will continue to work in the field of water resources engineering.

Permanent email: fagan.cassandra@gmail.com

This thesis was typed by Cassandra Fagan.