SMU Data Science Review

Volume 1 | Number 4 Article 9

2018

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Brian Cunningham
Range Resources, cunningham.ba@gmail.com

David Benepe
Southern Methodist University, dbenepe@smu.edu

Bryan Cikatz
Southern Methodist University, bcikatz@smu.edu

Evangelos Giakoumakis
Southern Methodist University, egiakoumakis@smu.edu

Framework for Evaluation of Flash Flood Models in Wildfire-Prone Areas

David Benepe[1], Bryan Cikatz[1], Evangelos Giakoumakis[1], Brian Cunningham[2]
[1] Master of Science in Data Science, Southern Methodist University, Dallas, TX 75275 USA
[2] Range Resources, Fort Worth, TX 76012 USA
{dbenepe, bcikatz, egiakoumakis}@smu.edu
cunningham.ba@gmail.com

Abstract. In this paper, we present an innovative framework for evaluating the increased risk of flash flooding in areas that have been subjected to wildfires. Wildfires cause large-scale damage to an area's soil and vegetation thus increasing both the likelihood and severity of flash flooding. Utilizing remote sensing to analyze aerial imagery of areas that have been affected by wildfires, we can investigate how much a landscape has changed and how that may adversely affect downstream areas in the event of a flash flooding event. There are currently no established frameworks from which downstream local officials can quickly assess the impact of a wildfire on the likelihood for flash floods in their area. The creation of flood maps from hydrologic and hydraulic models can take months due to the political nature of the discussion between local officials, insurance agents, and land developers. Our primary objective is to ensure the public's safety. Therefore, we developed a framework for quickly updating flood maps and preparing communities in response to a sudden environmental change.

1 Introduction

Extreme emergency situations are often the result of weather-related disasters such as flash-flooding, high winds and wildfires. Emergency response requires both planning and expertise in preparedness, containment, rescue and recovery. Societal costs include loss of life, housing and other infrastructure. Timeliness and adequacy of preparation are critical to effective response. Of all the natural disasters, flooding is the most dangerous – causing both immediate and long-term consequences. According to the World Economic Forum [3], floods were also the most frequently occurring of natural disasters around the world for the years 1995-2015.

The worst flood in history occurred in the past century. In 1931, between one million to four million Chinese citizens died. This event adversely affected the lives of roughly 50 million people [10]. These figures include the resulting famine and disease caused by the floods. The results of this flood were so extreme due to a combination of poor ecological practices, a lack of effective prediction techniques, and a lack of emergency-response infrastructure. However, a nation with cutting-edge prediction models and solid emergency infrastructure like the United States can mitigate many of the consequences that arise from flooding. In the United States, over 100 people per year die due to floods with most of the deaths coming from flash floods [5]. But even the

US is not fully prepared for many of the unpredictable elements associated with floods. Flooding from Hurricane Katrina caused between $100-$160 billion worth of damage and ended the lives of 1,833 people [6]. This was largely due to not being prepared in the event of the levees failing. Floods have an immense potential for destruction and therefore require the utmost vigilance to mitigate their effects.

A flash flood is a condition where the volume of water entering a geographic location in a sudden and unexpected manner exceeds the capacity of that location to contain it. Waters rise and people who cannot escape or be rescued may die. We are concerned with the additional problem of the compound effect of multiple disasters, such as a wildfire which changes the terrain, soil quality and vegetation of a region. If followed by a sudden heavy rainfall, destruction of a dam or other such event, it may take time to update the engineering work necessary to revise inputs to the maps and models used to prepare for flooding.

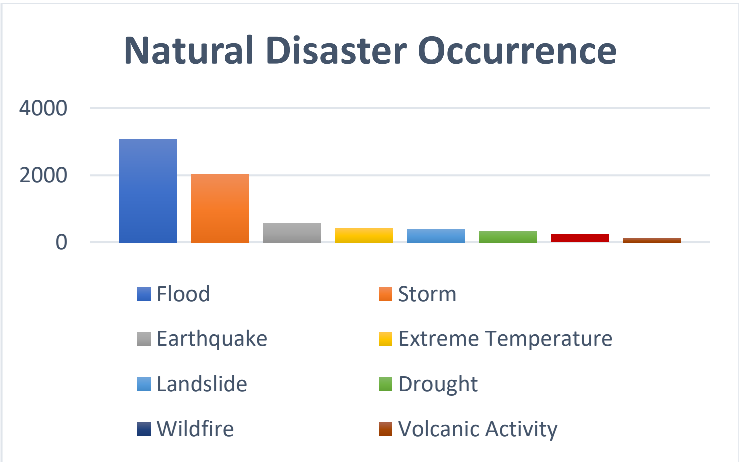

Fig. 1. Natural Disaster Occurrence by Type [3]

According to the National Oceanic and Atmospheric Administration (NOAA), "remote sensing is the science of obtaining information about objects or areas from a distance, typically from aircraft or satellites" [2]. The changes in land cover and soil stability that can be extracted from remote sensing imagery analysis can be input into pre-existing hydrologic and hydraulic models to determine if areas downstream are now at a greater risk of flash flooding because of the changes upstream. The new outputs from those models can then be utilized by emergency management personnel to devise updated evacuation and response plans in the event of a flash flood. However, local officials downstream from a wildfire may not be prepared to address this specific combination of events. In this paper we propose a framework to assist them in preparing to quickly assess the impact of a wildfire on the likelihood for flash floods in their area and mitigate its impact.

The Federal Emergency Management Agency (FEMA) is the main provider of flood maps in the United States, managing flood maps for roughly 22,000 communities [19]. However, the organization's map-updating process needs reform. Even though FEMA is required to update maps every five years, almost 2/3's of their maps fail to meet this criterion [19]. "Many areas that flooded when Sandy struck in 2012 had maps that were last updated in 1983" [19]. Most of FEMA's maps are outdated to such an extent that they provide little value under normal circumstances; the maps are practically worthless when faced with a sudden change in the environment such as a wildfire.

Our approach can be broken down into three distinct components. First, we use ArcGIS to view multi-spectral aerial imagery and identify locations that have been subjected to intense wildfires. Then, we perform hydrologic and hydraulic modeling on the previously identified location with the updated inputs in order to create the components that are used to generate the updated flood map. This modeling is done through the HEC-RAS software. With the output from HEC-RAS, we can then update the flood map which now considers the environmental changes wrought by the wildfire.

By going through this process, we develop a series of recommendations for how a community vulnerable to flash floods should respond in the event of a wildfire. We use the remote sensing and imagery change detection tools available within ArcGIS to analyze the different spectrums of the imagery and derive updated inputs for a hydrologic and hydraulic model. There needs to be regular interaction between the engineering firms responsible for creating the flood maps and the local officials in charge of public safety. Communication between these two groups ensures that flood prevention and mitigation efforts are properly coordinated. While it is impossible to defend against all eventualities, ensuring that the public has access to reliable and up-to-date information will be an improvement of the current situation.

The subsequent sections provide an overview of the various efforts and organizations that are involved in hydrological modeling. Section 2 focuses on the background of hydrological modeling. Section 3 is an overview of the various data sources needed to generate our models along with the respective collection and preprocessing methodologies. Section 4 covers the resulting output of the models. A formal analysis of our efforts is presented in Section 5. Ethical considerations regarding proper flood preparation procedures are explored in Section 6. Final conclusions and suggestions for potential future work are examined in Section 7.

2 Flood Prediction Modeling

2.1 Spatial Analysis

Public officials have a responsibility to make decisions whether to evacuate a region, given sufficient notice of the likelihood of flooding. Providing this information is the work of scientists and engineers who use geographic information systems (GIS) as a tool to study the problem. They build hydraulic and hydrologic models to represent the release and flow of water between locations. They study the effect of soil composition on the capability of land to absorb moisture, the composition of the land cover and its effect on the rate at which water flows across the surface, and account for impermeable surface area there is that results in or contributes to greater runoff. They construct geographic and topological maps to show the likelihood of a significant flooding in a given location or region. Such modeling techniques for topological, geographic or geometric properties form the basis for the broader field of spatial analysis.

2.2 ESRI Modeling

ESRI (Environmental Systems Research Institute) is an international supplier of GIS software and geodatabase management applications. The company was founded in 1969 as a land-use consulting firm.

GIS is a framework for gathering, managing, and analyzing data. Planted in the science of geography, GIS combines many types of data. It analyzes spatial location and organizes layers of information into visualizations using maps and 3D scenes. With its unique capabilities, GIS reveals deeper insights into data, such as spatial and geographic patterns, relationships, and situations, helping users make better decisions.

This project uses the ArcGIS software package to monitor change in the terrain of a specific area and forecast the effects that a future flood might have in that region. This paper focuses on areas that have experienced violent natural disasters, such as wildfires. These events can severely impact the landscape rendering past prediction models less effective. As a result, iterating through these models again, after considering the changes that occurred on the landscape, is paramount. So is comparing the results of the new model with that of the old one. As the great Benjamin Franklin once said, “By failing to prepare, you are preparing to fail.” [22] The intention is to take those differences and ultimately help save human lives by granting more accurate predictions to flood related disasters.

2.3 Flood Mapping Milestones

The recent history of United States (U.S.) Flood Mapping is a story of collaboration among academia, government and industry. Milestones 01 and 02 captures the highlights as told by David Maidenent, Professor of Civil Engineering at the University of Texas in Austin, in a recent article in ESRI’s ArcNews [1]. Milestones 1 and 2 show improvements in hydrology models since 1990, while Milestones 3 and 4 address improvement to hydraulic models and riverbed mapping since 2004. Our project seeks to build upon this trend – promoting greater coordination between the organizations responsible for mitigating flood damage.

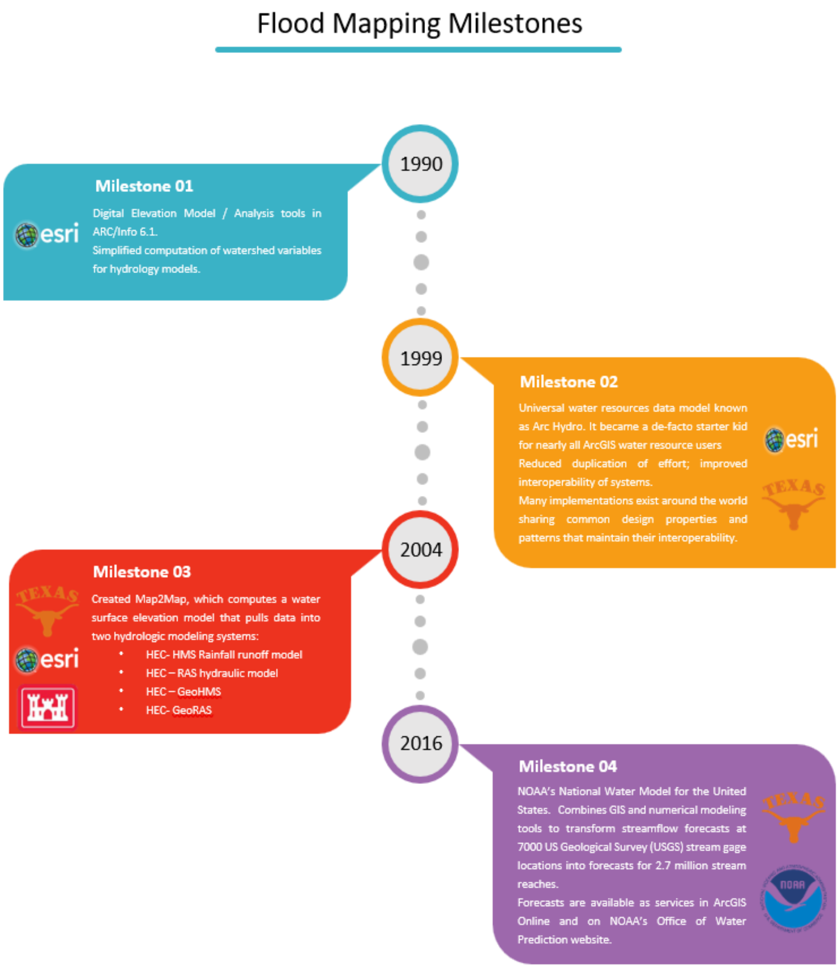

Fig. 2. Flood Mapping Milestones 1990-2016

2.4 Incorporating Changes from Wildfires

In 2017, wildfires in the United States burned almost ten million acres of land [8]. The total amount of burned acreage has been steadily increasing from about two million acres in 1990 [8]. The damage caused by wildfires means that more areas in the US are increasingly vulnerable to flash floods. Wildfires cause several issues in relation to floods – increasing both the likelihood of flooding as well as its severity. Intense fires destroy large swaths of vegetation and change the properties of local soil. These two consequences increase the runoff of water during a storm which means that a flash flood in the fire-affected area can occur with less rainfall [4]. The potential damage from flooding is increased because the weakened soil is more vulnerable to erosion and subsequent mudslides. These mudslides can undermine the foundations of man-made structures or bury them under a layer of displaced soil and debris [7]. The path of destruction also leaves behind dead trees and other debris that can easily be swept into streams and rivers, causing blockages at bridges, culverts and other pinch points that exacerbate the flash flooding potential. Depending on the intensity of the wildfires, the probability of flood damage in a fire-affected area remains high for more than two years if there is not human intervention [7]. Figure 3 shows how wildfires increase the probability of mudslides, especially in mountainous terrain.

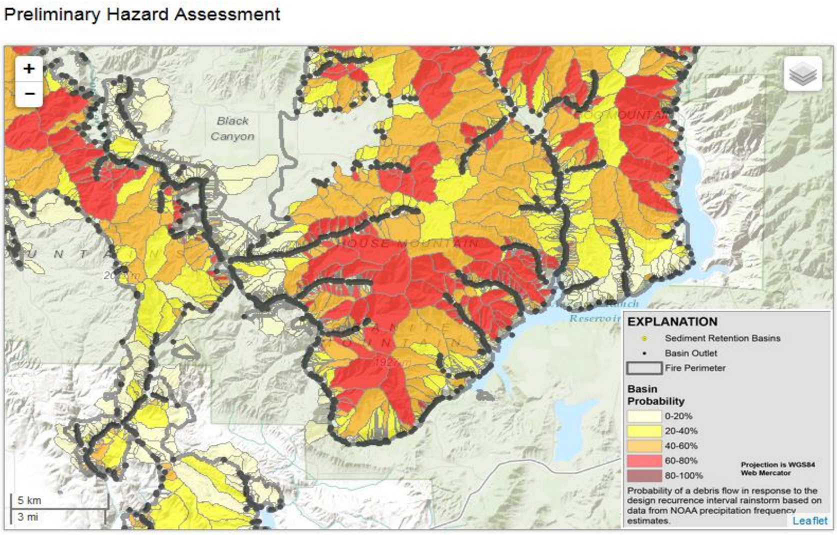

Fig. 3. Risk of Mudflows in Elmore County, Idaho After a Wildfire [9]

3 Data Sources

3.1 FEMA Flood Data

The Federal Emergency Management Agency (FEMA) is an agency of the United States Department of Homeland Security [11]. The agency's primary purpose is to coordinate the response to a disaster that has occurred in the United States and that overwhelms the resources of local and state authorities [11].

For this analysis we utilize the FEMA Flood Map Service Center (MSC), which is the official public source for flood hazard information. This is one of the inputs to the hydrologic model.

Table 1. Structure of FEMA Data

Field	Description	Type

STATION	station ID	String
STATION_NAME	station name	String
ELEVATION	elevation (inches)	Numeric
LATITUDE	latitude (dec degrees)	Numeric
LONGITUDE	longitude (dec degrees)	Numeric
DATE	date (YYYYMMDD HH:MM)	Datetime
HPCP	recorded precipitation (inches)	Numeric
Measurement Flag	measurement flag	String
Quality Flag	quality flag	String

3.2 NOAA Precipitation Data

The National Oceanic and Atmospheric Administration (NOAA) is an American scientific agency within the United States Department of Commerce that focuses on the conditions of the oceans, major waterways, and the atmosphere [12].

NOAA warns of dangerous weather, charts seas, guides the use and protection of ocean and coastal resources and conducts research to provide understanding and improve stewardship of the environment [12].

For this project, we use data available on NOAA's website as an additional input to our hydrologic model, in order to predict flood prone areas and generate flood maps.

Table 2. Structure of NOAA Data

Field	Description	Type
State	State where property is located.	String
Year	Four-digit year in which the loss occurred. Note that some events span multiple years.	Numeric
NumberOfClaimsClosedWithPayment	The total number of claims closed with payment for the given state and year.	Numeric
TotalPaid	The total dollar amount paid on closed claims for the given state and year.	Numeric
County	The name or phrase describing the U.S. county or county equivalent, or NWS Forecast Zone. For more information on NWS Forecast Zones.	String
Lat	The latitude used to map the event.	Numeric
Lon	The longitude used to map the event.	Numeric
NumEpisodes	The number of Flooding Episodes for the State/County/Year.	Numeric

3.3 Additional Data

Supplementary data is gathered from various sources to assist in the improvement of our model. These elements provide more detailed information for the land being analyzed such as (slope, soil type and porosity) [13].

Table 3. Structure of Additional Data

Field	Description	Type
Latitude	latitude (dec degrees)	Numeric
Longitude	longitude (dec degrees)	Numeric
Porosity	elevation (MSL)	Numeric
Slope	void space in soil (%)	Numeric
Soil Type	measurement flag	String

3.4 Satellite Imagery

Finally, satellite images are acquired from ARC-GIS mapping tool are utilized in the creation of flood maps [14]. These enable us to compare differences between events and models.

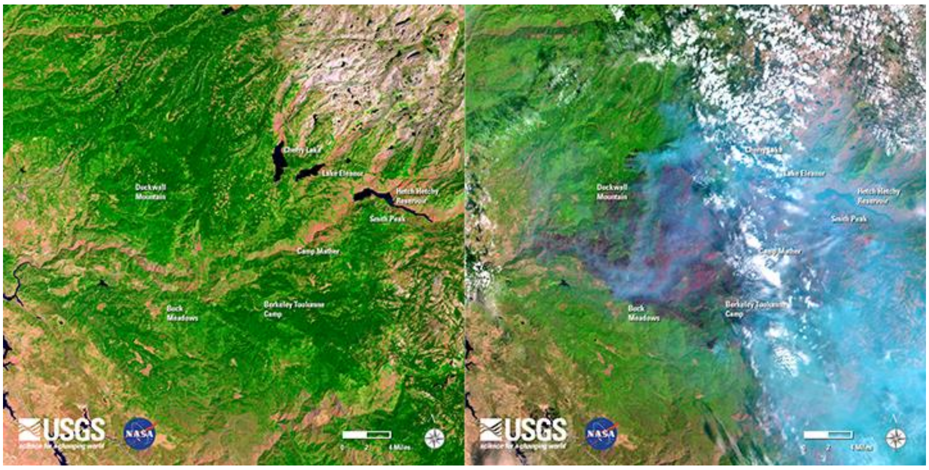

Fig. 4. Satellite image of Yosemite National Park After 2003 Wildfires [14]

3.5 Flood Analysis Methodology

In the figure below the outline shows the methodology that is used to arrive at the results. In the Data Preparation step, data from various sources (FEMA, NOAA, Additional, Satellite) is combined, and then processed, transformed, and interpreted. In the Analysis and Modelling section hydraulic and hydrologic models are generated and simulated. Finally, in the Solutions and Evaluation step, profiles and flood maps are created, and results are evaluated.

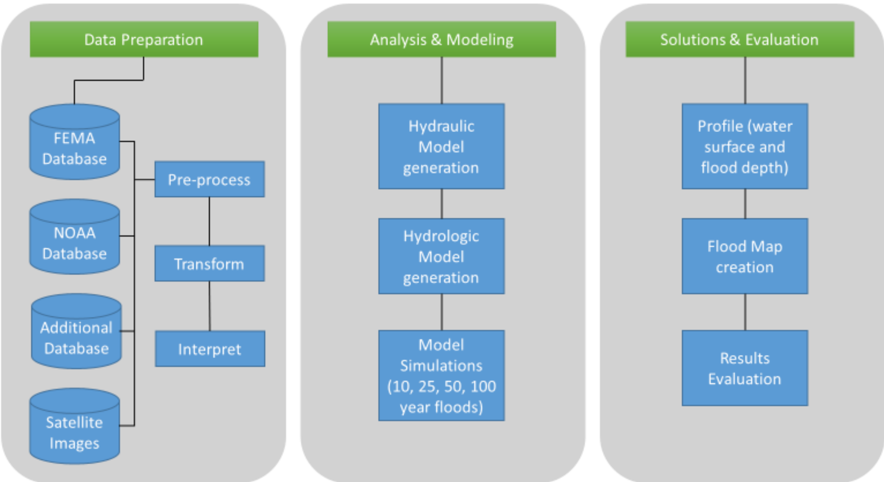

Fig. 5. Flowchart of Flood Analysis

4 Results

4.1 Wildfire Selection

A decision was made to analyze the effects of the Carr Fire which occurred in northern California near the town of Redding in July of 2018. An estimated 191,211 acres burned and the fire's effect on the flood map of the surrounding area is measured. Figure 6 below shows the before and after effects on the area outside of Redding. The affected area of the fire can be seen on the second picture depicting the magnitude of destruction.

We chose this wildfire for multiple reasons. The area around Redding consists of hilly terrain with many bodies of water. This makes it relatively easy to track and predict the flow of water. Also, Redding, a large population center, is "downstream" from the fire which means that the Carr Fire has increased the city's vulnerability to flash floods. Finally, even small towns that have been affected, like French Gulch, have detailed flood maps through the FEMA website. This means that if we wish to expand upon our work, there are other towns in the same geographic area that we can use for our model.

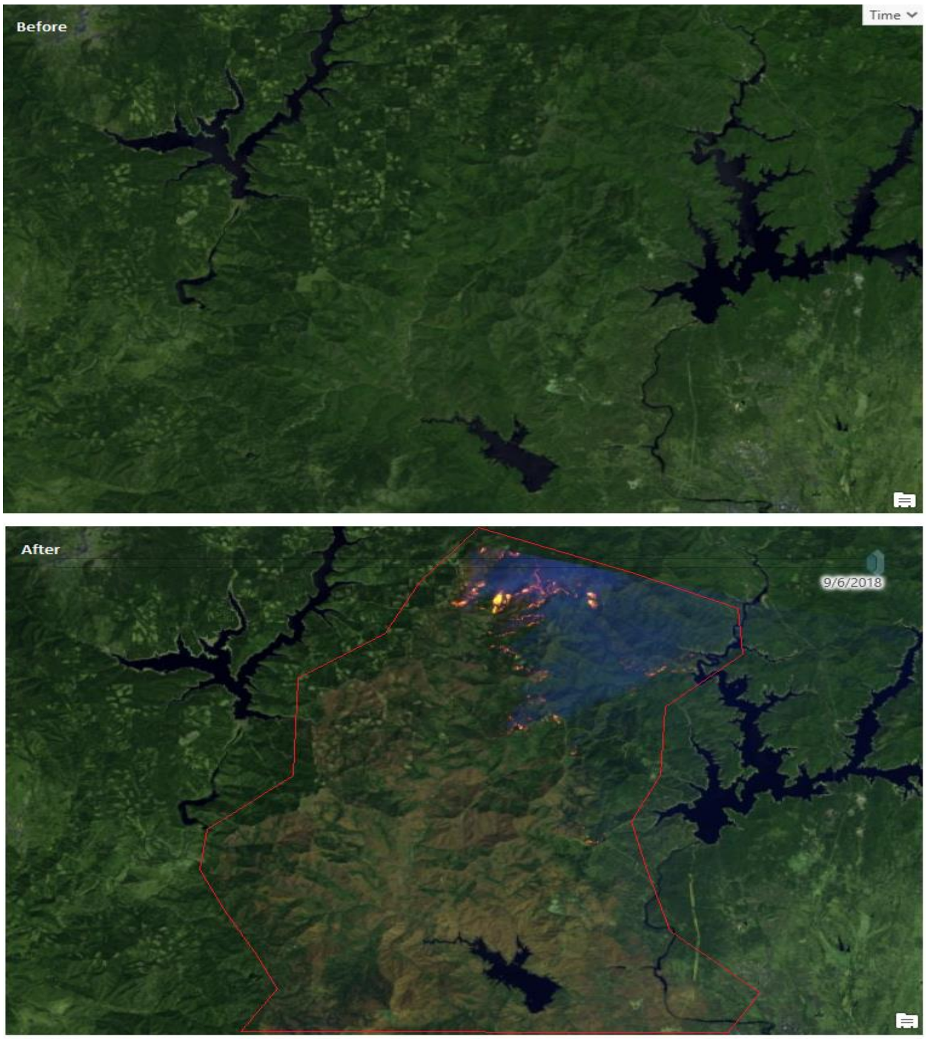

Fig. 6. Satellite Image Comparison of Redding Area Before and After the Carr Fire

The Shortwave Infrared (SWIR) spectrum of the Landsat Multispectral imagery is applied on ArcGIS Pro to generate the images above. The Landsat Multispectral imagery or SWIR is immediately adjacent to Near Infrared Light (NIR) in the electromagnetic spectrum and refers to non-visible light falling roughly between 1400 and 3000 nanometers (nm) in wavelength. SWIR light is reflective in nature and bounces off objects much like visible light. However, SWIR light is not visible to the human eye. As a result of its reflective nature, SWIR light has shadow and contrast in its imagery (contrast depends upon the radiometric resolution of sensor). Unlike visible light imagery, the SWIR light image is not in color. This makes objects easily recognizable and yields one of the tactical advantages of the SWIR, namely, object or individual identification. [25] Landsat imagery is sourced from the U.S. Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA).

4.2 H&H Modeling

Hydraulic & Hydrologic Modeling, or H&H Modeling as it is widely known, is a system that aids in understanding, predicting, and managing water resources. H&H modeling is constituted by 2 parts: Hydraulics and Hydrologic. Hydrology is generally related to the study of rainfall and water in connection to geography and geology. Hydraulics deal with the physical properties of water, it is the study of the motion of liquids in relation to the disciplines of fluid mechanics and fluids dynamics [21].

In order to perform said analysis, an additional tool is used. That tool is called HEC-RAS (Hydrologic Engineering Center River Analysis System). HEC-RAS is a software used to model reservoir operations. It was developed by HEC (Hydrologic Engineering Center) and is maintained by the US Army Corps of Engineers. Its main goal is to support the nation with its water resource management responsibilities.

A visualization of the procedure for Hydraulic and Hydrologic modeling can be seen in Figure 7 below. The inputs to the H&H model can be seen on the left (Precipitation data, Basin, characteristics, Losses, and Calibration data) and the outputs of the model on the right (Shapefiles).

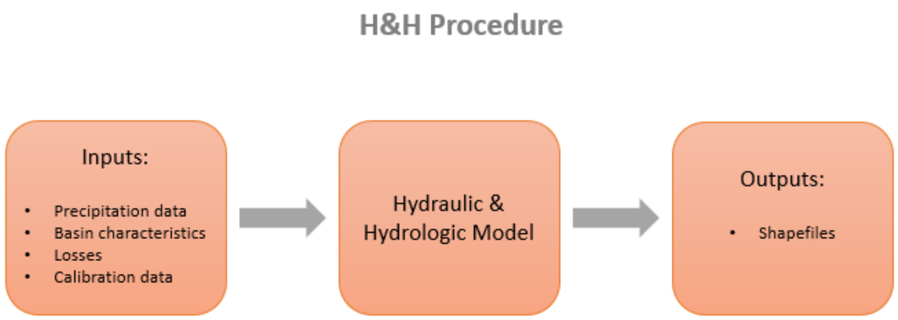

Fig. 7. Hydraulic and Hydrologic Model Analysis

A shapefile is a digital vector storage format for storing geometric location and associated attribute information. This format was created by ESRI and introduced in the early 1990s. It is now possible to read and write geographical datasets using the shapefile format with a wide variety of software [20].

The shapefile format is simple. It stores the data as primitive geometric shapes like points, lines, and polygons. These shapes, together with data attributes that are linked to each shape, create the representation of the geographic data [20].

The figure below depicts an instance of HEC-RAS in action and the various attributes it uses to analyze a specific stream. The blue line depicts the centerline of the river or stream analyzed, the blue arrow depicts the flow of water, the green lines represent the cross-sections of the stream and the numbers next to them represent the distance that the cross section is from the downstream terminus of the stream. The distance is measured in a project defined unit of measurement. The cross sections also have elevation attributes associated with them that represent the different flooding elevations for the different scenarios (100yr, 500yr, etc…) at that cross section.

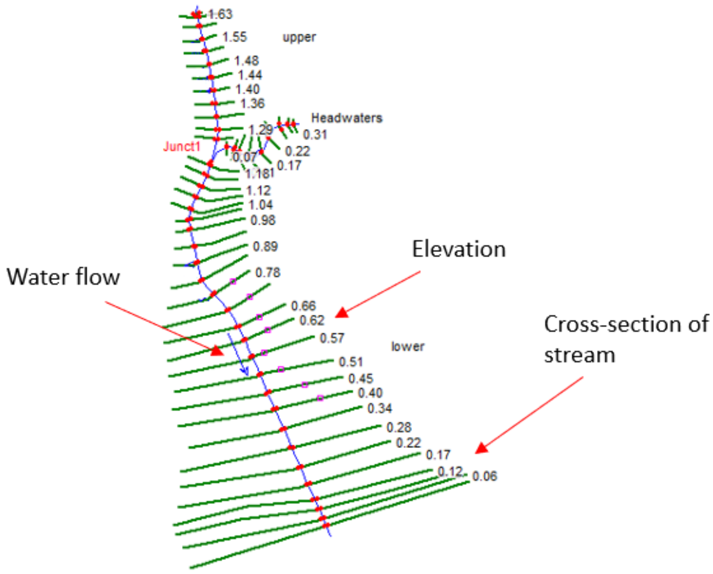

Fig. 8. Instance of HEC-RAS Modeling of Sacramento River

The output of the H&H Model (Shapefile) is imported into ArcGIS to continue our analysis and generating the flood map.

5 Analysis

5.1 Flood Map generation

Flood mapping is an exercise in which we attempt to define areas at risk of flooding under extreme weather conditions. In order to do so, another piece of software must be used. That software is called ArcGIS (Geographic Information System) and was created by ESRI. Its goal is to aid in the analysis of mapped information by compiling geographic data.

While ArcGIS comes in many different flavors, there are three being used for this project. ArcGIS Pro is the full desktop version of the software. ArcGIS Online is a limited web-based version of the software, and the ArcGIS Python API is a library that can be used in Python to access all the ArcGIS tools to automate processes.

The shapefile of cross sections generated from the hydraulic & hydrologic model is imported into an ArcGIS map of Redding, CA and the floodplain polygons are generated by following contours and matching the elevations at each cross section. ArcGIS provides tools that generate these polygons in an automated fashion by using the cross sections and elevation contours as inputs. The flood map in figure 9 is the result of this process. This map represents the floodplain for the city of Redding as calculated by our modeling procedure.

5.2 Flood Map Data

Flood data is gathered for the Redding area from before July 1st, 2018; this is the official start date of the Carr Fire. This data is used to model a flood map which is compared with the data gathered from after start of the Carr Fire (**since** July 1st, 2018) to identify their differences and update the existing models.

Of particular interest is the change in size of the special flood hazard areas after a large fire. The FEMA map below shows the areas affected by a 100-year flood (light blue) and a 500-year flood (orange) under nominal conditions. However, this map is no longer accurate after the Carr Fire. A consequence of wildfires is that they decrease the amount of rain needed to cause a flash flood. Therefore, a serious flooding event is far more likely to occur compared to under nominal circumstances.

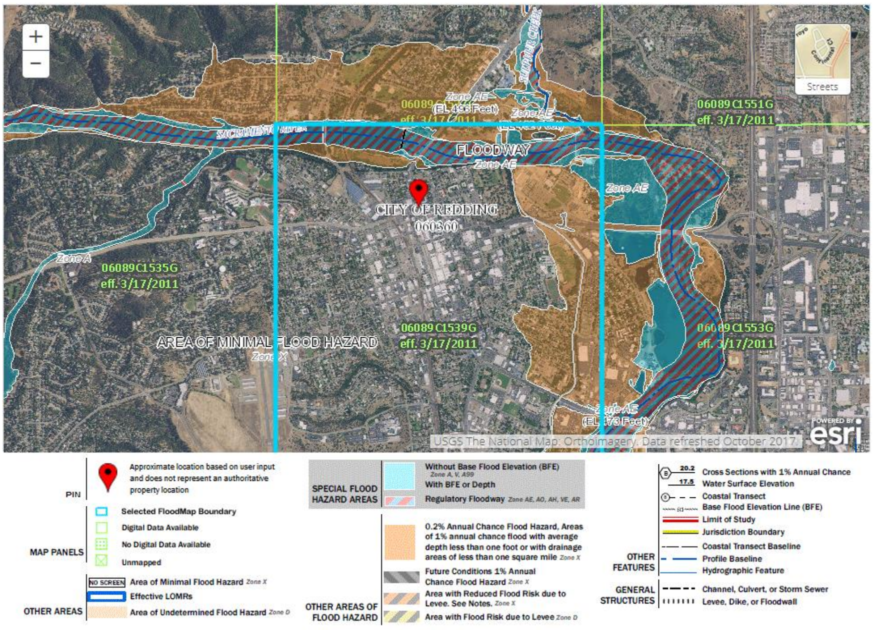

Fig. 9. Redding, CA Current Flood Map [24]

5.3 Debris Removal

GIS software was also utilized by Redding officials in the removal of debris left over from the CARR Fire. The following dashboard, figure 10, was created by the Redding officials in order to quickly identify large pieces of debris that need to be removed. This cleanup process is the first step in mitigating the consequences of the wildfire because the presence of debris exacerbates the danger posed by a flash flood.

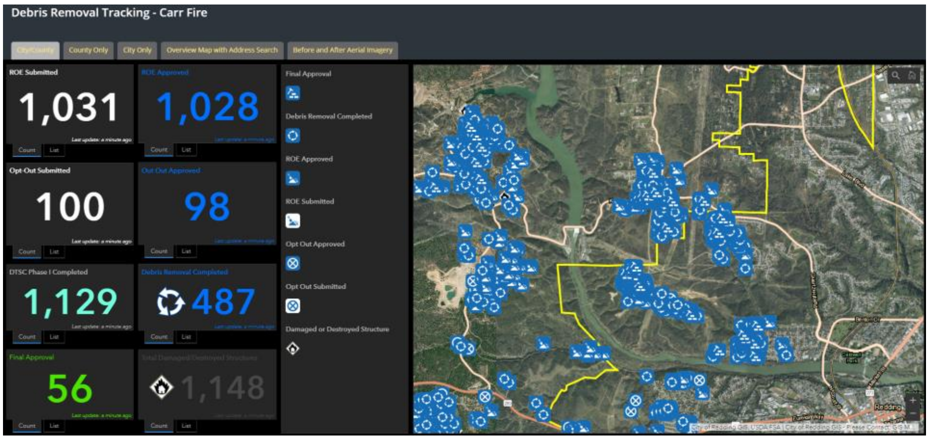

Fig. 10. Redding, CA Debris Dashboard [23]

6 Ethics

Ethical issues in flood control arise from the inherently political nature of the way FEMA flood plain maps are approved and from the downstream impact of the exercise of jurisdictional authority over the release of water from lakes and reservoirs.

6.1 Flood Map Politics

Flood map politics relates to ACM rule 3.1: "Ensure that the public good is the central concern during all professional computing work" [17].

The Federal Emergency Management Agency (FEMA) partners with Tribal nations, States, and communities through the Risk Mapping, Assessment, and Planning (Risk MAP) program [15]. Further, "this data is incorporated into flood maps, known as Flood Insurance Rate Maps (FIRMs), that support the National Flood Insurance Program (NFIP) and provide the basis for community floodplain management regulations and flood insurance requirements" [15]. A key element of these maps are notations of flood elevation levels. Thus, FEMA's floodplain maps are not just based on scientific modeling, but also on negotiations with local entities to determine where land development may occur and at what cost to the users of the land in terms of insurance premiums. This makes official updates to the map a political process. One cannot rely on the maps themselves to make informed decisions about flood risk, because several types of revisions may be accomplished by a … Letter of Map Change (LOMC).

6.2 Downstream Impact of Local Decisions

The downstream impact of local decisions relates to ACM rule 1.4, "Be fair and take action not to discriminate" [17].

As noted in section 2.3, in recent years there has been significant progress in interagency cooperation during tropical events, such as tropical storm Harvey in 2017. Harvey brought significant rainfall to areas of the Texas Gulf Coast, in and around Houston. Participants in this effort were able to "provide situational awareness for county judges and emergency management coordinators in the dozens of affected communities, and … provide daily flood inundation maps for … search and rescue" efforts [16].

However, even with perfect information, these local public officials are required to make difficult ethical tradeoffs, such as whether to release water from a dam or spillway into an already overflowing river, increasing the burden on areas downstream, while delaying or avoiding their own local catastrophe should the reservoir overflow its bounds on all sides.

7 Conclusions and Future Work

A framework is needed to guide local officials in preparation for the downstream effects of a wildfire. We propose a five-step framework: First, work with officials in wildfire prone areas to coordinate and expedite debris removal after a fire. Second, develop expertise in and access to GIS mapping tools. Third, establish a consulting relationship with an engineering firm with expertise in hydrologic and hydraulic modeling. Fourth, establish legal authority for the preparation and use of flood plain maps after the wildfire that may be used to predict flash flood severity and manage evacuation and rescue efforts, free from the politics of official flood plain maps used for flood insurance purposes. Fifth, establish a cross-functional, cross-jurisdictional team that can quickly assemble once a fire is contained to execute the flood analysis methodology (as shown in Figure 5) and be available to support local officials in the event of an imminent flash flood event. This team should include key personnel involved in steps 1-4.

Future work in this area could include preparation of both hardcopy and online media explaining the issue and proposed framework, as well as a completed example. The information provided could include contact information for the software vendors and engineering firms as well as links to the various websites. Another direction for future work could be developing flood maps that deal with predicted future changes in the environment such as rising sea levels. While ambitious, following our proposed framework would put flood mapping organizations on the right footing to implement these ideas.

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