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Risk Assessment of Post-Fire Floods on Dams and Their Floodplains

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THESIS

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Dedication

To my mother and father

Mahalakshmi and Apparao Simma

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ABSTRACT

The rapidly changing global climate and the increased dependence on infrastructure networks make our society vulnerable to natural disasters. Decision makers need to understand the intensity of potential natural disasters to take necessary actions to minimize their impacts. In Southwest United States, wildfires are increasing in frequency and magnitude. The literature review shows limited studies in evaluating the impacts of post-wildfire floods on civil infrastructures and residential zones. Earth dams are vulnerable to post-wildfire floods. The increased post-wildfire runoff volumes due to changes in soil characteristics and reduced vegetation could result in overtopping failure of an earth dam (dam-break scenario), and the accumulation of sediment and debris flow could reduce the capacity of the reservoir (no-dam break scenario). In this study, a framework to evaluate the impacts of post-fire floods on earth dams is proposed.

First, pre and post-wildfire runoff volumes are estimated considering a distribution of runoff coefficients found in the literature, different watershed burnt areas and historic rainfall data. Second, based on these runoff volumes, potential dam overtopping failure is modeled using WMS: SMPDBK developed by National Weather Services.

The model predicts downstream flooding due to dam failure. The dam-break results are interpolated with HAZUS (developed by Federal Emergency Management Agency) inventory data to assess the downstream economic, environmental and social impacts. Finally, the impacts of dam failure and no-dam failure scenarios are evaluated with inputs from Hazus results and from an interview to a dam safety manager about disaster response alternatives and procedures. The framework is demonstrated using three earth dams in the Southwest United States. The results showed that with increased fire intensity and post-fire rainfall, increase in impacts on earth dams due to increased runoff and sediment yields resulting in a potential dam failure and thereby increased impacts on its floodplain. These impacts are integrated into a decision matrix and a decision tree that could be used to prioritize dams and high hazard zones in the watershed.

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Chapter 1: Introduction

1.0. Introduction

Infrastructure is the key for a successful nation. Natural disasters can trigger a wave of disruptions in a given infrastructure system. The rapidly changing global climate and the increased dependence on the infrastructure networks make our society vulnerable to any natural disaster. The outcome of these natural disasters could breakdown the infrastructure networks like transportation, telecommunication, electricity, water supply etc., which disrupts the economy at various levels (e.g. local, state and federal) depending upon the magnitude of the event. The severity of the damage can be increased further if we are not prepared enough to deal with such events. Recent instrumental records demonstrate the rise in average temperatures which are projected to continue and accelerate (Isaak et al. 2009). The change in climate can trigger or increase the severity of a natural disaster (e.g. wildfire, flood) (Fried et al. (2004), Westerling and Bryant, (2007) Arnell et al. 2014). It is important for decision makers to consider these changes in climate to protect the vulnerable infrastructure and minimize the damage caused due to such natural disasters.

In this study, the impact of post-fire flood event on an earth dam and its floodplain are evaluated. Wildfire event causes a disturbance in the characteristics of a watershed often altering the hydrologic response to a normal rainfall event resulting in a significant increase in water discharge (Moody and Martin, 2001). These post-fire floods results in increased runoff discharge and bring in more debris and sediments to the reservoir. This study focuses on the impact of increased runoff discharge, debris and sediments resulting from post-fire flood on an earth dam. Later, the impacts of both dam failure and non-dam failure on infrastructure and communities are assessed.

The dam failure results in rapid discharge of flood water to the downstream floodplain causing damages to residential zones, displacement of population and damage infrastructure networks which can disrupt the local economy along with the social life. Therefore, identifying and quantifying the impacts of post-fire flood and their impacts on earth dams-floodplains can help decision-makers to identify and prioritize the potential high hazard zones (watershed-dam-floodplain) and allot funds to mitigate the impacts.

1.1. Research Motivation:

Human and economic losses from wildfires are increasing due to global climate change and urban population growth (Bradstock et al. 2012). The severity and frequency of wildfires has increased in recent years (Son et al. 2015). With these increased events of wildfire and their intensities, there is considerable impact on the ecosystems besides their impacts on human population (Son et al. 2015). The post-fire storms are resulting in excess runoff and sediments from the watersheds (Prosser and Williams 1998). The impact of these runoff and sediments can be severe which need to be studied to minimize losses. Additionally, the American Infrastructure report card released in 2013 by ASCE reports the nation's infrastructure as D^+. The highways and dams across the nation are at grade D whereas inland waterways and levees are at even lower rate of D^-. The average age of the 84,000 dams in the country is 52 years old. The nation's dams are aging and the number of high-hazard dams is on the rise to nearly 14,000 in 2012. The number of deficient dams is currently more than 4,000. Therefore it is crucial to identify the impacts on dams from post-fire floods and evaluate their response. For this study earth dams in the state of New Mexico are considered.

1.2. Research Questions:

The main objective of this research is to develop a framework that will identify the potential impacts of post-fire rainfall flood on earth dams and their floodplains which could help decision-makers to identity and prioritize high hazard zones (watershed-dam-floodplain).

The following research questions are addressed in this thesis:

- What criteria can be considered to evaluate the severity of a post-fire rainfall event?
- What are the impacts of post-fire flood on earth dams and reservoirs?
- How can the dam-break impacts be incorporated in decision making?

1.3. Overview of Methodology:

The proposed framework consists of four steps: (1) post-fire flood estimation, (2) dam-break modeling, (3) Risk assessment of floodplain, and (4) Decision-making. In the first step, post-fire runoff and sediment yield are estimated. The runoff estimates are used in dam-break modeling. The dam-break results are used to identify and categorize the floodplain impacts into social, economic and environmental impacts. The impacts of no dam-break scenario are also identified and categorized. These impacts are used to form the matrix with the purpose of prioritizing the high hazard zones intended to help decision makers in allotting funds to mitigate the impacts on floodplain stakeholders. The methodology will be illustrated with three different case-studies dams in New Mexico, USA.

1.4. Organization:

The research is comprised of five chapters. Chapter 1 introduces the topic of wildfire and post-fire flood events and the importance of quantifying their impacts. Chapter 2 summarizes the literature on climate change and risk of wildfire, post-fire flood and impacts on earth dams, downstream flooding, and risk assessment. Chapter 3 describes the developed framework including tools and methods used along with the illustration of three different case studies of earth Dams. Chapter 4 describes and discusses the results to demonstrate and verify the proposed methodology. Chapter 5 summarizes the entire study, its contribution and limitations and proposes directions for future research.

Chapter 2: Literature Review

2.0. Introduction:

Wildfires have increased in both severity and frequency due to climate change. This research focuses on the impacts of post-fire floods on earth dams. A post-fire flood results in excess runoff compared to a normal flood (Mayor et al. 2007). Wildfire destroys the majority of the ground cover (Prosser and Williams 1998) and also increases the water repellency of the surface (Neris et al. 2013) which causes additional runoff, sedimentation (Robichaud 2005) and debris flow in a post-fire flood. The additional runoff reaching the river streams can have a significant impact on an earth dam. The potential impacts can vary from a partial damage to total failure of the dam in which enormous amount of water will be discharged to the downstream of the dam. The impact of this flood depends on the occupancy of floodplain with infrastructures like residential buildings, road networks, bridges among others. (Baecher et al. 1980). The risk of dam-break can be assessed by analyzing the occupancy rate of floodplain for the dam.

The impact on the dam depends on the amount of watershed affected by the wildfire and post-fire flood. This can result in massive runoff discharge from the drainage area to the reservoir. The additional amount of runoff can potentially fail the dam causing a flooding event which disrupts the downstream floodplain of the dam (Cleary et al. 2014).

To provide the basic foundation for the proposed study, pervious work done on the relevant topics are summarized. It is important to summarize the previous work done on the proposed field of study and address their findings and limitations which helps to build the foundations of this research. Previous research related to post-fire flood, runoff discharge, debris flow and types of earth dam failure and its consequences are discussed in this chapter. The summary on specific researches related to the above mentioned fields are provided along with their area(s) of emphasis, modelling tools, analysis performed, the main findings and limitations. The literature analysis on these area helped to identify the point of departure for this study.

2.1. Climate Change and Risk of Wildfire

The rapid change in climate observed in recent years lead to increased wildfire activity in US (Westerling and Bryant (2007) Robichaud et al. (2000)). The warmer temperatures in spring and summer, reduced precipitations, earlier snowmelts and longer drier summers are some of the reasons stated by Westerling and Bryant, (2007) for intensified wildfires in western US. In other words, the severity and frequency of wildfire has increased as a consequence of extended dry periods and hotter days (Crouch et al. 2006). The risk posed by wildfires becomes a serious calamity that we need to assess in order to minimize its impact. Over the years, quite a few landscape fire regime models were built to simulate the wildfire propagation (Bradstock et al. 2012). Bradstock et al. (2012) used FIRESCAPE model to simulate various scenarios to observe the response of key measures for wildfire activity that governs the risk of people and property. The research was focused to determine the treatment rate per annum to minimize the risk to people and property (Bradstock et al. 2012). However, there was no specification on type of property (e.g. infrastructures like buildings, road networks, bridges, telecommunication networks etc.) targeted in their study.

2.2. Post-Fire Flood and Impact on Earth Dams

Wildfire impacts the surface soil and alters its physical and chemical properties as the soil structure is distorted (Son et al. 2015). The resulting debris and the loose soil is eroded through the surface runoff due to post-fire flood. In a post-fire flood event, three changes to the runoff characteristics can be observed:1) reduced canopy interception increases the percentage of rainfall available for runoff; 2) reduced water loss due to evapotranspiration increases base flow; 3) ground cover, litter, duff, debris increase runoff velocities and reduces interception and storage (Moody and Martin, 2001). The runoff from these watersheds reach the river stream and bring in large amounts of runoff and sediments to the reservoirs.

The increased runoff volumes and sediments can have adverse effects on dam (for instance failure of dam). The intensity of these damages depend on the intensity of post-fire rainfall event and the quantity of runoff with sediments brought into the reservoir which could lead to the dam failure. The failure of the dam could result in sudden discharge of the reservoir water which creates flooding on the downstream side of the dam because the flood resulting from a dam failure possess extreme discharge characteristics that may exceed the classical floods (Raška and Emmer 2014). In a database complied of 900 dam failures across 50 different countries (like U.S., U.K., India, Australia and others) by Zhang at al. (2009) 66% of failures were accounted by earth dams resulting in severe damage both in terms of human life and property (Cleary et al. 2014) (Zhang et al. 2009). There are numerous cases in which an earth dam fails, but the frequent reasons which account for majority of these failures are 1) Overtopping failure, 2) Piping. 3) Sliding failure (Foster et al. 2000).

These reasons make earth dams more vulnerable and increase their risk of failure and the property on downstream side of the dam.

To observe and assess the risk involved in earth dam failure, we need to study the dam failure scenarios and their consequences. The impact of failure depends on the extent of dam failure (e.g. structural failure like slope failure has different consequence when compared with a piping failure (Cleary et al. 2014)) which was studied by many researchers over the years. Cleary et al. (2014) developed a scenario-based risk framework to determine the consequences of different modes of failure of earth-dams. The research developed a risk framework for computational models which consists a database for pre-computed dam-break events. Various failure scenarios were modeled to observe the progressiveness of the dam breach by the rate of flow of water. However, the impacts these waters have on the infrastructure located in the downstream floodplain were not addressed by the author. Singh and Scarlatos (1988) developed analytical models to analyze earth dam breach erosion. The simulation models were based on water depletion equation, weir hydraulics and breach-erosion relations. Mathematical solutions were derived for various breach shapes and a sensitivity analysis was also performed on various parameters (e.g. discharge coefficient, erosivity coefficient, initial hydraulic head, breach width, breach side slope, etc.). These observations are limited to specific case of Teton dam failure (Singh and Scarlatos 1988). Peng and Zhang (2013) developed a dynamic decision making framework for dam-break emergency management to help decision making in evacuation population at risk. The mathematical and empirical models were used to find the optimal time to evacuate the population at risk with minimum total loss.

The damage due to dam failure was evaluated in terms of human life and evacuation cost but does not address the impact on infrastructure networks (Peng and Zhang 2013). Observing all the above research findings, it is evident that a dam-break will result in serious flooding towards the downstream which can potentially disrupt the normal live of the communities living close by.

The post-fire runoff and sediment quantities are focused in many earlier researches. Some of those researches are reviewed in this thesis to obtain the coefficients to estimate the runoff and sediments quantities from a watershed. The coefficient of runoff for burnt and unburnt areas are obtained from previous researches (Prosser and Williams 1998) (Johansen et al. 2001a) (Robichaud 2005) (Larsen et al. 2009) are shown in **Table 1**. These coefficients account for initial losses of rainfall through initial abstraction and soil retention. The burnt runoff coefficient values are higher than unburnt runoff coefficients, this indicates that the majority of rainfall volume flows out of burnt area as surface runoff compared to runoff volume from unburnt area. The increased runoff from burnt area is attributed to factors such as soil water repellency, loss of surface cover, soil sealing by sediment particles and soil sealing by ash particles among others (Larsen et al. 2009).

Table 1: Runoff Coefficients for Burnt and Unburnt Plots

Ranges of Runoff generated for unburnt plots	Ranges of Runoff generated for burnt plots	Source
0.28	0.70	(Prosser and Williams 1998)
0.23	0.45	(Johansen et al. 2001)
0.20	0.63	(Robichaud 2005)
0.35	0.55	(Larsen et al. 2009)

The burnt surfaces produce significant amount of easily movable ash and sediment compared to an unburnt surface (Johansen et al. 2001). The easily movable sediments and ash get carried away during a post-fire flood. The surface runoff will carry the sediments to the drainage basin which can be transported to the reservoir. These sediments can have adverse effects such as reducing the reservoir storage and damage the water quality, among others (Fox et al. (1997), Son et al. (2015), Robichaud (2005)). The coefficients of sediment yield for burnt and unburnt plots are given in **Table 2**.

Table 2: Coefficients for Sediment yield from Burnt and Unburnt Plots

Burnt	Unburnt	Source
4563kg/ha	0.12kg/ha	(Mayor et al. 2007)
300 - 7500kg/ha	-	(Johansen et al.2001)
0-37kg/ha/mm	0-14kg/ha/mm	(Robichaud 2005)
28.2-113.3kg/ha/mm	2.3-4.2kg/ha/mm	(Larsen et al. 2009)
75kg/ha/mm	3kg/ha/mm	(Prosser and Williams 1998)

2.3. Types of Earth Dam Failures

A dam failure triggers a flood discharge to the downstream floodplain. This flood discharge has the potential to have a severe impact on the underlying infrastructures such as residential buildings bridges and road networks among others. For instance, a heavy rainfall resulting high runoff discharge could cause the dam to fail (due to various failure criterions such as, overtopping, landslide, piping among others as explained in **Table 3** and result in major flooding.

Table 3: Types of failures in Earth Dams

Types of Failure	Source	Description
Piping failure	(Cleary et al. 2014)	Occurs due to seepage of water through the dam structure towards the downstream end.
Overtopping Failure	(Cleary et al. 2014)	Inadequate spillway capacity leads to the outburst of the reservoir allowing the water to flow over the top of dam structure.
Landslide Failure	(Peng and Zhang 2013)	Erosion of dam material or an earthquake can cause the slope of the dam to slide resulting in a failure.

2.4. Downstream Flooding and Risk

The dam failure results in extensive discharge creating a flood event in the downstream floodplain affecting various infrastructure networks. This flood event has the potential to disrupt the normal functioning of infrastructure systems which can trigger a socio-economic impact in the potential flood zone. In a flood event scenario, Liu and Pender, (2012) proposed a new method to apply rapid flood spreading model (RFSM) using cellular automata.

The objective of the proposed model is to develop a fast inundation model that produced predictions comparable with those obtained from 2D shallow water equation models or observations (Liu and Pender 2012). Baecher et al. (1980) analyzed the dam failure in terms of cost. The direct losses due to dam failure are influenced by the occupancy of the floodplain on the downstream side of the dam (Baecher et al. (1980) Broaddus (2013) Ward, (2007)). Some of the properties at risk on the downstream side of the dam include buildings, bridges, roads, sewers, raw materials, materials in production etc. (Baecher et al. 1980). The failure in one of the above mentioned infrastructures could trigger a chain reaction of failures in other infrastructure based on their interdependence. The chain reactions of failure will increase the severity of risk posed by the dam failure.

Interdependency is bilateral relationship between two infrastructure influences or is correlated to the state of the other (Rinaldi et al. 2001). Disruption in one infrastructure can directly or indirectly affect other infrastructures which can impact the entire economy of the region. To analyze the risk involved due to the failure of the dam, we need to understand the concept of interdependency and how each infrastructure is interrelated with other infrastructure. Numerous studies were conducted to identify and understand the interdependency between infrastructures. It helps to quantify the vulnerability of any network of infrastructures. Rinaldi et al. (2001) classified the interdependency between infrastructures into four different types, (1) physical interdependency, (2) cyber interdependency, (3) geographical interdependency, and (4) logical interdependency.

Table 4: Types of Interdependency

Type of Interdependency	Source	Definition
Physical Interdependency	Rinaldi et al. (2001), Filippini and Schimmer (2012)	The dependency of one infrastructure on the output of the other structure is classified as physical interdependency
Cyber Interdependency	Rinaldi et al. (2001), Chou et al. (2010)	It is the dependency on the information exchange/flow through the network infrastructure
Geographic Interdependency	(Chou et al. 2010)	A local environmental event in one infrastructure impacts the remaining infrastructures in a system due to physical proximity
Logical Interdependency	Filippini and Schimmer (2012) Rinaldi et al. (2001)	There is no clear definition for this type of interdependency. Any dependency that doesn't fall under the above three cases is termed as logical interdependency. For example, the reduced gasoline prices increases the consumption of gasoline and traffic flow. In general, the dependency of infrastructure is based on human decisions and actions (Min et al. 2007).

The infrastructures occupied in the floodplain might fall into one of the categories mentioned in **Table 4** depending on the demographics of the regions. McDaniels and Chang (2007) stated that failure in interdependent infrastructure systems are due to an initial infrastructure failure stemming from an extreme event (e.g. post-fire flood resulting in a dam failure). Val et al. (2014) proposed a numerical model to study the performance of interdependent infrastructure based on an extended work network flow approach. The models were illustrated by probabilistic assessment of the performance of two interdependent infrastructure system when effected by flooding (Val et al. 2014). To identify the potential impact of a dam failure, risk posed on the infrastructure due a dam-break need to be measured. This could help the decision makers to take necessary steps to protect the critical infrastructure and minimize the impacts of dam failure event. To measure the risk, we need to define and identify the risk involved in a dam-break event.

2.5. Risk Assessment in Infrastructure

Many authors have defined risk in their own terms depending on the problem they are dealing with. **Table 5** provides few of those risk definitions provided over the years.

Table 5: Definitions of Risk

Source	Definition
US Department of Homeland Security (Fred and Robert 2008)	*Risk is defined as a potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and the associated consequences*
(Ezell and Ph 2003)	*A measure of the probability and severity of adverse effects*
(Kaplan 1997)	*A triplet of scenario, likelihood and consequences*
(McDaniels and Chang, 2007)	*A triplet of conditions: what could go wrong, how likely it is to go wrong and the consequences if it does go wrong*

For this specific study, we define risk as:

Risk: "The measure of impacts of post-fire rainfall runoff on earth dams resulting in a dam failure causing inundation in the downstream floodplain"

Risk assessment is a crucial step in protecting any infrastructure around the globe. Over the years numerous techniques were developed and employed to identify the risk in various categories of infrastructures. In identifying treats, measuring resilience of infrastructure, evaluating socio-economic impacts risk assessment's role is indispensable (Filippini and Schimmer 2012).

To help decision makers in protecting critical infrastructure wide variety of risk assessment methodologies have been developed. Each infrastructure system is different from the other and the impacts and consequences vary widely. Therefore, each infrastructure system might need different assessment methodologies to identify the risk accurately. **Table 6** presents some of the risk assessment methodologies that are found in the current literature which target specific infrastructure networks.

Table 6: Risk Assessing Tools

Source	Developed By	Tool	Infrastructure system	Target Criteria
(Drabble et al. 2009)	On Target Technologies, Inc. Sponsored by National Laboratories for the US Air force	Athena	Electrical, Natural Gas, Oil, pipelines, Drinking water, Telecom, Computer Network, Railways, and Banking & Finance.	Analysis of interdependent infrastructure networks, including political, military, economic and social aspects
(Sandia labs et al 2004)	Sandia National Laboratories	COMM-ASPEN	Electrical, telecommunications, Banking & Finance	Effects of both market decisions and interruptions of telecommunications infrastructure in the economy.
(Quarles and Haimes 2007)	Sandia National Laboratories and Los Alamos National Laboratories	IIM	Electrical, Drinking water, Telecommunications, Computer Networks, Highways and Roads	Determine the impact of a terrorist attack on an infrastructure and the cascading effects on all other interconnected infrastructures
(Beyeler et al 2002)	Sandia National Laboratories	Modular Dynamic Model	Electrical	Tracks the interactions between the electric infrastructure system in California
(Santella, et al. 2009)	Sandia National Laboratories & Argonne National Laboratories	CIPDSS	Analyze high-level behavior of metropolitan and regional infrastructure	Disruption in road & Telecom network due to a natural disaster (e.g. flood, earthquake)
(Cavdaroglu et al. 2011)		Mathematical formulation	To restore essential services provided by interdependent infrastructure after a natural event	Earthquake & Flooding
(Bradstock et al. 2012)		FIRESCAPE	To simulate landscape-scale fire regimes spread	Simulates wildfire spread across Australian eucalyptus forests.
(Liu and Pender 2012)		RFSM	To simulate a flood event using cellular automata	Flood Event
(Singh and Scarlatos 1988)		Analytical model	To analyze Earth-Dam breach erosion	Earth dam breach (rectangular, triangular, trapezoidal breaches)
(Cleary et al. 2014)		Scenario based risk-framework	To determine the consequences of different modes of earth dam failure	Earth dam failure (piping failure, overtopping failure)
(Peng and Zhang 2013)		Dynamic Decision Making framework	To help in decision making in evacuating the population at risk during a dam-break scenario	Earth dam failure (landslide failure)
(Chen et al 2012)		Numerical Model	To capture seepage passages and overtopping failure of the dam	Earth dam failure (seepage failure of earth-rock dams)
(Baecher et al. 1980)		Cost Analysis	Risk of dam failure is analyzed based on cost	Dam failure
(Newman et al. 2005)		CASCADE	Electrical	Failures in electricity transmission infrastructure

These tools can help assessing the risk in a given infrastructure when faced with a disaster. In this research a framework is developed to help assess risk defined earlier in this section targeting a specific set of infrastructures. The target infrastructures for this risk assessment study are earth dams. The interdependency and interaction of these infrastructure systems need to be studied to accurately assess the risk involved when one infrastructure fails.

2.6. Summary and Point of Departure

Previous researches reviewed in this chapter are limited to specific case studies as in case of Bradstock et al. (2012) where wildfire and climate change scenarios were modeled for Australian eucalyptus forests and Singh and Scarlatos, (1988) where the Teton dam failure was analyzed. Son et al., (2015) and Moody and Martin (2001) research discusses the change in characteristic properties of the landscape after a wildfire and change in runoff characteristics after a post-fire flood respectively. Both these studies does not expand further to study the impact of increased runoff and sediments on dams. Other studies like Cleary et al. (2014) and Peng and Zhang (2013) where dam failure scenarios were analyzed do not address the dam failure impact on infrastructure. Liu and Pender (2012) RFSM targets to reduce the computational data required to simulate a flooding event but does not focus on the effect of flood on infrastructure networks. The limitations in the above mentioned areas formulate the area of focus for this particular study where, the impact of a post-fire flood (considering climate change and wildfire) on an earth dam causing partial damage or complete failure is analyzed. The impact and extent of dam failure is analyzed by studying the disruptions caused in the floodplain of the dam. This analysis can help the decision makers to make efforts in prioritizing and protecting the vulnerable infrastructure from the climate change scenarios and natural disasters.

Chapter 3: Methodology

3.0. Introduction

As shown in **Figure 1**, the proposed framework in this thesis consists of four steps: (1) post-fire flood estimation, (2) dam-break modeling (3) risk assessment, and (4) risk-based decision-making matrix. In the first step the volume of runoff and sediments generated in a selected watershed are estimated. Based on runoff estimates, the dam-break models are built on WMS: SMPDBK. The results from the dam-break models are used to estimate the affected population, number of residential buildings and other infrastructures within the flood plain using Hazus inventory data and ArcMap. These estimates are used to assess the risk of dam-break in terms of Social, Economic and Environmental impacts. Finally, using the results obtained from the estimates, a decision-making matrix to prioritize the watershed-dam-floodplain zones is proposed to assist decision makers in allotting funds effectively to minimize loss of lives and property.

The process of post-fire flood estimation and their potential impacts is described in section 3.1. The dam-break modeling using WMS: SMPDBK is discussed in section 3.3. Section 3.4 describes the dam-break model results and categorization of impacts into social, economic and environmental. Section 3.5 proposes a decision making matrix based on the risk due to a post-fire flood and dam-break event.

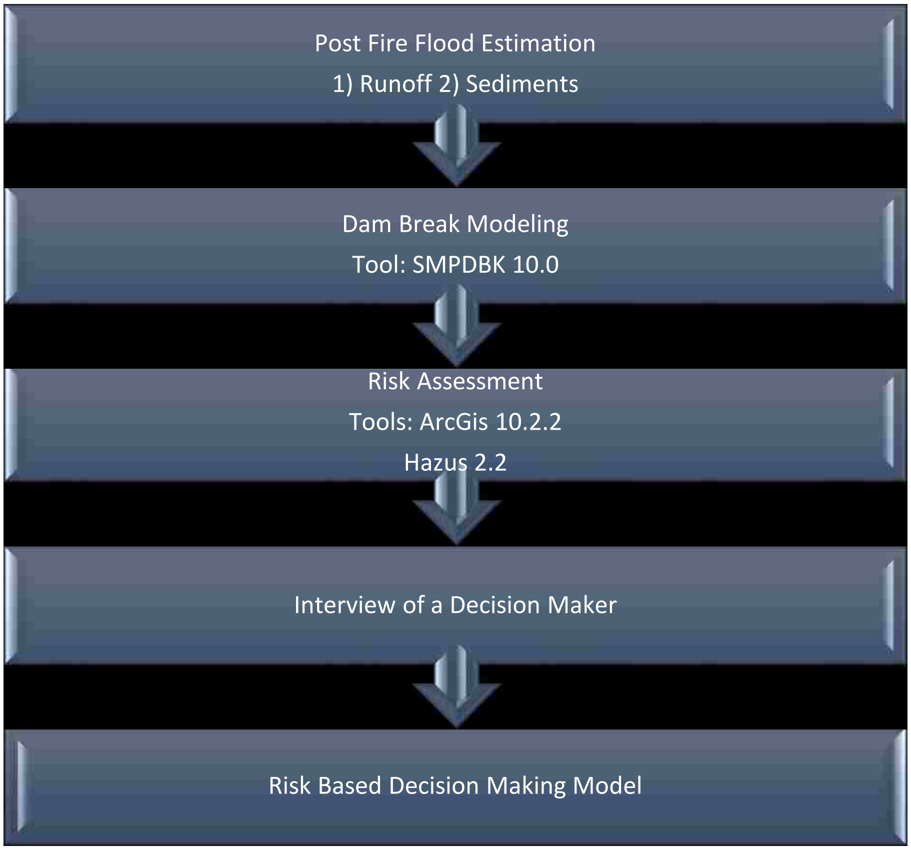


Figure 1: Framework of Methodology

3.1. Post-Fire Flood Estimates

3.1.1. Runoff Estimates

A wildfire event potentially changes the soil characteristics of the affected area. When the wildfire zone overlaps with a reservoir's drainage area, the changed soil characteristics can potentially affect the reservoir and dam. In order to determine the impacts of wildfire the following quantities were estimated: 1) the surface runoff from a post-fire flood, and 2) and the sediments generated from burnt area. The primary assumption to estimate the runoff is that a specific percentage of watershed area is burnt which produces higher amount of runoff compared to runoff produced under normal condition (unburnt condition).

The runoff from a post-fire rainfall is estimated using the empirical relation shown in **Table 7**. The empirical relation consists of burnt and unburnt runoff coefficients, percentage area affected by wildfire, percentage area affected by rainfall, rainfall over the watershed as variables. Each of these variables are given under different probability distribution (given in **Table 8**) based on the values obtained from previous studies and other sources (as in case of rainfall over the watershed which was obtained from USGS). The percentage of area affected by rainfall indicates the extent of area in a given watershed experiences a post-fire rainfall and similarly the percentage of area affected by wildfire. The runoff generated in a post-fire flood is estimated using @Risk that uses Monte Carlo simulation. The Monte Carlo simulation helps us to model the uncertainty of the runoff volumes generated based on the probability distributions of the variables. The probability distributions of the variables used in the empirical relation used to estimate the runoff volume are given in **Table 8**. The runoff is estimated based on relations provided in **Table 7** and three different scenarios (i.e., 100%, 75% and 50%) of burnt watershed are considered. For each watershed, runoff and sediments are estimated for 25-year rainfall storm with 95% confidence.

Table 7: Runoff Estimation equations

Area of watershed (Acres)	Percentage of area affected by wildfire	Percentage of area affected by rainfall	Rainfall Intensity (ft.)	Runoff coefficient unburnt area	Runoff coefficient burnt area	Runoff Volume (ft^3)	Source
A	100%	A_{R1}%	P	0.26	0.58	R_1 = Ax100%x A_{R1}%$_1$[0.58P]	(Prosser and Williams 1998)
A	75%	A_{R2}%	P	0.26	0.58	R_2 = (Ax A_{R2}%)x75%[0.58P]+(Ax A_{R2}%x)25%[0.26P]	
A	50%	A_{R3}%	P	0.26	0.58	R_3 = (Ax A_{R3}%)x50%[0.58P]+(A A_{R3}%)x50%[0.26P]	

Table 8: Probability Distribution of Variables used in Runoff Estimation using @Risk

Variable	Values			Distribution
	Min	Average	Max	
Unburnt Coefficient	0.2	0.28	0.35	Pert
Burnt Coefficient	0.45	0.58	0.7	Pert
Area of Burnt Watershed	0	-	100	Uniform
Area Affected by Rainfall	0	-	100	Uniform
Rainfall	1.64	1.93	2.21	Pert (Values are for Case II watershed)

The runoff volumes (R) are estimated using the empirical relations shown in **Table 7** For a 25 year rainfall with 90% confidence interval. The average life expectancy of a dam is about 50 years(U.S. Army Corps of Engineers, 2012), therefore a 25 year rainfall event is selected which might occur twice in the life span of a dam resulting in its failure or which might inflict adverse effects on the lifespan of the dam. The runoff volumes estimated based on **Table 7** empirical relations are used to estimate a ratio between a post-fire rainfall runoff and normal rainfall runoff for different burnt watershed scenarios. These ratios are used to convert the peak-stream flow values obtained from stream gages located on the upstream inlets of the reservoirs. The peak-stream values are from a normal rainfall flood and these values are converted to a post-fire rainfall based on the runoff ratios.

The stream gage data is available on the USGS-National Water Information System. The USGS website consists of historical stream gage data at different locations across the nation. Peak stream flow data is downloaded to estimate a 95% confidence interval peak stream discharge value with a 25 year return period. To estimate the 25 year peak flow, "PeakFQ" a flood frequency analysis tool developed by USGS is used. This program allows us to estimate the peak discharge value for different flood return periods. Using stream gage data as the input to PeakFQ, peak discharge in that location for a 25 year return with 95% confidence is generated. From the stream gage data, a '100 year historical data' is obtained. Using the PeakFQ's peak discharge estimates, an event similar to the 25 year return discharge event is selected from the '100 year historical data', and the total runoff generated in that event is estimated. The runoff volumes are multiplied with the ratios generated using the expressions given in **Table 9**. The P (rainfall intensity) values are obtained from NOAA's National Weather Service Hydro meteorological Design Studies Center (www.nws.noaa.gov) for 25-year rainfall with 90% confidence intervals. The data provided in the website is obtained from different rain gage stations located all over United States. For each reservoir stream gage data is collected and total runoff discharge volume is estimated. These runoff volumes are used in dam-break modeling. The total runoff generated from the watershed is assumed to reach the reservoir without any losses during their transport for simplicity purposes.

Table 9: Relations to Estimate Runoff Volume Ration between Post-fire Rainfall and Normal Rainfall

Area of watershed (ft^2)	Percentage Area affected by wildfire	Percentage of area affected by rainfall	Rainfall (ft.)	Post-fire Runoff (R) (ft^3)	Normal Runoff (R_2)(ft^3)	Ratio of Runoff Volume Change
A	100%	A_{R1}%	P	R_1 = Ax100%x $A_{R1}\%_1$[0.58P]	R_N = $A_{R1}\%_{1x}$Ax100%[0.26P]	$R_{100} = R_1/R_N$
A	75%	A_{R2}%	P	R_2 = (Ax A_{R2}%)x75%[0.58P]+(A x A_{R2}%x)25%[0.26P]	R_N = A_{R2}%xAx100%[0.26P]	$R_{75} = R_2$/RN
A	50%	A_{R3}%	P	R_3 = (Ax A_{R3}%)x50%[0.58P]+(A A_{R3}%)x50%[0.26P]	R_N = A_{R3}%xAx100%[0.26P]	$R_{50} = R_3$/RN

Table 9 shows the equations to compare the increased percentage of runoff from a normal flood to a post-fire flood. These percentage estimates can help in understanding the change in flood intensities for a post-fire flood.

3.1.1.1. Critical Runoff Inflow Volume (Q_{crit})

In this research, overtopping failure is considered as the only failure criteria for earth dams. Considering the overtopping effect, a variable named 'Critical Runoff Inflow Rate', Q_{crit} is introduced for each dam. The critical runoff inflow rate is the runoff inflow rate that causes overtopping of dam leading to its failure. The critical inflow rate is estimated based on the reservoir capacity (volume of the reservoir), and outlet or spillway capacity. To estimate the Q for a given watershed and dam, various parameters are used which are listed in **Table 10**. V_{rev} is the total active capacity of reservoir. V_{cur} indicates the current volume of water stored in the reservoir. V_{pfr} indicates the volume of runoff generated in a post-fire rainfall.

Q_{out} is the outflow capacity of the dam, or the total spillway capacity which includes primary and secondary spillways. Q_{in} is the runoff inflow value which indicates the rate at which the reservoir receives the runoff generated by post-fire rainfall. Q_{acc} is the rate at which the water accumulates in the reservoir. V_{rem} is the volume of the reservoir that needs to be filled to reach the maximum storage capacity of the reservoir. T_{dur} is the duration of the post-fire rainfall event and T_{otp} is the time taken to fill V_{rem}. To estimate Q_{crit}, the input variables are V_{rev}, V_{cur}, V_{pfr}, and Q_{in}. V_{rem} is estimated using V_{rev} and V_{cur}. $V_{rev,}$ V_{cur}, and Q_{out} are readily available for a given dam. The V_{pfr} is the runoff volume generated from the watershed that is estimated using the relations provided in **Table 9**. The T_{dur} is the duration of the rainfall event that occurred in a given watershed which is an assumed quantity in this analysis, however, this is a known quantity in for an actual post-fire rainfall event. The runoff generated from the watershed is assumed to be uniform during the duration of rainfall event to minimize the complexity of the model. To estimate the Q_{crit}, the total runoff volume generated (V_{pfr}) during the post-fire rainfall event is assumed to reach the reservoir in T_{dur} Hours. This assumption allows us to estimate the Q_{in} as shown in **Table 10**, which is the rate at which the runoff volume (V_{pfr}) is received at the reservoir. Using the values of Q_{out} and Q_{in}, the Q_{acc} (the rate at which the reservoir reaches its maximum storage capacity) is estimated as shown in **Table 10**. The time taken to reach the reservoir's maximum capacity at the rate Q_{acc} is T_{otp}. If T_{otp} is less than T_{dur}, the reservoir reaches its total capacity before the flood runoff inflow ends. This indicates that the reservoir is receiving more runoff than it can store and release. This imbalance causes an overtopping situation in which an earth dam fails. If the T_{otp} is more than T_{dur} the dam can store and release the entire runoff volume without reaching the reservoirs maximum capacity.

In such case, no overtopping situation is observed and hence the dam is safe. From this hypothesis, an overtopping condition is observed if $T_{otp} >= T_{dur}$. The runoff inflow (Q_{in}) that causes $T_{otp} = T_{dur}$ is termed as Q_{crit}, as this Qcrit is responsible for an overtopping effect. If Q_{in} reaches Q_{crit}, dam overtopping is observed leading to its failure. The V_{pfr} that causes Q_{crit} (as $Q_{in} = V_{pfr}/ T_{dur} *60*60$) can be termed as critical runoff volume (V_{crit}) resulting from a certain burnt and post-fire rainfall conditions in a given watershed. The burnt and post-fire rainfall conditions that causes Q_{crit} can be termed as critical burnt and rainfall conditions.

Table 10: Description of Variables Used in Q_{crit} Estimation

Variable Description	Symbol	Quantity	Units
Current reservoir capacity	V_{rev}	Known quantity	Acre-ft.
Current volume stored in the reservoir	V_{cur}	Known quantity	Acre-ft.
Duration of the post-fire rainfall event	T_{dur}	Known quantity	Hrs.
Runoff volume from Post-fire rainfall	V_{pfr}	Estimated based empirical relation	Acre-ft.
Outflow capacity(spillway)	Q_{out}	Known quantity	ft^3/s
Inflow	Q_{in}	$V_{pfr}/ T_{dur} *60*60$	ft^3/s
Rate of runoff accumulation in the reservoir	Q_{acc}	$Q_{in} - Q_{out}$	ft^3/s
Reservoir capacity to be filled	V_{rem}	$V_{rev} - V_{cur}$	Acre-ft.
Time taken to reach V_{rem}	T_{otp}	$[(V_{rem} / Q_{acc})/60*60]$	Hrs.

When the runoff volume exceed reservoir storage capacity it can result in overflowing (dam overtopping) at the dam crest. Overtopping or overflow causes an earth dam to fail and it is one of the major cause of earth dam failure leading up to 36.4% of all failure causes (Zhang et al. 2009). Therefore a dam-break analysis has to be performed to estimate the risk associated with dam-break flooding.

Various software tools such as FLDWAV or DAMBRK, FLO-2D, and WMS-SMPDBK among others, are available to perform a dam-break analysis and flood forecasting in downstream valley. Out of these available tools, WMS-SMPDBK (Watershed Modeling System-Simplified Dam Break flood forecasting model) is selected to run the dam-break analysis. WMS-SMPDBK was developed by National Wealth Service (NWS).

The reasons for opting WMS as a dam-break modeling tool are given below.

1. WMS: SMPDBK is economic in terms of cost compared to DAMBRK and FLO-2D
2. WMS: SMPDBK models are more accurate compared to models built using DAMBRK (Moharrampour et al. 2011)
3. WMS: SMPDBK model requires much less computational power compared to other dam-break modeling tools (Moharrampour et al. 2011).

The program was aimed to reduce the time, data and expertise required to develop a dam-break model (Moharrampour et al. 2011). It precisely reconstructs the river channels, watershed terrain and boundaries conditions, and its drainage flows (Shahraki et al. 2012).

3.2.2. Sediments Estimates

The sediment yield from a post-fire flood is estimated using the average coefficient values obtained from various studies listed in **Table 2**. **Table 11** provides the equations to estimate the sediment yield from watersheds due to a post-fire rainfall storm. The sediment yield is affected positively by the total rainfall in that given time (Robichaud et al. 2013). Similar rainfall duration as mentioned in section 3.1.1 (25yr rainfall storm with 95% confidence) is used to estimate the sediments generated from the watershed. The post-fire rainfall that occurs after a wildfire generates excess runoff and sediments from the watershed (Cerdà and Doerr 2008) and hence the same rainfall intensity is used to estimate both the runoff and sediments generated from the watershed. The annotations used in equations shown in **Table 11** are given in **Table 12**.

Table 11: Expressions to estimate sediments from post-fire flood

Area effected	Total Runoff Volume R (ft^3)	Total Sediment yield (tons)
100%	R_1 = Ax100%x A_{R1}%$_1$[0.58P]	{(A x A_{R1}x100%[0.58P])X28.31X16.97}/1000000
75%	R_2 = (Ax A_{R2}%)x75%[0.58P]+(Ax A_{R2}%x)25%[0.26P]	{(A x A_{R1}x75%[0.58P]X28.31x16.97)+(A x A_{R1}x25%[0.26P]X28.31X1.32)/1000000}
50%	R_3 = (Ax A_{R3}%)x50%[0.58P]+(A A_{R3}%)x50%[0.26P]	{(A x A_{R1}x50%[0.58P]X28.31X16.97)+(A x A_{R1}x50%[0.26P]X28.31X1.32)/1000000}

Table 12: Annotation for expressions in Table 10

Precipitation	P
Area of watershed	A
Burnt runoff coefficient	0.58
Unburnt runoff coefficient	0.26
Burnt sediment yield coefficient	16.97
Unburnt sediment yield coefficient	1.32
Ft^3 to liters conversion factor	28.31

3.3. Dam-Break Modeling with WMS: SMPDBK

The Simplified Dam-Break (SMPDBK) is developed by the National Weather Service (NWS) for predicting downstream flooding produced by a dam failure. The SMPDBK flood prediction model uses GIS environment and elevation data to generate the flood maps (Shahraki et al. 2012). SMPDBK requires minimum computer facility and data to predict the downstream flood due to dam-break. This program is capable of producing the information necessary to estimate flooded areas resulting from dam-break floodwaters while substantially reducing the amount of time, data, and expertise required to run a simulation of the more sophisticated unsteady NWS DAMBRK, or FLDWAV (Shahraki et al. 2012). SMPDBK uses Digital Elevation Model (DEM), Triangulated Irregular Network (TIN) and Geographic Information System (GIS) to process the terrain data and boundary conditions. The downstream hydraulic geometry model of the river is built using DEM and TIN files which can be imported from online data sources. A stream centerline is constructed which represents the river path on the downstream of the reservoir as shown in **Figure 2.** The river stream centerline is cut at different locations as shown in **Figure 3** which has the cross section data of the river channel. The area adjacent to the river stream is divided into various polygons and are assigned with a specific area property such as, grassland, residential area, and river drainage among others as shown in **Figure 4** with annotations provided in **Table 13**.

Each area polygon is assigned with respective Manning's roughness coefficient which affects the flood velocity and extent of flood (Prakash et al. 2014). Manning's coefficients values are provided by the program (WMS-SMPDBK). Other variables like elevation of water in the reservoir, volume of reservoir, surface area of reservoir are available from U.S. Department of Interior Bureau of Reclamation. **Figure 5** shows the input window in SMPDBK where the dam/reservoir data is entered. Few parameters (time for breach to develop, and rectangular breach width) are unaltered in the input window of SMPDBK as we consider only overtopping failure at the dam crest which is not associated with dam breach mechanism.

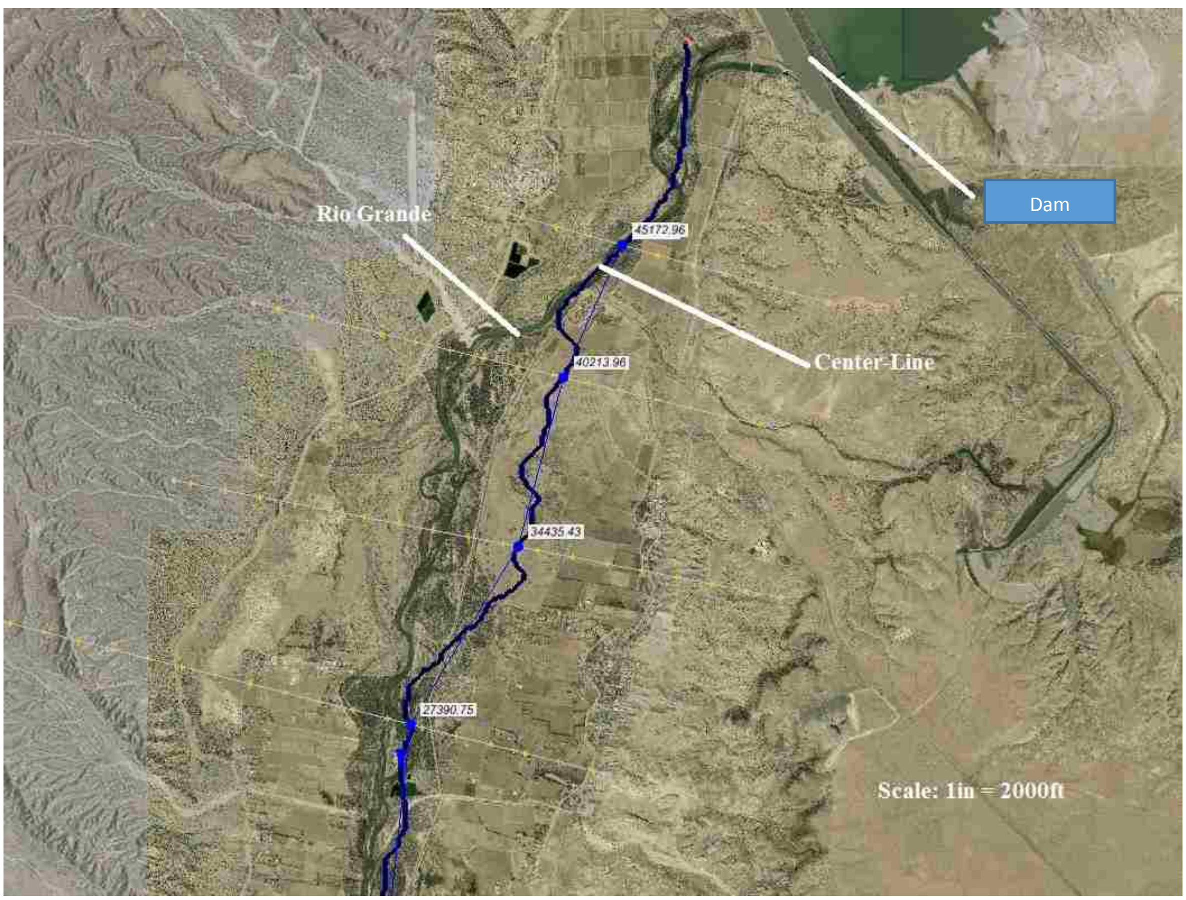


Figure 2: River Stream Centerline

The remaining parameters are assigned appropriately based on each scenario which are shown later in chapter 4. SMPDBK uses these parameters to create water surface elevation data set which can be used to generate a flood delineation map.

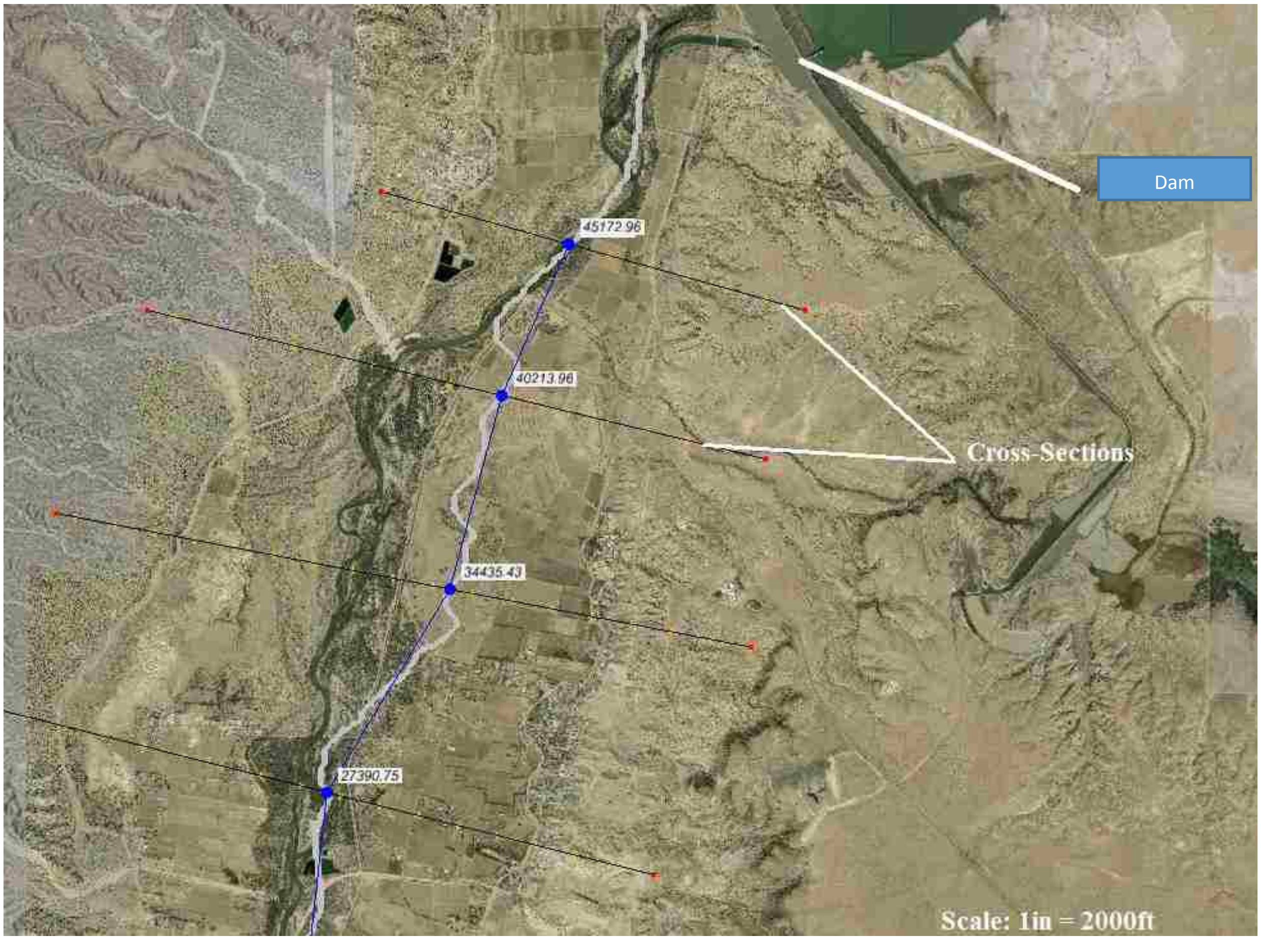


Figure 3: River Stream cross sections

Figure 4: Types of area divided into polygons
[Scale: 1in = 1mile]

Table 13: Annotation for polygon colors

	River Drainage
	Residential Area
	Farmlands

Item	Value	Units
Dam name:	Cochiti	
River name:	Rio Grande	
Dam type:	Earth dam	
Elevation of water when dam breaches:	5471.0	ft-msl
Elevation of breach bottom:	5230.0	ft-msl
Volume of the reservoir:	736000.0	ac-ft
Surface area of the reservoir at dam crest:	9060.0	acres
Width of rectangular breach:	125.0	ft
Time for breach to develop:	60.0	minutes
Non-breach flow (includes outlet, spillway, and overtopping):	14790.0	cfs
Dead storage equivalent Manning's N:	0.5	
Number of cross sections:	8	
Distance to primary point of interest:	20.0	miles
Define maximum cross section depth:	Define	
Maximum cross section depth:	200.0	ft

Figure 5: SAMPDBK Dam Break Model Inputs

Units:

cfs = Cubic feet per sec
ft = feet
ft-msl = mean sea level (elevation in feet)
ac-ft = acre-feet

In **Figure 5**, the values shown are for one of the three scenarios analyzed for Case II dam. The variables such as elevation of water, elevation of breach bottom, volume of reservoir, non-breach flow (which is essentially overtopping and spillway), and surface area of reservoir are updated for each scenario based on the volume of runoff estimated in each scenario. The river name and dam name are assigned by for each dam separately. The type of dam can be selected by the drop-down menu, where earth dam is selected in all cases. Dead storage equivalent Manning's N is unaltered in all cases, where the initial value is taken by the program as 0.5.

Number of cross-sections is automatically assigned based on number of cross-sections cut by the user as shown in **Figure 3**. The runoff volumes measured from the historic data is used in building the models on WMS for each scenario (100%, 75% and 50% burnt watersheds).

3.4. Risk Assessment:

The dam-break results in inundation of downstream floodplain. The impacts due to dam-break can be severe depending on flood plain occupancy rate (Baecher et al. 1980). Therefore, it is necessary to study the floodplain inundation to estimate the impacts of post-fire flood and dam-break events. SMPDBK gives a flood plain water depth map. SMPDBK is a simplified dam-break analysis and hence it does not account for a detailed impact on the floodplain. Additional data required for the analysis is imported from Hazus inventory for New Mexico. HAZUS is multi-hazard loss estimation software developed by FEMA that is able to estimate the losses from earthquakes, hurricanes, and floods events (FEMA, 2015). The flood delineation map from SMPDBK and Hazus inventory data are imported to ArcMap. All further analysis is performed on ArcMap 10.2. Hazus inventory data is specifically focused on floodplain occupancy (total population, number of residential buildings, residential buildings, public utility buildings, schools, emergency centers, hospitals and fire stations among others) of each dam under consideration. From SMPDBK output, a flood extent polygon is generated as shown in **Figure 6** and imported to ArcMap. Hazus inventory data is overlapped with the flood extent polygon of SMPDBK. The population and infrastructure (such as houses, public buildings, fire stations, schools, and hospitals among others) within the flood extent polygon is considered to be at risk due to the dam-break inundation.

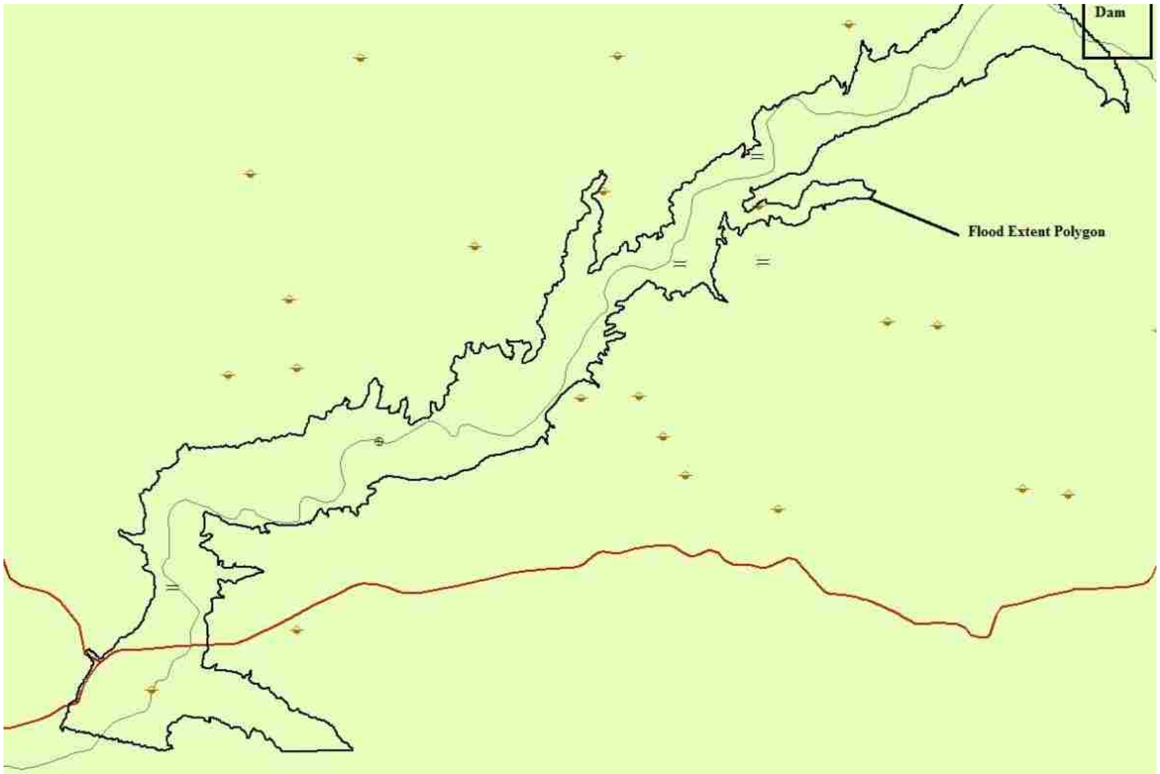


Figure 6: Flood extent in Case I Dam's Floodplain
[Scale 1in -1 mile]

Few operations such as buffer, intersect, and field calculator are performed within ArcMap to estimate the population, number of residential buildings and different infrastructures under the impact of inundation. The flood extent for each scenario varies based on runoff volumes estimated with 95% confidence for each burnt scenario. These are the impacts when the dam fails due to excess runoff, however if the runoff does not exceed the reservoir capacity, the dam might not fail.

If the runoff generated from a post-fire flood exceeds the reservoir capacity, the dam fails and the above mentioned impacts can be assessed. But, if the runoff is not high enough, it might not result in a dam failure. In no-dam-break scenario the excess runoff and sediments can have adverse effects (such as reducing the reservoir capacity, increasing vulnerability of dam to future floods (Robichaud 2005)) on the dam. In both dam-break and no-dam break scenarios the impacts are classified into social, economic and environmental impacts.

Summing up the above mentioned hypothesis, there is uncertainty in percentage of watershed burnt, rainfall intensity that occur over the burnt region, runoff generated from burnt region, dam failure, population affected, and residential buildings affected. To provide a solid ground for decision making model, a decision-making matrix is proposed which aggregates all the above mentioned uncertainties. The idea behind decision-making matrix is to identify the watershed with a chance of higher impacts on the floodplain due to dam-break flooding. Before forming the decision-making matrix, a detailed hierarchy of risk assessment is presented in **Figure 7**, consisting of a flow chat of events that could occur after a wildfire event. Depending on the amount of runoff and sediments, two possible outcomes are considered, (1) dam-break scenario, (2) no dam-break scenario.

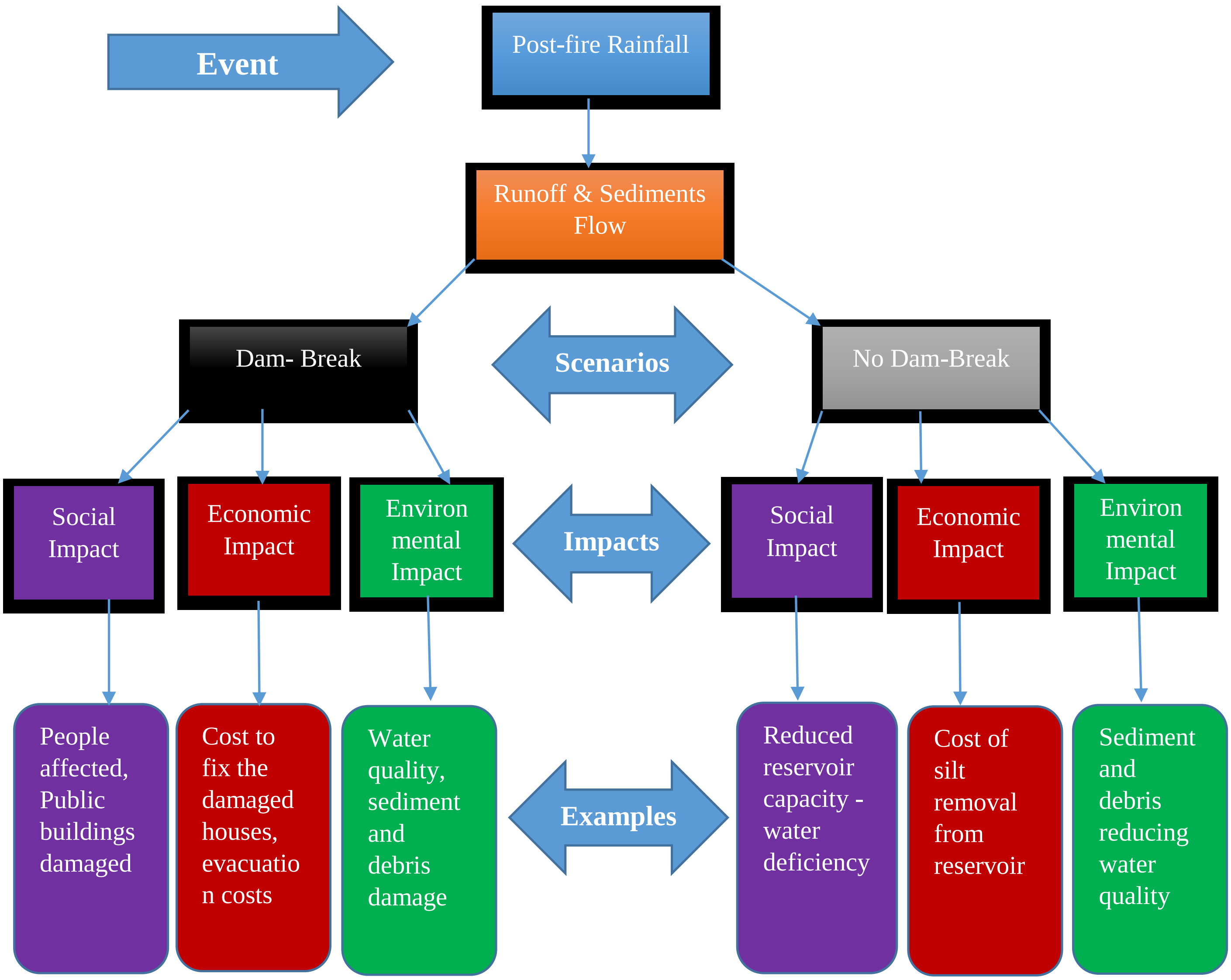


Figure 7: Risk Assessment Hierarchy

This research majorly focuses on the economic impact of a post-fire dam-break flood. Residential zone in the floodplain faces major impact from a dam-break flooding event (DeKay and McClelland 1993). Therefore it is important to estimate the approximate cost of damage due to post-fire flood. National Flood Insurance Program (NFIP) a division of FEMA runs a website (floodsmart.gov) which consists of information related to various flood scenarios, flood damage cost for residential buildings, flood facts, media sources, preparation and recovery tips, and other resources to help people minimize flood impact. The website consists of illustrative animations showing various types of flooding events. The information we seek from this website is to obtain the cost of flooding event for residential buildings. The website provided costs for two different sizes of residential buildings (1)1000 square feet, (2)2000 square feet for different flood levels ranging from one inch to four feet. However, the costs were provided for illustrative purpose and the values may vary from state to state.

The costs provided in the NFIP website does not account for post-fire flood scenario, therefore a comparison of impacts between a post-fire flood and normal flood are listed in **Table 14** to identify the similarities and differences. The table consists of impacts listed in social, economic and environmental categories obtained from previous studies on flooding and post-fire flooding events. **Table 14** provides evidences that a normal flood can approximately have similar or higher impact as a post-fire flood. Based on this hypothesis, the values provided in **Table 15** obtained from NFIP (floodsmart.gov) can serve as an approximate minimum cost of damage for residential buildings in the floodplains observed in this study. **Table 15** has the cost values for three different flood depths 6inch, 12inch and 24inch. The values provided are for illustrative purpose and to approximately estimate the economic impact of the post-fire and dam-break flooding.

Table 14: Comparison of post-fire flood and normal flood impacts

Social		Economic		Environmental		Source
Post-fire Flood	Flood	Post-fire Flood	Flood	Post-fire Flood	Flood	
Similarities		**Similarities**		**Similarities**		
Lives threatened and Public Health	Lives threatened and Public Health	Relocation cost(evacuation and sheltering costs)	Relocation cost(evacuation and sheltering cost)	Damage to economic resource zones	Damage to economic resource zones	(Tony 2011) (Diaz 2012) (Ganderton 2000) (Townsend and Douglas 2004) (Erickson, n.d.)(Meyer et. al. 2009) (Scheuer, et al. 2011)(Peng et. al. 2013) (Costa et al. 2004).
Damage to public utility buildings	Damage to public utility buildings	Partial to complete residential building damage	Partial to complete residential building damage	Temporary or permanent Wildlife habitat destruction	Temporary or permanent Wildlife habitat damaged	
Disruption of daily routine	Disruption of daily routine	Damage to public buildings	Damage to public buildings			
Social hot-spots and Recreation centers	Social hot-spots and Recreation centers					
Evacuation	Evacuation	Economic zones access restricted	Economic zones access restricted			
Differences		**Differences**		**Differences**		
Police barricading and controlled traffic movement	Traffic diversion	Additional cost due to traffic diversions and cost of sediment and debris removal	Additional cost due to traffic diversions	Watershed and water quality damage	Water quality degradation	
		Watershed and water quality restoration	Water quality restoration	Sediments, ash debris deposition	Sediments might deposit	

The values in **Table 15** are listed for various individual damages in a residential building. In later part of the research, the number of residential buildings under the flood impact are estimated for each dam failure scenario and the cost of damage values from **Table 15** are used to calculate the total damage to the residential zone in the floodplain.

Following assumptions were made in estimating the total damage of residential sector, 1) all the residential buildings in the floodplain fall under the sizes of 1000sqft and 2000sqft, 2) each residential building holds the items listed in **Table 15**, 3) the cost of flood damage values can be approximately equal to the post-fire flood damage costs.

Table 15: Cost of Damage for residential buildings

Depth of Flood	6"		12"		24"	
Size of building	**1000Sft**	**2000Sft**	**1000Sft**	**2000Sft**	**1000Sft**	**2000Sft**
Cleaning	$1,000.00	$2,000.00	$1,300.00	$2,600.00	$1,800.00	$3,500.00
Doors & Base trim & Windows	$1,100.00	$2,150.00	$1,100.00	$2,150.00	$1,100.00	$2,150.00
Electrical & Plumbing	$150.00	$320.00	$900.00	$1,660.00	$1,600.00	$3,000.00
Finished floor-wood-Carpet	$7,900.00	15,870.00	$7,900.00	15,870.00	$7,900.00	15,870.00
Interior wall-Finishes	$1,000.00	$1,920.00	$1,000.00	$1,920.00	$1,000.00	$1,920.00
Wall Insulation, Drywall or Plumbing	$1,500.00	$2,910.00	$1,500.00	$2,910.00	$1,500.00	$2,910.00
Kitchen & Bath Cabinets	$2,400.00	$4,500.00	$2,400.00	$4,500.00	$2,400.00	$4,500.00
Appliances	$90.00	$180.00	$2,200.00	$4,200.00	$2,200.00	$4,200.00
Repair of furnace/AC	$250.00	$270.00	$450.00	$470.00	$2,200.00	$2,200.00
Bedroom furniture	$950.00	$1,800.00	$2,900.00	$5,500.00	$4,500.00	$8,500.00
Dining Room Tables & Chairs	$900.00	$1,700.00	$900.00	$1,700.00	$1,300.00	$2,400.00
Kitchen ware & Food	$150.00	$330.00	$400.00	$730.00	$400.00	$730.00
Living room-Furniture	$1,400.00	$2,700.00	$1,400.00	$2,700.00	$1,900.00	$3,600.00
Computer Accessories	$600.00	$1,100.00	$600.00	$1,100.00	$600.00	$1,100.00
Television-Stereo etc.	$80.00	$150.00	$150.00	$280.00	$650.00	$1,200.00
Washer / Dryer	$80.00	$150.00	$500.00	$980.00	$500.00	$980.00
Accent Furniture & Accessories	$250.00	$450.00	$250.00	$450.00	$850.00	$1,620.00
Loss of personal items	$350.00	$650.00	$1,300.00	$2,500.00	$1,300.00	$2,500.00
Total loss due to flood	**$20,150.00**	**$39,150.00**	**$27,150.00**	**$52,220.00**	**$33,700.00**	**$62,880.00**

The impact on the floodplain is not limited to the residential zone, it extends to public utilities such as fire stations, gas stations, telecommunication infrastructures, road networks, railroad networks, bridges, industries among others. The interdependency between these infrastructures can adversely increase the impact of dam-break thus adding to the impacts of post-fire flood and wildfire events. Types of infrastructure interdependencies are (Physical Interdependency, Cyber Interdependency, Geographical Interdependency, and Logical Interdependency) explained in Section 2.3. When the dam-break model results are interpolated with Hazus data as mentioned earlier in this section the infrastructures under the flood impact can be identified.

The cost of damages to the residential buildings are estimates as shown in **Table 16** using the costs given in **Table 15**. The damage costs are estimated for the worst case scenario (100% watershed burnt scenario). The total buildings under impact in the worst case scenario are divided equally between the sizes and the depths of flooding as shown in **Table 16**.

Table 16: Residential Building Damage Cost Estimating Table

Size of Building(ft^2)	Depth of Flood (in)	Cost to Fix each Unit	Total number of units	Total Cost
1000	12	$ 27,150.00		
2000	24	$ 52,220.00		
1000	12	$ 33,700.00		
2000	24	$ 62,880.00		
Total Cost of Damage				**$ -**

3.5. Decision-Making Matrix

Based on the hypothesis stated in section 3.4, there is uncertainty in the events of dam-break flooding, population affected, residential buildings and infrastructure impacted due to inundation. To present the uncertainty a decision-making matrix is proposed based on the estimated impacts resulted from each dam-break scenario. The three scenarios of wildfire are (1)100% watershed burnt in a wildfire, (2)75% watershed burnt in a wildfire, and (3)50% watershed burnt in a wildfire. The flood extent maps were interpolated with Hazus inventory data to obtain the floodplain impacts. The impacts are summarized in the form of matrix shown in **Table 17** where one can compare the impacts of dams for different scenarios. The higher the impacts, higher is the risk due to dam-break and post-fire flood event. The higher the risk due to dam failure, higher the vulnerability of the dam. Based on the impacts, the watershed-dam-floodplain zone is prioritized and the zone with highest impact is considered as high hazard zone. This categorization of each zone can help the governing agencies to allocate necessary funds on mitigation alternatives to minimize the impacts on stakeholders.

Table 17: Decision-Making Matrix

Dam	Impacts in Floodplain	50 % watershed burnt scenario	75 % watershed burnt scenario	100 % watershed burnt scenario	Critical Watershed Burnt Percentage	Critical Watershed Affected by Post-fire Rainfall Percentage
Case I	Population affected					
	Residential Buildings affected					
	Cost of Damage to Residential Buildings					
	Sediment Yield					
	Infrastructures at risk					
Case II	Population affected					
	Residential Buildings affected					
	Cost of Damage to Residential Buildings					
	Sediment Yield					
	Infrastructures at risk					
Case III	Population affected					
	Residential Buildings affected					
	Cost of Damage to Residential Buildings					
	Sediment Yield					
	Infrastructures at risk					

The uncertainty matrix provided in **Table 17** lists the impacts over three different watershed burnt scenarios for three different dams. For each dam-break scenario, the total population, total number of residential buildings, cost of damages to the residential buildings and infrastructures impacted are identified and listed. The numbers are estimated from the runoff volumes generated for a 25-year peak-stream flow with 95% confidence. The potential number of population affected, residential buildings damaged and infrastructure under impact are estimated for the 25-year rainfall storm. Various infrastructures such as bridges, roads and other essential facilities impacted by flood inundation are listed in the matrix. The three dams studied in this research are described in section 3.6.

3.5.1. Interview with Decision-Maker:

A telephone interview is conducted with a decision-maker to validate the assumptions made and justify the hypothesis assumed in risk assessment. A set of questions related to the dam safety, life-time, emergency responses, and decision-making are posed to the decision-maker whose responses are taken as input from in assessing the risk for dam-break and no dam-break scenarios. The questions posed to the decision-maker are listed in the appendix.

3.6. Case Study:

The three different earth dams are studied as Case I, Case II and Case III. All the three dams are earth dams built in different regions of New Mexico. The dams are picked based on their watershed's proximity to a wildfire event in New Mexico. A map with active and inactive wildfires in New Mexico is provided in **Figure 8**. The Map is provided by NMWatch which is a public website developed and hosted by the Earth Data Analysis Center, University of New Mexico. This website provides information about wildfires affecting the State of New Mexico. In **Figure 8** the watershed of dams selected are highlighted with a circle. At least one wildfire (active and inactive) events are recorded in these regions. Therefore the selected watersheds might have a risk of wildfire and post-fire rainfall events resulting in excess runoff and sediments.

The symbols annotation used in the map are given below:

-  In active wildfire
-  Active wildfire
-  Active fire report
-  Prescribed burn active

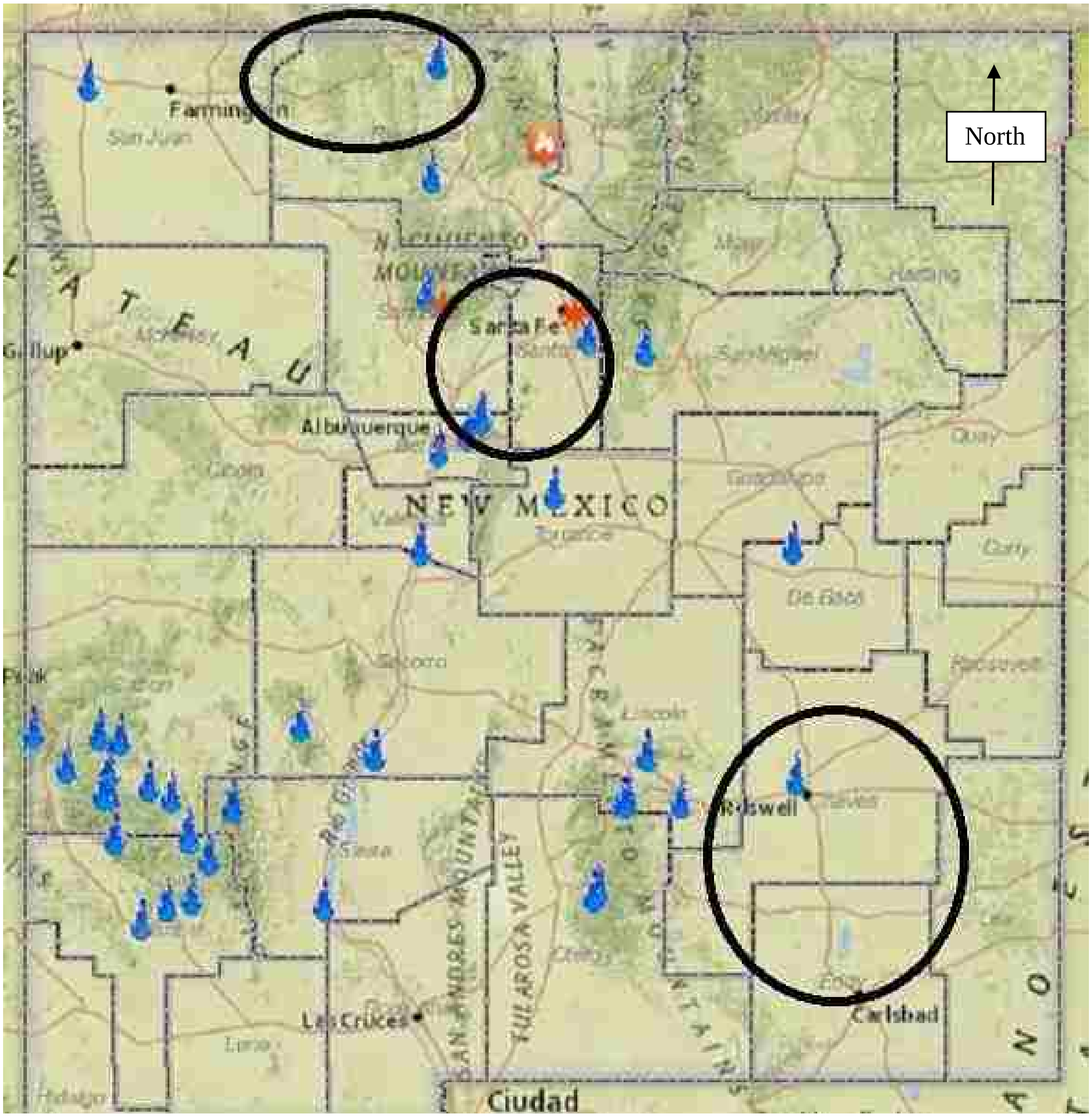


Figure 8: Active and Inactive wildfires in New Mexico

Scale [1: 4,622,324]

3.6.1. Case I Dam:

Case I is a rolled earth fill dam constructed across San Juan River in northeastern New Mexico. The dam was opened in 1962 with a height of 402ft. The spillway crest elevation is 6,085ft above sea level is with a spillway discharge capacity of 34,000 ft^3/s. The current reservoir capacity is at 1,696,000 acre-feet with an active storage of 1,036,100 acre-feet.

3.6.2. Case II Dam:

Case II is an earthen fill dam constructed across Rio Grande in Sandoval Country, New Mexico. The dam started its operations in 1973 and is maintained by United States Army Corps of Engineers. The dam height is 251ft with a spillway discharge capacity of 14,790f^3/s. The current reservoir capacity is 602,000 acre-feet with a crest height of 5479 feet above sea level.

3.6.3. Case III Dam:

Case III dam is a zoned earth fill structure originally built in 1888 across Pecos River in New Mexico. The dam washed out in 1893, and in 1904 by Pecos River flood. The Bureau of Reclamation rebuilt the dam in 1907 and later the dam height was increased in 1912 and in 1936. The current dam height is 60 feet with a reservoir storage capacity 4,466 acre-feet. The maximum water surface elevation is 3,185 feet above sea level with a spillway capacity of 34,000ft^3/s.

The three different watershed burnt scenarios are applied to these three dams and the excess runoff, sediments and floodplain impacts are estimated.

3.7. Summary

The methodology of this research is discussed in four steps, 1) post-fire flood estimates, 2) dam-break modeling, 3) risk assessment, and 4) decision-making matrix. The relations to estimate post-fire flood runoff and sediments are listen in tables which are used later in Chapter 4. The steps involved in dam-break modeling on WMS: SMPDBK are discussed. And then the steps involved in importing the dam-break model results and Hazus inventory data to ArcMap are discussed. The dam-break results and Hazus inventory data are used to estimate the potential impacts of dam-break due to post-fire flood event under risk assessment. In the final step, a decision-making: matrix is proposed to prioritize the high risk dams based on their failure impacts. In the end, the details of dams studied in this research are presented.

Chapter 4: Results and Analysis

4.0. Introduction

The post-fire runoff and sediments are estimated for each scenario in this chapter. These runoff volumes are used to design the dam-break models in WMS: SMPDBK, where each dam is tested for 6 different scenarios. The resulting flood extent map is interpolated with Hazus inventory data for each study region to estimate the impacts of dam-break on the floodplain. These impacts are further analyzed to estimate risk of dam-break event. Based on the estimates a decision-making: matrix is proposed to help the decision makers allocate funds to minimize the risk of dam-break due to post-fire flood event.

4.1. Post-fire Flood Estimates:

The post-fire flood estimates, runoff and sediments generated from burnt watershed are estimated in this section. The runoff estimates for each dam are used in dam-break modeling. The runoff and sediments generated are estimated using the empirical relations presented in **Table 7** and **Table 11** in Chapter 0. Runoff from each watershed is estimated from the amount of rainfall received by the watershed for a given duration. As mentioned earlier in section 3.1.1, a 25 year rainfall storm is estimated for each watershed. The rainfall intensities for each watershed is presented in **Table 18.**

Table 18: 90% Confidence Rainfall Interval at each Watershed (Source:www.nws.noaa.gov)

Dams	Lower Limit (in)	Upper Limit (in)
Case I	1.37	2.23
Case II	1.64	2.21
Case III	2.47	3.15

The runoff and sediments are estimated for the watershed (drainage) area of each dam. The drainage areas for each dam are presented in **Table 19**.

Table 19: Drainage area of each Dam

Dams	Area (sq. mi)	Area (sq. ft.)
	1.00	27,880,000
Case I	3,190	88,937,200,000
Case II	11,695	326,056,600,000
Case III	22,000	613,360,000,000

4.1.1. Runoff Estimates:

The runoff generated from the drainage area of three dams are estimated for three different scenarios: 1) 100% burnt watershed/drainage area, 2) 75% burnt watershed/drainage area, and 3) 50% burnt watershed/drainage area. The runoff generated from post-fire rainfall is estimated using @Risk model presented in **Table 7** for each watershed. The runoff volume histograms are generated by @risk are presented in **Figure 9** to **Figure 11**. The runoff generated from each watershed and the ratio of post-fire rainfall runoff and normal rainfall runoff are estimated using the relations given in **Table 7** and **Table 9**.

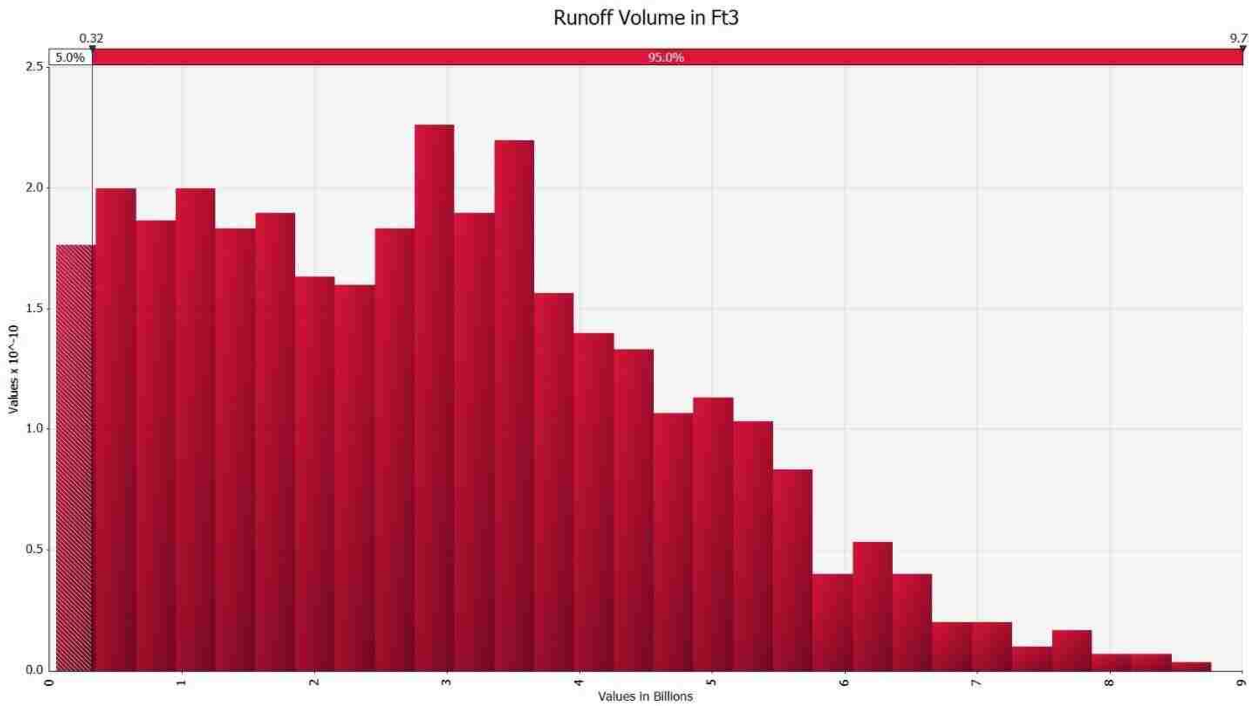


Figure 9: Runoff Volume Distribution for Case I Watershed

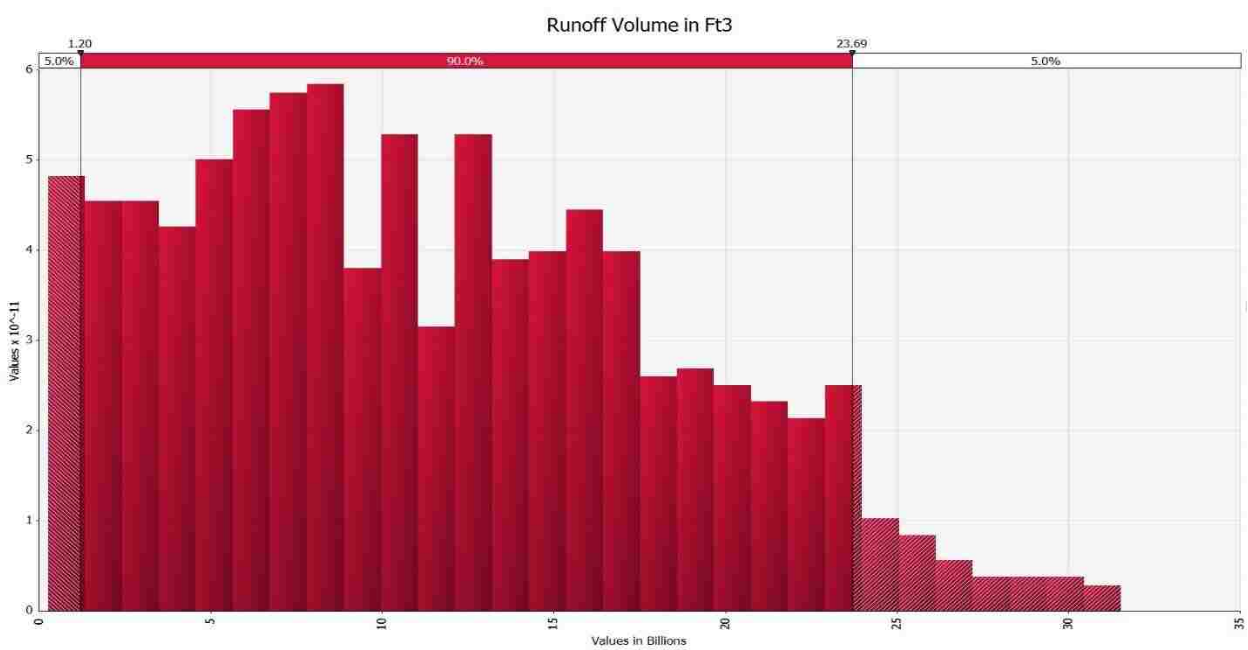


Figure 10: Runoff Volume Distribution for Case II Watershed

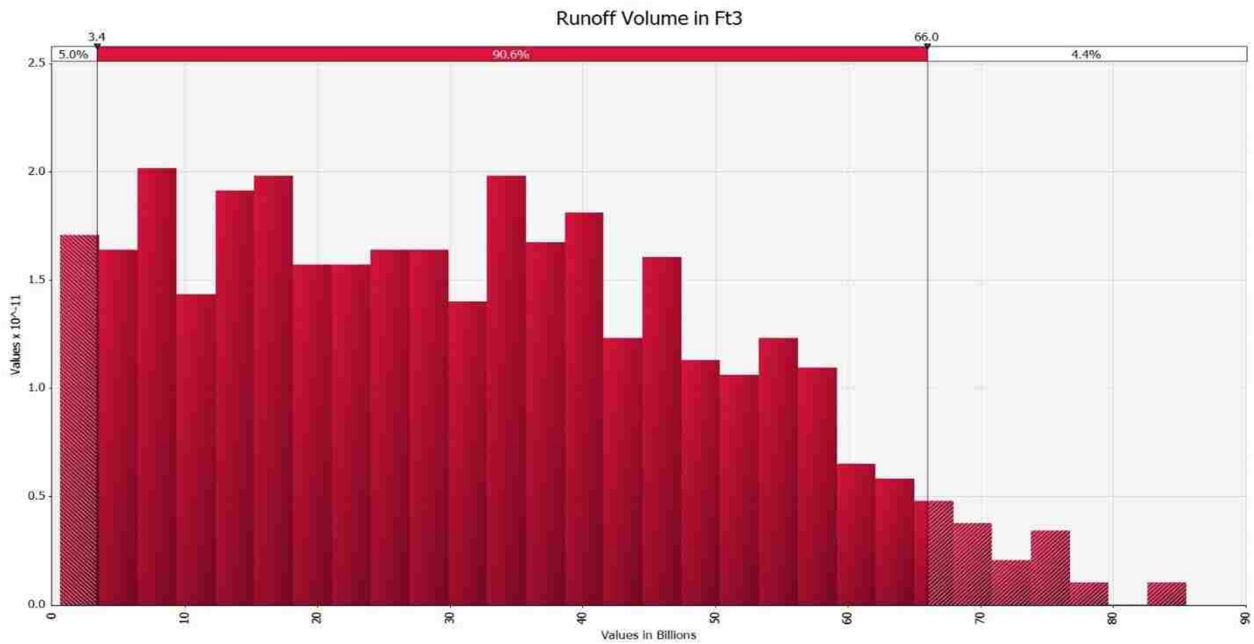


Figure 11: Runoff Volume Distribution for Case III Watershed

The runoff trends presented in **Figure 9** to **Figure 11** indicate the probability densities of the runoff volume estimated based on the set of variables and their probability distributions. In **Figure 9** to **Figure 11** we can observe that the higher runoff volumes corresponding to the higher burnt watershed areas are higher and has lower probability. As explained in section 3.1.1, the burnt region of watershed produces higher runoff volume compared to the unburnt region. Therefore, the scenarios in which the percentage of burnt watershed is higher, higher volumes of runoff is observed. Similar trend is observed in all watersheds considered in this study.

4.1.1.1. Rank for Variables

The @risk model also ranks the most influential variables in the empirical relation used in estimating the runoff. **Figure 12** shows the ranks of each variable based on their influence on the final runoff volume.

The ranks given in the **Figure 12** show that percentage area affected by the rainfall has the highest impact on the runoff volume followed by percentage of area affected by wildfire, burnt runoff coefficient and rainfall over the watershed. The area affected by rainfall is an important variable which is the highest influential variable according @risk rankings. The reason for these rankings could be the type of distributions assigned for each of the variable. The area affected by rainfall and wildfire are given a uniform distribution which indicates equal probability for all the scenarios. This need not be necessarily true in all cases. However, the volume of runoff generated from a watershed depends majorly on the area of watershed affected by rainfall and wildfire.

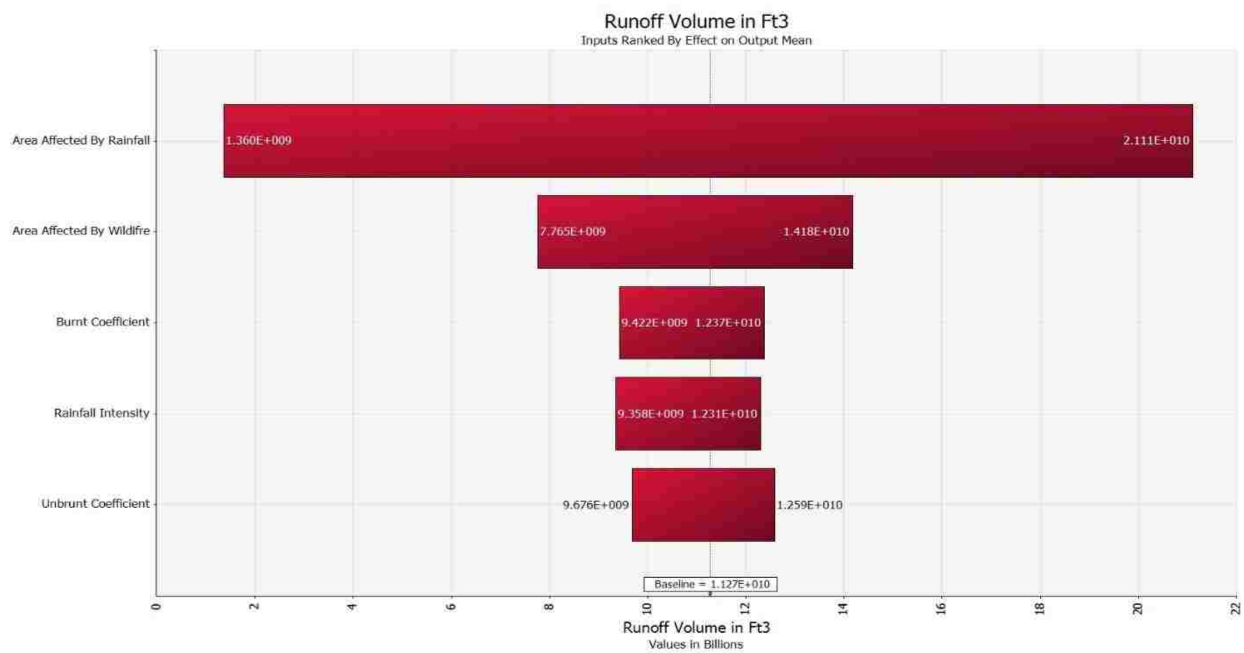


Figure 12: Ranks of @Risk Variables

For example, let us consider two scenarios: scenario I and scenario II. In scenario I, the area affected by watershed affected by wildfire is 100 ft^2 and the area of watershed affected by a rainfall is 200 ft^2. In scenario II, the area of watershed affected by wildfire is 200 ft^2 and rainfall is 100 ft^2.

Both the scenarios are for the same watershed with constant rainfall intensities (1in), burnt (0.5) and unburnt runoff (0.25) coefficients. In these scenarios, the runoff generated in scenario I is 177liters (or 6.25ft^3) than runoff generated in scenario II (118 liters or 4.16ft^3) following the empirical relation used in the runoff estimation. This indicates, that irrespective of the probability of wildfire occurrence, the area of watershed affected by rainfall have significantly higher impact on the total runoff generated in a post-fire rainfall event. Similarly various sample scenarios can be considered in which other variables are kept constant and their impact on the final runoff can be observed to conclude the same. This research aim is to demonstrate the post-fire flood impacts on floodplain therefore the uniform distributions of area affected by wildfire and rainfall are arguable.

4.1.1.2. Runoff Ratios for Post-fire Flood

From **Table 20** to **Table 22** the runoff ratios to convert the normal flood peak stream volumes to post-fire flood peak stream volumes are estimated using the runoff's obtained from the @risk models.

Table 20: Ratio of Post-fire Rainfall Runoff Volume to a Normal Rainfall Runoff Volume (Case I Dam)

Area of watershed (Acre)	Area Affected by Wildfire	Post-fire Runoff Volume (Ac-ft.)	Normal Runoff (Ac-ft.)	Ratio of Runoff
2,041,717	100%	220,063	98,650	2.23
2,041,717	75%	189,710	98,650	1.92
2,041,717	50%	159,356	98,650	1.62

Table 21: Ratio of Post-fire Rainfall Runoff Volume to a Normal Rainfall Runoff Volume (Case II Dam)

Area of watershed (Acre)	Area Affected by Wildfire	Post-fire Runoff Volume (Acre-ft.)	Normal Runoff (Acre-ft.)	Ratio of Runoff
7,485,229	100%	799,548	358,418	2.23
7,485,229	75%	689,266	358,418	1.92
7,485,229	50%	578,983	358,418	1.62

Table 22: Ratio of Post-fire Rainfall Runoff Volume to a Normal Rainfall Runoff Volume (Case III Dam)

Area of watershed (Acre)	Area Affected by Wildfire	Post-fire Runoff Volume (Acre-ft.)	Normal Runoff (Acre-ft.)	Ratio of Runoff
14,080,808	100%	2,143,806	961,016	2.23
14,080,808	75%	1,848,109	961,016	1.92
14,080,808	50%	1,552,411	961,016	1.62

The normal rainfall runoff volumes in **Table 20** to **Table 22** are estimated using the same unburnt coefficient. Therefore the normal runoff volumes from each watershed are proportional to each other and hence, the runoff ratios are same for all the watersheds. These runoff ratios are used to estimate a post-fire peak-flow values for all the scenarios considered for each dam.

The peak discharge values are estimated using PeakFQ program as explained in section 3.1.1 for each dam from different stream gages located upstream of the reservoirs. The peak-flow runoff volumes estimated for each dam are provided in **Table 23**. **Table 24** to **Table 26** provides the post-fire runoff volumes estimated from the peak-stream flow as explained in section 3.1.1.

Table 23: Stream Gage Peak-Flow Volumes for Each Dam

Dam	Gages Observed	Peak flow volume (Acre-ft.)	Total Volume of runoff (Acre-ft.)
Case I	Gage 1	39,015	126,327
	Gage 2	17,831	
	Gage 3	21,699	
	Gage 4	24,971	
	Gage 5	13,468	
	Gage 6	9,342	
Case II	Gage 1	234,446	499,041
	Gage 2	264,595	
Case III	Gage 1	37,388	192,238
	Gage 2	132,535	
	Gage 3	22,314	

Table 24: Post-fire Runoff Volume Estimates from a 25 year Rainfall Storm (Case I)

Percentage of watershed burnt	Runoff volume from peak stream data (Acre-ft.)	Runoff Ratio	Post-fire Runoff Volume (Acre-ft.)
100%	126,327	2.23	281,710
75%	126,327	1.92	242,548
50%	126,327	1.61	203,387

Table 25: Post-fire Runoff Volume Estimates from a 25 year Rainfall Storm (Case II)

Percentage of watershed burnt	Runoff volume from peak stream data (Acre-ft.)	Runoff Ratio	Post-fire Runoff Volume (Acre-ft.)
100%	499,041	2.23	1,112,862
75%	499,041	1.92	958,159
50%	499,041	1.61	803,456

Table 26: Post-fire Runoff Volume Estimates from a 25 year Rainfall Storm (Case III)

Percentage of watershed burnt	Runoff volume from peak stream data (Acre-ft.)	Runoff Ratio	Post-fire Runoff Volume (Acre-ft.)
100%	192,238	2.23	428,691
75%	192,238	1.92	369,096
50%	192,238	1.61	309,503

The post-fire runoff volumes generated in **Table 24** to **Table 26** are from an actual rainfall storm that occurred in the last 100years which has a peak-flow value to the 25 year rainfall storm predicted by PeakFQ program with 95% confidence. These runoff volumes are used in the dam-break modeling with WMS: SMPDBK. The surface runoff generated from the drainage area is assumed to reach the reservoir without any further losses (loss of runoff due to infiltration is accounted via burnt and unburnt coefficients). Each of the reservoirs have designed capacity to hold the flood water and if the runoff volume exceeds this capacity, there is a chance of overflow at the dam which results in failure of the dam via overtopping (Samuel W Speck, 1994). Based on the hypothesis explained in section 3.1.1.1, critical runoff inflow rate (Q_{crit}) is estimated for all the dams. To estimate the runoff inflow rate, the duration of post-fire rainfall event is assumed to be 48hrs.

This assumption is based on the peak-stream data obtained from USGS-National Water Information System. Most of the peak-stream flow is from a rainfall event that lasted for approximately 2 days (48hrs). However, in an actual scenario, the duration of the rainfall event can be obtained. Using the duration of the rainfall event the critical inflow rate is estimated as explained in **Table 10**. **Table 27** to **Table 29** provides the Q_{crit} estimates for Case III, Case II and Case I floodplains.

Table 27 : Q_{crit} for Case III Watershed

Variable Description	Symbol	Quantity	Units
Current reservoir capacity	V_{rev}	339,520	Acre-ft.
Current volume stored in the reservoir	V_{cur}	86,645	Acre-ft.
Runoff volume from Post-fire rainfall	V_{pfr}	38,7761	Acre-ft.
Outflow capacity(spillway)	Q_{out}	34,000.00	ft^3/s
Inflow (also *Q_{crit}* in this case)	Q_{in}	97,748.20	ft^3/s
Rate of runoff accumulation in the reservoir	Q_{acc}	63,748.20	ft^3/s
Reservoir capacity to be filled	V_{rem}	252,875	Acre-ft.
Duration of the post-fire rainfall event	T_{dur}	48.00	Hrs.
Time taken to reach V_{rem}	T_{otp}	48.00	Hrs.

Table 28: Q_{crit} for Case II Watershed

Variable Description	Symbol	Quantity	Units
Current reservoir capacity	V_{rev}	602,000	Acre-ft.
Current volume stored in the reservoir	V_{cur}	47,053	Acre-ft.
Runoff volume from Post-fire rainfall	V_{pfr}	613623.00	Acre-ft.
Outflow capacity(spillway)	Q_{out}	14,790.00	ft^3/s
Inflow (also *Q_{crit}* in this case)	Q_{in}	154,684.15	ft^3/s
Rate of runoff accumulation in the reservoir	Q_{acc}	139,894.15	ft^3/s
Reservoir capacity to be filled	V_{rem}	554,947	Acre-ft.
Duration of the post-fire rainfall event		48.00	Hrs.
Time taken to reach V_{rem}	T_{otp}	48.00	Hrs.

Table 29: Q_{crit} for Case I Watershed

Variable Description	Symbol	Quantity	Units
Current reservoir capacity	V_{rev}	1,696,100	Acre-ft.
Current volume stored in the reservoir	V_{cur}	1,562,207	Acre-ft.
Runoff volume from Post-fire rainfall	V_{pfr}	268,770	Acre-ft.
Outflow capacity(spillway)	Q_{out}	34,000.00	ft^3/s
Inflow (also Q_{crit} in this case)	Q_{in}	67,752.31	ft^3/s
Rate of runoff accumulation in the reservoir	Q_{acc}	33,752.31	ft^3/s
Reservoir capacity to be filled	V_{rem}	133,893	Acre-ft.
Duration of the post-fire rainfall event	T_{dur}	48.00	Hrs.
Time taken to reach V_{rem}	T_{otp}	48.00	Hrs.

The estimated critical inflow rate values are resulted from a specific watershed burnt and post-fire rainfall affected conditions. If the duration of post-fire rainfall is kept constant at the assumed value of 48hrs, we can estimate the minimum percentage area of watershed burnt and minimum percentage of watershed affected by rainfall for Q_{in} to reach Q_{crit}. The minimum burnt percentage of watershed area and the minimum watershed area affected by post-fire rainfall are termed as critical burnt area affected by wildfire and post-fire rainfall. Based on the Qcrit estimates and the @risk models used to estimate the post-fire rainfall runoff, the critical percentage area affected by wildfire and post-fire rainfall are determined using Palisade's Evolver. Evolver is an optimizing tool that optimizes an objective, subjected to certain constraints by changing the values of an adjustable cells (in excel). However, it can also be used to force a target cell to a specified value. Using this specific feature of Evolver, the runoff volume (V_{crit}, V_{pfr} that results in Q_{crit}) estimated using the relations provided in **Table 7** is made as a target cell and the area affected by wildfire and area affected by rainfall are made the adjustable cells to find the critical percentage of area burnt and area affected by wildfire.

The evolver is set to run to generate the critical percentages of areas for each watershed and the values are listed in **Table 30**.

Table 30: Optimized Percentage Area of Watershed from Evolver

Dams	Percentage Area Affected by Wildfire	Percentage Area Affected by Wildfire
Case I	96%	99%
Case II	75%	86%
Case III	20%	36%

The values listed in **Table 30** are the minimum percentage of areas affected by wildfire and post-fire rainfall required to cause a critical inflow rate leading to an overtopping failure for the respective dam. From the table we can notice that Case III watershed needs little burnt percentage compared to Case I and Case II to produce V_{crit}. And in case of Case I, the percentages indicate that the entire watershed need to be burnt and experience rainfall to cause an overtopping effect which is highly unlikely. From this we may understand that Case I dam is safe for any burnt scenarios below 96%, similarly, Case II is safe for any burnt scenario below 75%. Case III's low percentage of watershed affected can be attribute to its huge watershed area compared to Case I and Case II. Case III watershed is 6.89 times the size of Case I watershed and 1.89 times the size of Case II watershed. Therefore, for lower burnt percentages, Case III watershed generates enough runoff to cause an overtopping effect. From these results it is evident that not all scenarios cause a dam failure due to overtopping. In such case, the failure of dam might depend on other criteria such as structural integrity of dam, and age of dam among others. However, a dam break analysis is performed for lower runoff volumes for observational purposes and a non-dam break scenario and its possible outcomes are discussed in section 4.5.

4.1.2. Sediment Estimates:

The wildfire event causes burnt scares on the surface of watershed/drainage with loose soil and ash and debris which can be carried away as sediments in a post-fire rainfall (Larsen et al. 2009). The sediment yield estimates can provide an insight on their potential impacts on dams and reservoir storage capacities. Therefore the amount of sediments are estimated in this section using the coefficients given in **Table 2** and applying relations shown in **Table 11**. Sediments generated in the watershed are assumed to reach the reservoir.

Table 31: Sediment Yield from Case I Drainage Area

Area of watershed (Acre)	Area effected by wildfire	Rainfall (in)	Post-Fire Runoff Volume (Acre-ft.)	Post-Fire Sediment Yield (tons)
2,041,717	100%	1.37	281,710	5,895,376.77
2,041,717	75%	1.37	242,549	4,467,307.58
2,041,717	50%	1.37	203,387	3,041,351.35

Table 32: Sediment Yield from Case II Drainage Area

Area of watershed (Acre)	Area effected by wildfire	Rainfall (in)	Post-Fire Runoff Volume (Acre-ft.)	Post-Fire Sediment Yield (tons)
7,485,229	100%	1.64	1,112,864	23,289,006.06
7,485,229	75%	1.64	958,161	17,647,583.42
7,485,229	50%	1.64	803,458	12,014,507.78

Table 33: Sediment Yield from Case III Drainage Area

Area of watershed (Acre)	Area effected by wildfire	Rainfall (in)	Post-Fire Runoff Volume (Acre-ft.)	Post-Fire Sediment Yield (tons)
14,080,808	100%	2.47	428,691	8,971,265.77
14,080,808	75%	2.47	369,097	6,798,107.25
14,080,808	50%	2.47	309,504	4,628,164.13

The runoff and sediment estimates are from a post-fire rainfall. To understand the impact of a post-fire flood, runoff and sediments generated from a normal rainfall (without a pre-fire event) are estimated and the change in percentage of runoff and sediments are calculated. The runoff and sediments for a normal flood are calculated using the unburnt coefficient for runoff and unburnt coefficient for sediments values from **Table 1** and **Table 2** respectively. The increase in percentage of runoff and sediments for a post-fire rainfall compared to a normal rainfall at Case II reservoir are shown in **Table 34** and **Table 35**.

Table 34: Increased Percentage of Runoff

Area of watershed (Acre)	Area effected by wildfire	Post-fire Runoff (Acre-ft.)	Normal Runoff (Acre-ft.)	Additional runoff (Acre-ft.)	% of excess Runoff
7,485,229	100%	1,112,864	499,041	613,822	123%
7,485,229	75%	958,161	499,041	459,119	92%
7,485,229	50%	803,458	499,041	304,416	62%

Table 35: Increased Percentage of Sediment Yield

Area of watershed (Acre)	Area effected by wildfire	Post-Fire Sediment Yield (tons)	Normal Sediment yield (tons)	Excess sediment (tons)	% of excess sediment yield
7,485,229	100%	23,289,006	583,433	22,705,573	97%
7,485,229	75%	17,647,583	583,433	17,064,150	95%
7,485,229	50%	12,014,507	583,433	11,431,074	93%

The increased percentage of runoff and sediments infer that the impact of post-fire rainfall is greater than a normal rainfall (without a pre-fire event). In a telephone interview, the Dam Safety Program Manager at local dam confirmed that an increase in flood inflow and sediment yield was observed at Case II's reservoir for a post-fire rainfall compared to a normal rainfall. The percentages estimated in **Table 34** and **Table 35** can provide an insight on a pre-wildfire event's impact on the rainfall runoff and sediments of a watershed. These estimated quantities can play a significant impact on the dam and the downstream floodplain. To learn the downstream floodplain impacts due to a dam failure, the dam break analysis is performed.

4.2. Dam-Break Analysis - WMS: SMPDBK

The overtopping condition in an earth-dam results in a dam failure and causes downstream flooding followed by inundation of floodplain. The impact on the floodplain can be severe depending on the intensity of the flood in other words the volume of water discharged (runoff from watershed). The dam-break analysis in WMS gives us the flood extent on the downstream floodplain of each scenario. This flood extent map is used to estimate the range of population, residential buildings and other infrastructure under the risk of inundation. Hazus inventory data and ArcMap are used in estimating the floodplain impact due to dam-break.

The dam-break models are designed as explained in section 3.3 where the runoff volumes exceeding the reservoir capacity are given as overtopping volume in each dam-break scenario. The overtopping volumes and the elevation of water at dam crest are the two variables that change in each scenario for a given dam. The WMS: SMPDBK analysis is performed for eighteen dam-break models built for the three dams with different runoff volumes as shown in **Table 36**. WMS: SMPDBK gives a flood depth and extent map of downstream floodplain. This flood extent map is used to estimate the dam-break impacts in the floodplain. Flood extent map for 100% burnt watershed dam-break scenario are provided from **Figure 13** to **Figure 15**. The flood extent maps for the remaining cases listed in **Table 36** are given in the appendix.

Table 36: Cases Developed in Each Scenario in Building WMS Models with Runoff Volumes

Dam	Percentage of Watershed burnt	Runoff Volume (Acre-ft.)	Cases
Case I	50%	203,387	Case 1
	75%	242,549	Case 2
	100%	281,710	Case 3
Case II	50%	803,458	Case 4
	75%	958,161	Case 5
	100%	1,112,864	Case 6
Case III	50%	309,504	Case 7
	75%	369,097	Case 8
	100%	428,691	Case 9

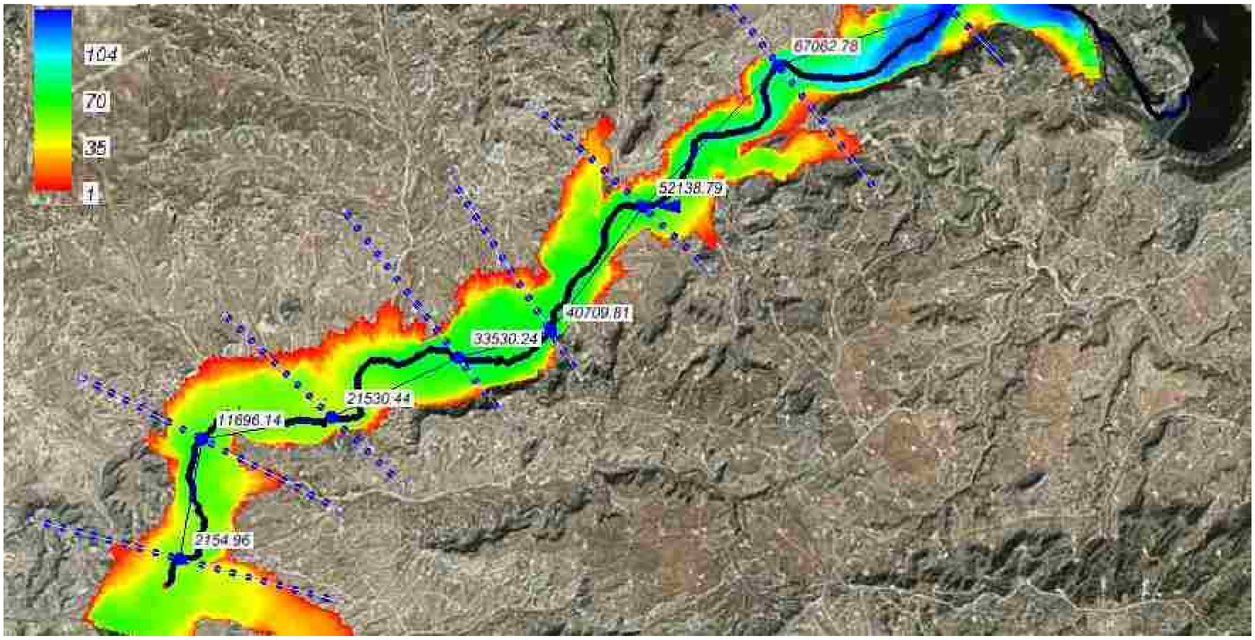


Figure 13: Case I Dam Flood - 100% drainage burnt
[Scale: 1 inch – 1 mile]

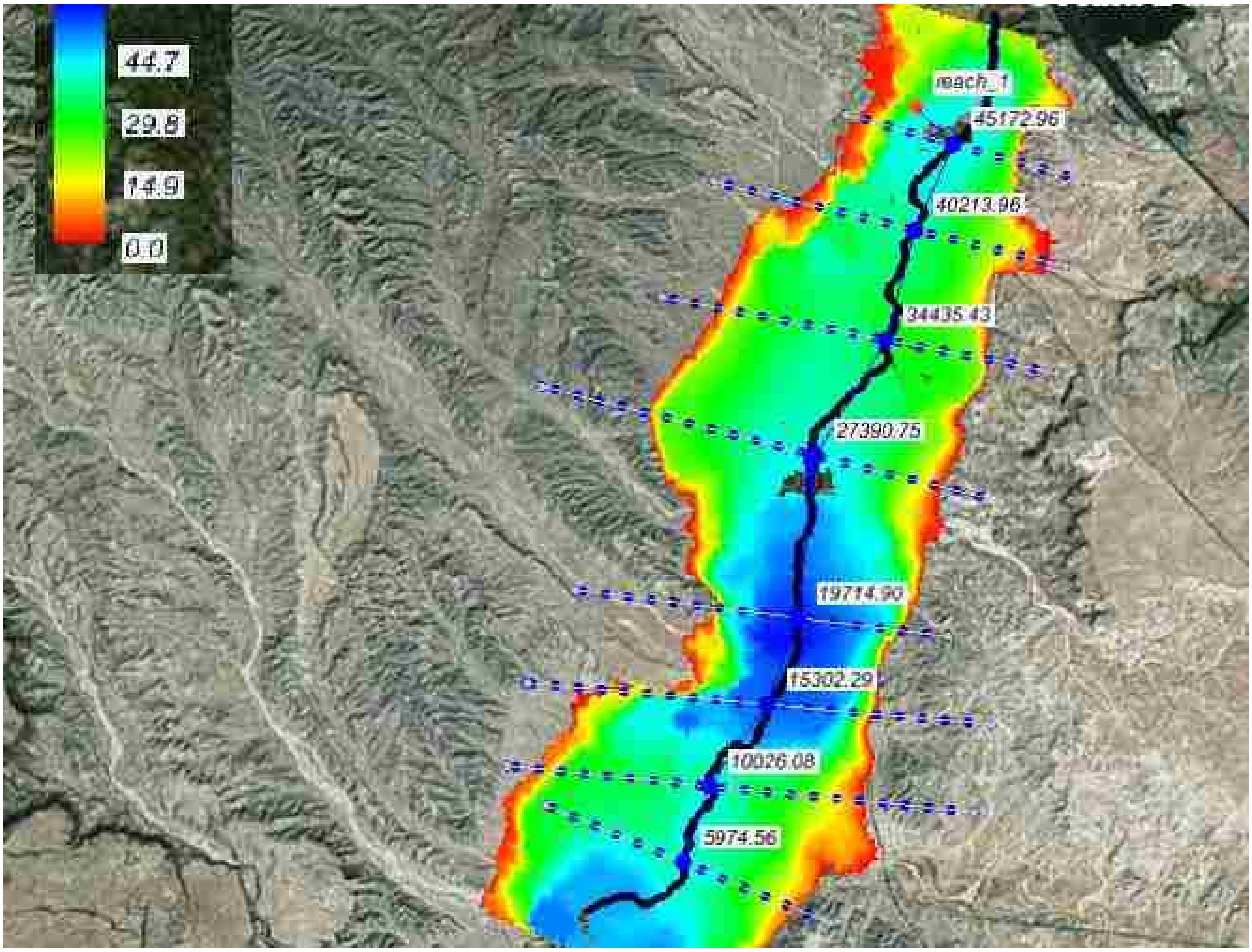


Figure 14: Case II Flood - 100% drainage burnt
[Scale: 1 inch – 1 mile]

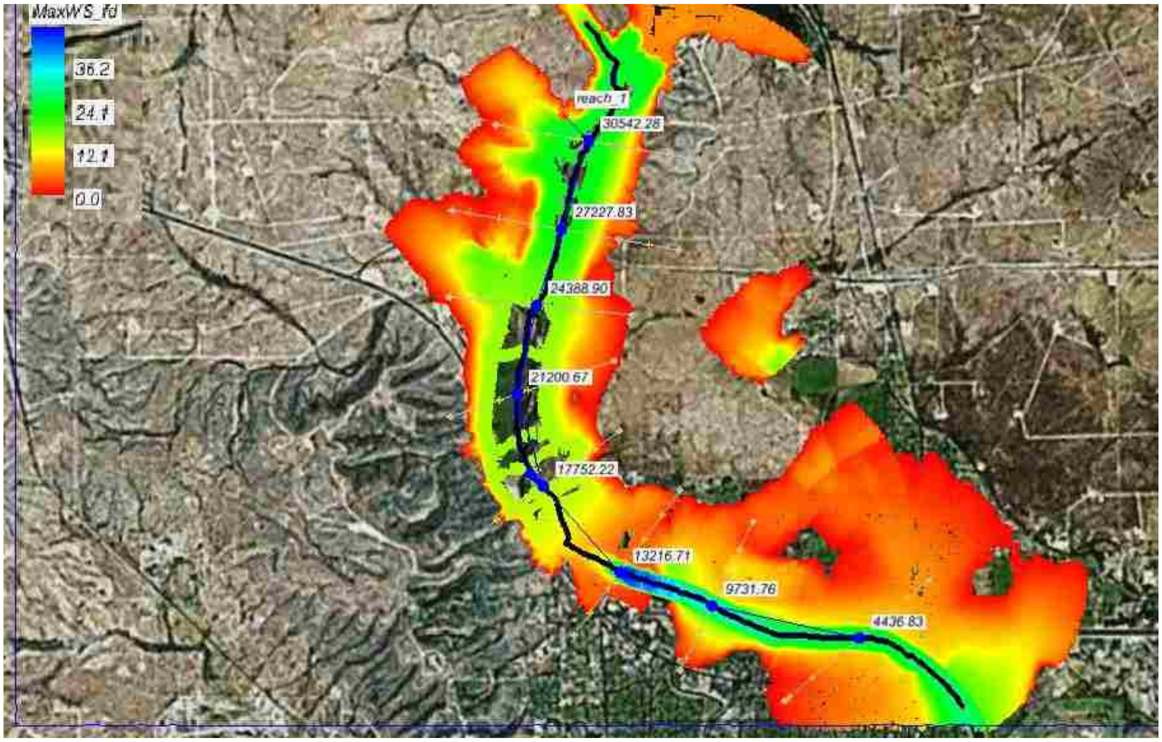


Figure 15: Case III Dam Flood - 100% drainage burnt
[Scale: 1 inch – 1 mile]

Figure 13, **Figure 14**, and **Figure 15** show the flood extent maps of Case I, Case II and Case III dam-break models respectively. The flood extent maps show the water elevation and potential inundation of the downstream floodplain based on the volume of water discharged due to dam-break. The colored portion in the flood extent maps show the potential inundation zone of the floodplain estimated by SMPDBK. The color legend is provided on the right hand top corner of each map that indicates the depth of water for colors shown (blue being the deepest and red is the shallowest) in the inundation zone. The flood elevation detail was shown up to a distance of 20 miles downstream from the dam crest.

The flood extent for each scenario varies with change in volume of runoff given in the dam-break model. Greater extent of flood is observed for higher runoff volumes compared to lower volumes in all dam-break models. The greater extent of flood could possibly bring more population, residential buildings and infrastructures into the flood zone.

There are four instances (Case I 75% burnt, Case I 50% burnt, Case II 75% burnt, and Case II 50% burnt) where the total runoff and reservoir current storage volume did not exceed the total storage capacity of the reservoir. This will not cause an overtopping effect and the failure of the dam may or may not occur depending on the structural integrity of the dam. However, a dam-break model is built for the four instances stated above to observe the potential impact of the dam-break flood. In the telephone interview, the dam safety manager at a local dam mentioned that, if the flood volume is high enough to set a record water elevation in the reservoir, it might put the dam in an untested region. The result of this scenario is uncertain where any outcome might be possible including a dam failure and hence round the clock inspections and maintenance works are enforced to check the structural integrity of the dam. Therefore dam-break analysis is performed for non-overtopping runoff volumes (assuming that they might set a record water levels in the reservoir).

The WMS: SMPDBK is not a sophisticated tool and it does not provide any floodplain occupancy data. The floodplain occupancy data is crucial to estimate the impacts of the dam-break flooding. Higher the occupancy of floodplain, higher the impact of dam-break event (Samuel W Speck, 1994) and higher is the impact of post-fire flood and higher the impact of wildfire that disturbed the normal conditions of the watershed/drainage area of the reservoirs. Therefore Hazus inventory data is obtained for each dam's floodplain which is freely available. A flood extent polygon is created within WMS and it is saved as a shapefile. This shape file can be imported to ArcMap where the Hazus inventory data is imported. The flood extent polygon is overlaid on the Hazus census data of the floodplain as shown in **Figure 16**. This allows us to estimate the total population, residential buildings and infrastructures that fall within the flood polygon. To estimate these quantities simple operations are performed within ArcMap explained in section 4.4.1

4.3. Floodplain Impact Estimation:

Out of the listed impacts in **Table 14**, the total population, number of residential buildings and infrastructures within the flood polygon of WMS are estimated in this section (the Hazus inventory data is limited to these quantities and therefore the other quantities are opted out). These quantities within the flood polygon have higher probability of inundation during a dam-break flooding event, therefore under risk. The population within the flood polygon need to be evacuated and moved to safer locations, the inundated residential buildings contributes to the economic impact and the infrastructure damage (infrastructure interdependency) can elevate the damage of dam-break event. The floodplain impact estimation is done in two steps, first the total population within the flood polygon is estimated and then the number of residential buildings within the flood polygon are estimated.

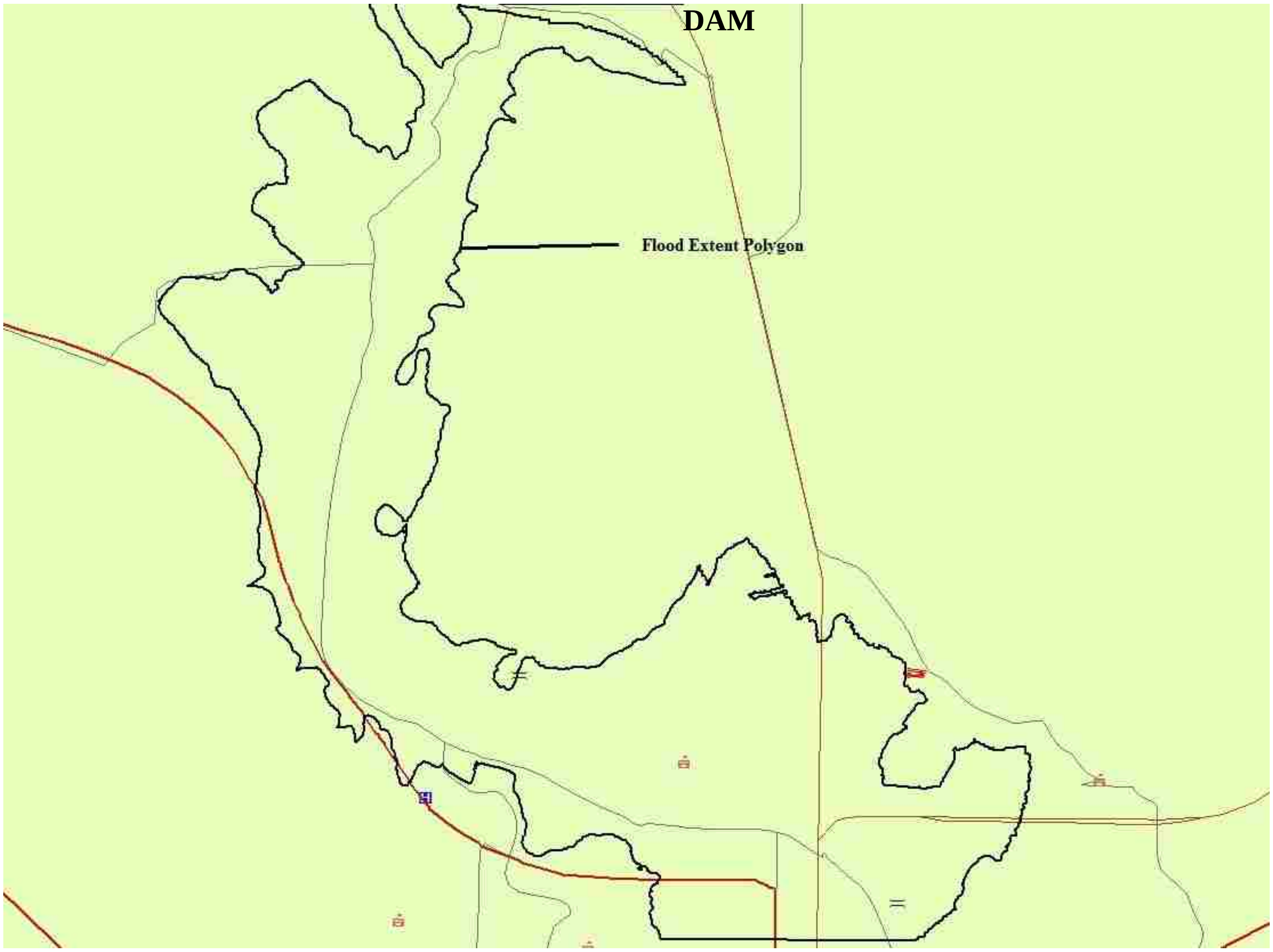


Figure 16: Flood Extent Polygon overlaid on Case III Dam's Floodplain
[Scale: 1 inch – 1 mile]

The Hazus inventory data consist census blocks (the total floodplain is divided into blocks of different sizes). Each of these blocks hold the information of population within the block in the form of attribute tables and each block has different population densities. The flood polygon is overlaid on the census block as shown in **Figure 16**.

This polygon cuts through the census blocks where the portion of each block within the polygon is under the impact of flood. Assuming that the population in each block is equally represented, the population in the portion (of the census block) within the flood polygon is estimated using the attribute tables of the census data. The attribute table consists of total area of each block, population within each block, number of residential buildings, total male population, and total female population along with other statistical data. A buffer layer is created for the flood polygon within ArcMap and this buffer layer is overlaid with the population census using "interest" tool. This tool creates a new area that can be calculated using a "geometry calculator" within the attribute table. The geometry calculator calculates the portion of area of each census block within the flood polygon. This area is multiplied by the population density of the census block which gives the population of each census block within the flood polygon. This population within the flood polygon is under risk of inundation. A similar operations are performed to estimate the total population and number of residential buildings under the risk of inundation for all cases listed in **Table 36**.

Three flood polygon maps are obtained for each dam (one for each burnt scenarios). The dam-break causing runoff was estimated from a 25 year storm with 95% confidence. Assuming the runoff generated from the drainage area and the WMS flood predictions are accurate, the estimated population and residential buildings under impact can have significant probability.

4.4. Risk Due to Dam-Break Event:

4.4.1. Population and Residential buildings at Risk

The dam-break event results in downstream flooding and inundation of floodplain. The impacts on the floodplain are uncertain and it is important to assess this uncertainty to minimize the damage if ever a disaster (dam-break) occurs. The calculations performed in ArcMap provide an insight on total population affected, number of residential buildings affected and the infrastructures within the inundation zone. **Table 37** provides the data of population and residential buildings affected in each scenario for the three dams.

Table 37: Population and Residential buildings Affected by Dam Break Flooding

Dams	Impact Categories	50 % watershed burnt scenario	75 % watershed burnt scenario	100 % watershed burnt scenario
Case I	Population affected	535	552	563
	Residential buildings impacted	224	232	237
Case II	Population affected	1734	2041	2151
	Residential buildings impacted	391	461	489
Case III	Population affected	2537	3010	3494
	Residential buildings impacted	1161	1338	1542

From **Table 37** we can notice that the population and buildings affected increased with increase in burnt percentage of watershed. However, the increase is not uniform in all three floodplains considered here. There is significant increase in the population for Case III floodplain and the increase in population for Case I floodplain is minimal.

To investigate the reason for this difference in the floodplains, more dam break models were built for lower burnt watershed conditions. The dam-break analysis was performed for the additional burnt scenarios and the population affected for each burnt scenario was estimated using Hazus and ArcMap. The population affected is plotted against each burnt watershed scenario for the three watersheds. The plots are presented in **Figure 17** to **Figure 19**.

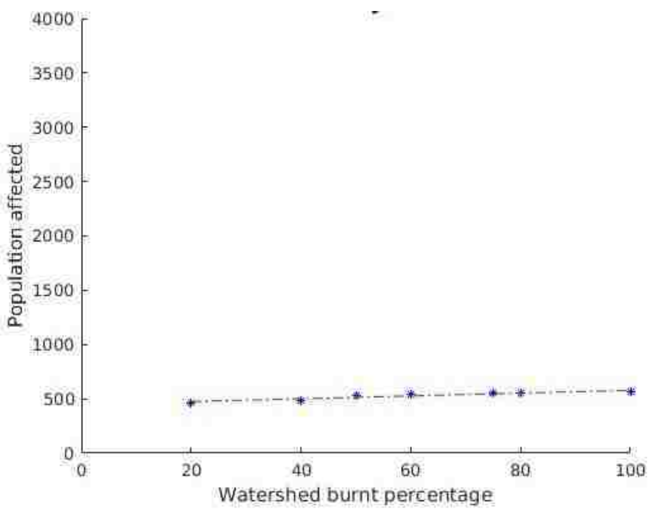


Figure 17: Population Affected in Case I Floodplain

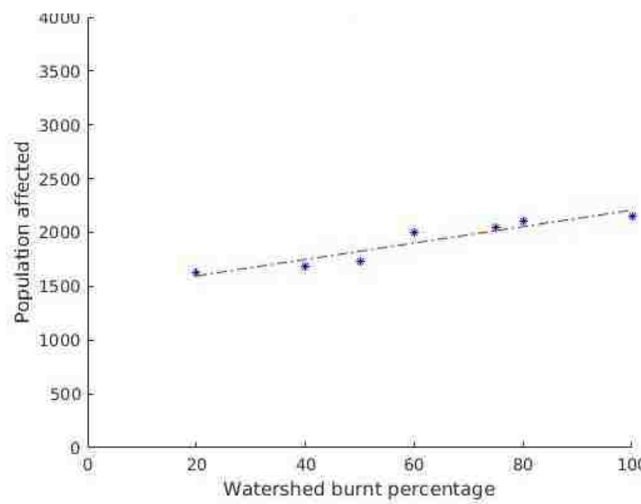


Figure 18: Population Affected in Case II Floodplain

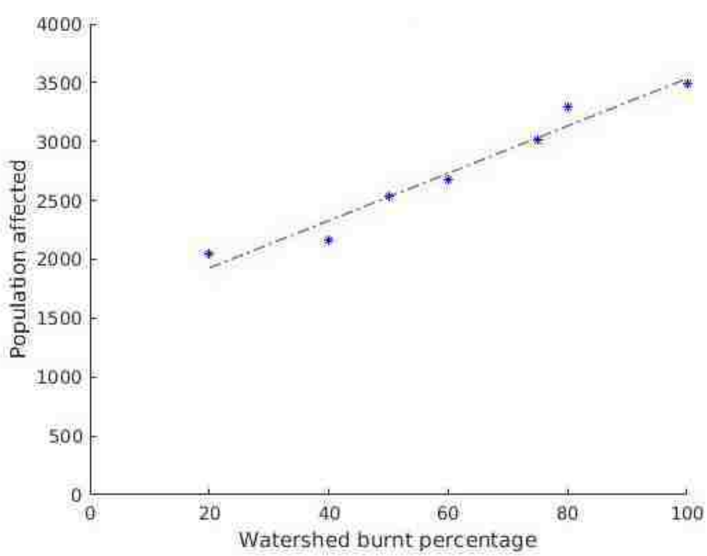


Figure 19: Population Affected in Case III Floodplain

From **Figure 17** to **Figure 19** we can observe that the change in population affected in Case III floodplain remained higher over all the scenarios. And the change in population affected in Case I floodplain remained significantly lower in other words the change in population affected is negligible. To understand this pattern, further investigation was done in terms of topography of the three floodplains. The possible reason for the Case I's minimal variation could be related to its floodplain topography. The topography of Case I floodplain is shown in **Figure 20**.

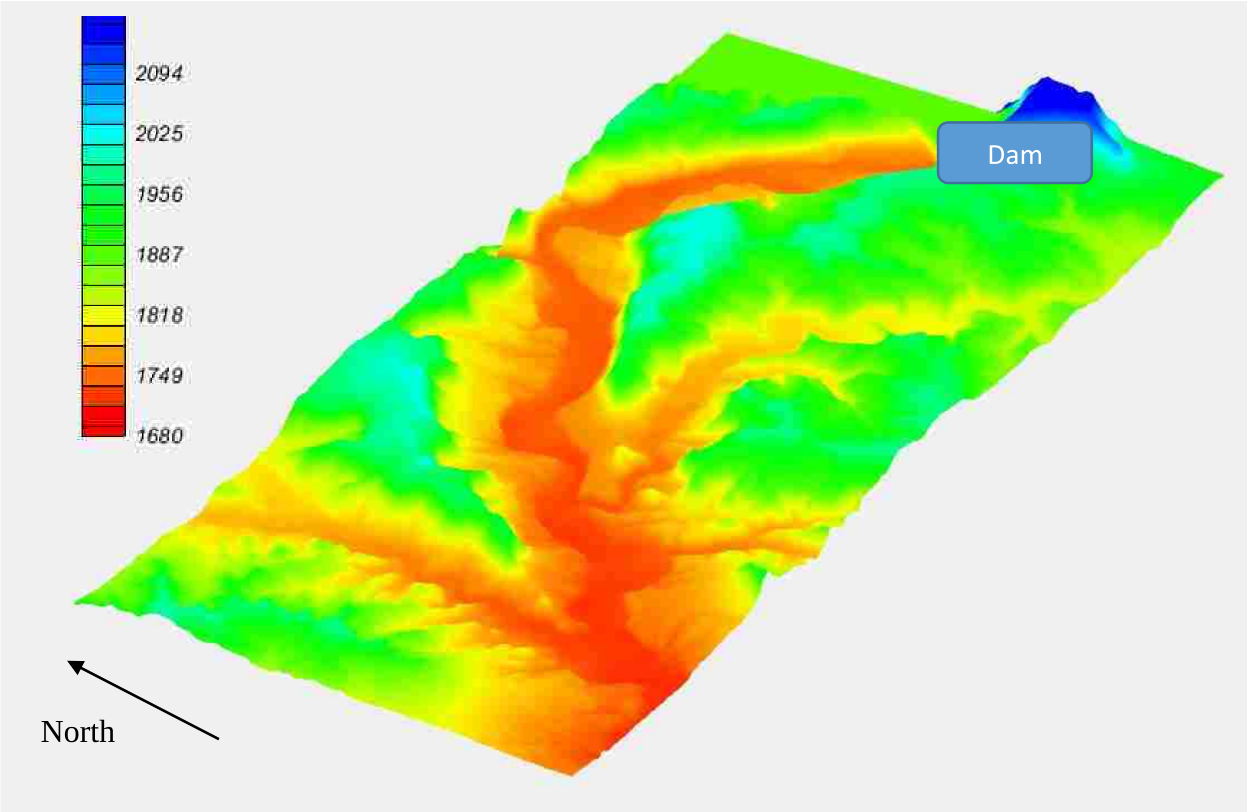


Figure 20: Case I Floodplain Topography
[Scale: 1 inch – 1 mile]

Figure 20 shows the 3D DEM image of Case I Floodplain. The elevations corresponding to the colors on the map are shown in the legend on left top corner of the figure. From the figure we can observe the red (indicating the lowest elevation) portion as a narrow valley through which San Juan River flows downstream of Case I Dam. When the dam-break flooding occurs, the flood inundation remains within the valley inundating all possible residential buildings and its occupants. With increase in flood level due to higher burnt watershed area the flood inundation depth (depth of inundation is observed from SMPDBK output) increased instead of extending the inundation zone. **Figure 21** shows the flooding in the Case I floodplain for 100% watershed burnt scenario. From **Figure 21** it is evident that the flood stayed within the valley for the highest burnt scenario which supports the above hypothesis.

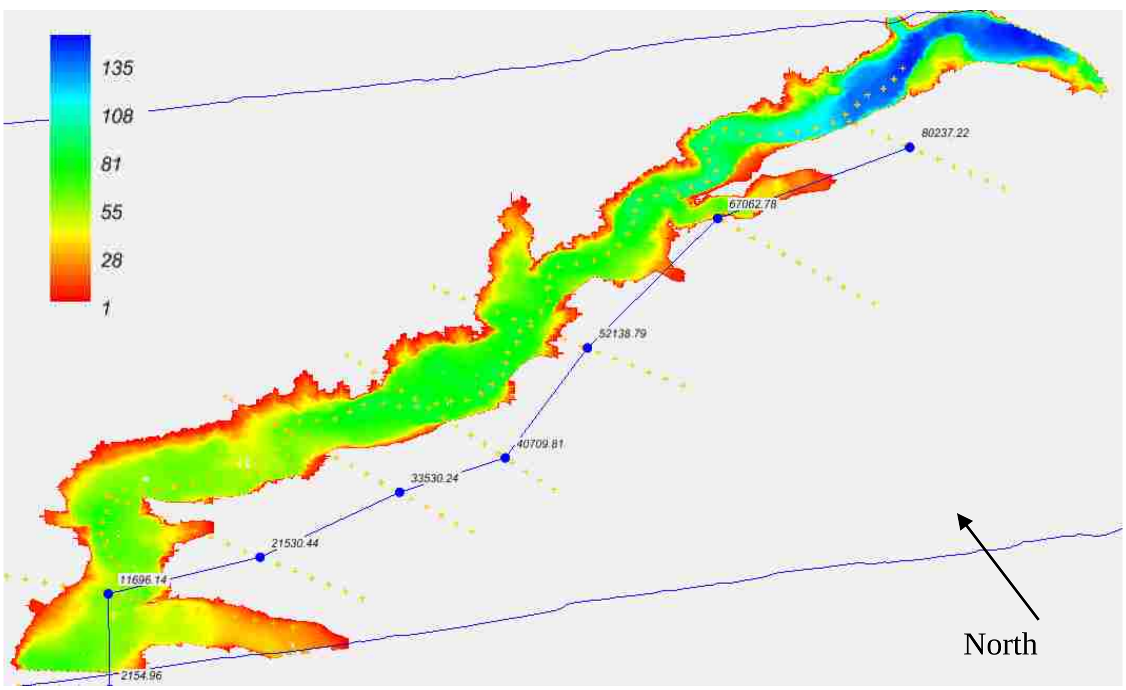


Figure 21: Case I Dam-Break Flooding
[Scale: 1 inch – 1 mile]

For comparison, the topography of Case II and Case III are presented in **Figure 22** and **Figure 23**. From the DEM images we can clearly notice that Case II and Case III floodplains are not similar to Case I. Both Case II and Case III floodplain topographies are wide spread low elevation (no valley shaped narrow) regions compared to Case I floodplain. As the flood volume from dam break increases, there is more scope for the water to spread and increase the inundation zone area. This can bring more houses into the inundation zone increasing the number of houses under inundation. However, we can observe a significant difference between the slopes of linear curve for Case II and Case III floodplain's affected population in **Figure 18** and **Figure 19**. This is understandable from the fact that the Case III floodplain majorly consists of highly populated town and Case II flood consists of less densely populated pueblos.

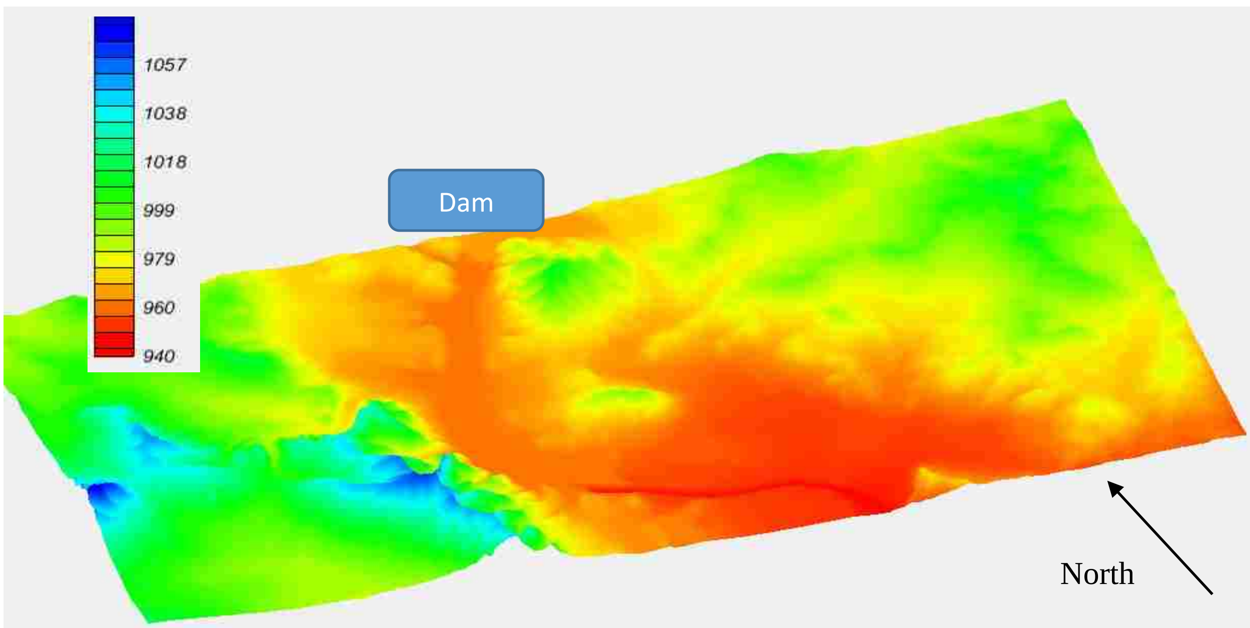


Figure 22: Case III Floodplain Topography
[Scale: 1 inch – 0.7 mile]

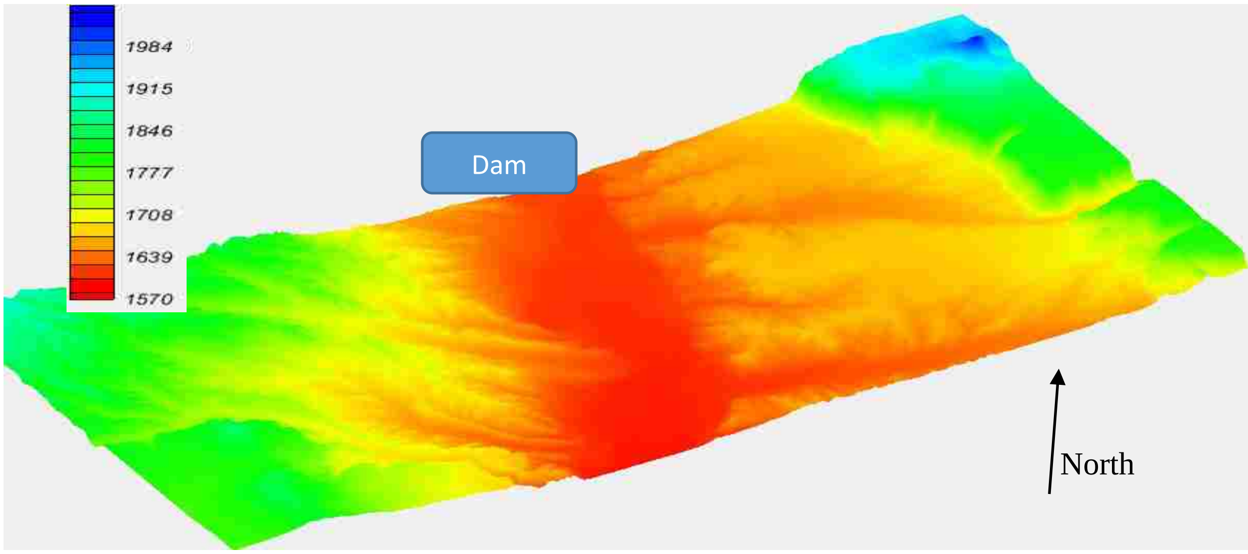


Figure 23: Case II Floodplain Topography
[Scale: 1 inch – 1 mile]

Figure 24 shows the maximum potential population affected at each dam in which Case III floodplain shows highest impact in terms of population and residential buildings affected as explained above in this section.

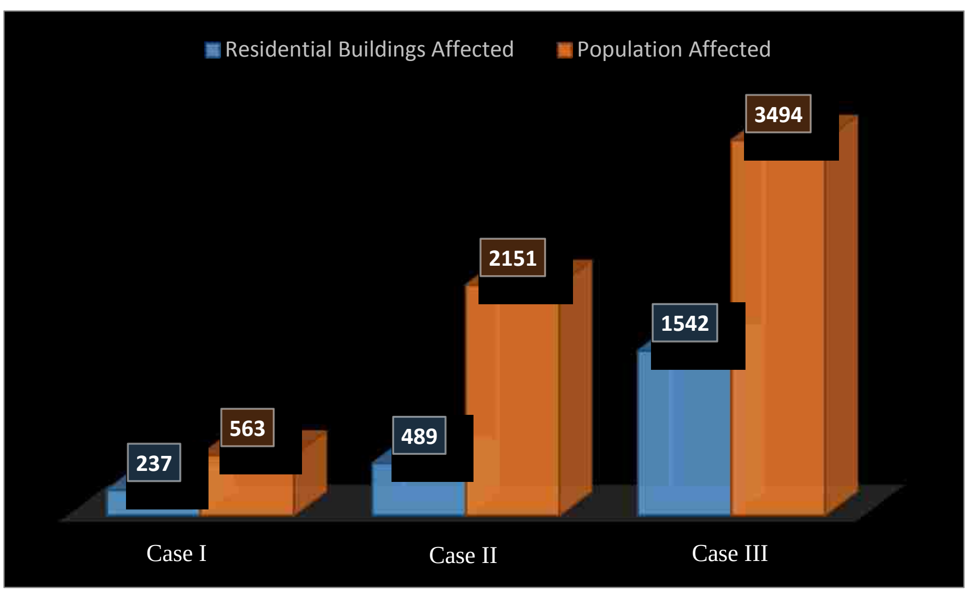


Figure 24: Population and Residential Buildings under Impact

The flood polygons are overlaid on census data in ArcMap as shown in **Figure 25**. This process is performed for all the scenarios and the population and residential buildings affected are estimated.

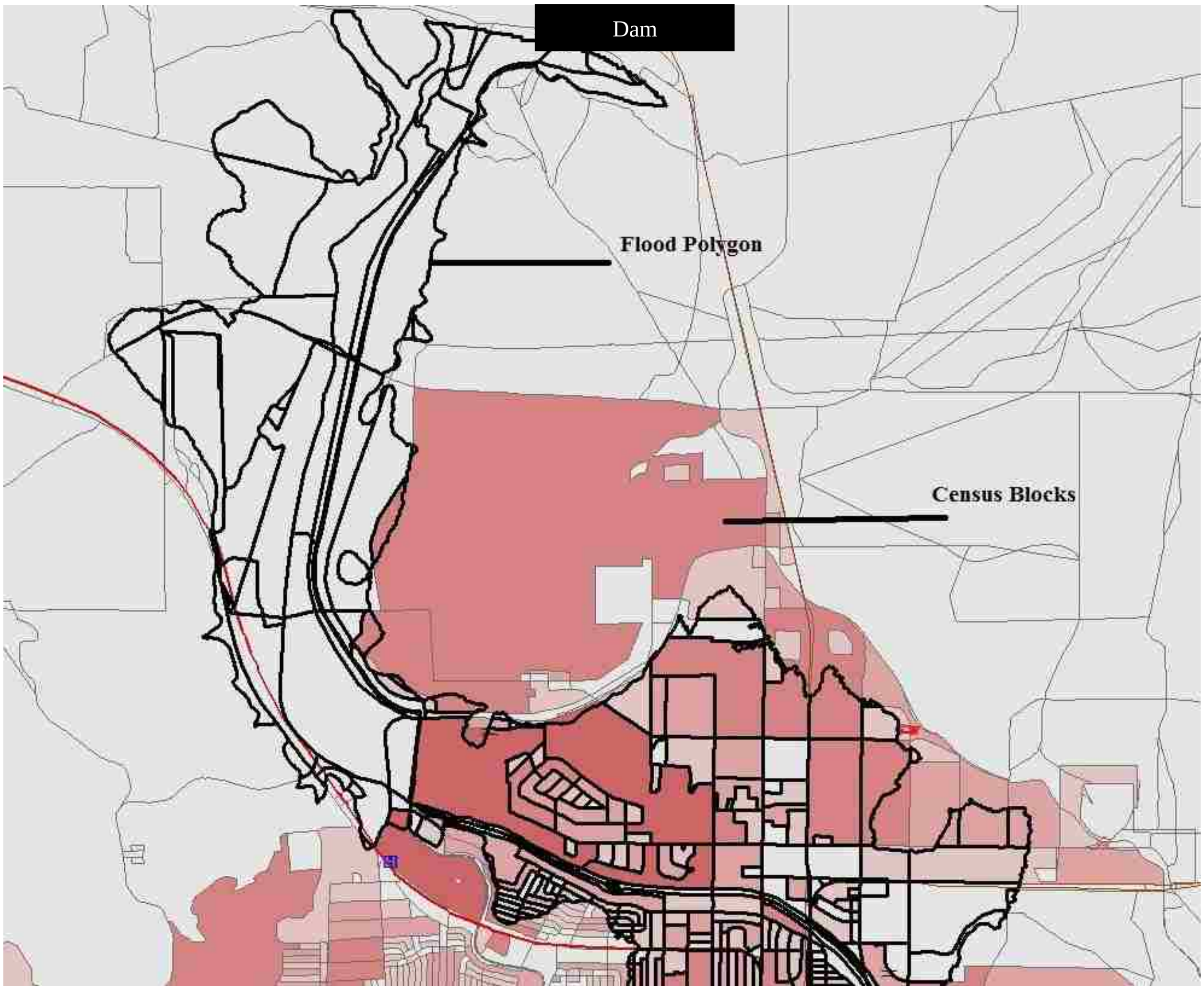


Figure 25: Case III Flood Polygon Overlaid on Census Blocks
[Scale 1in = 1mile]

The residential buildings within the flood zone experience inundation and damages due to inundation. The flood inundation damage costs given in **Table 15** are used to estimate the approximate cost of damage to the residential zones for all the three dam floodplains. The estimated cost of damages are presented in **Table 38** to **Table 40**.

From **Table 37**, we obtain the total number of residential buildings affected by dam-break flood inundation. For each dam, the number of residential buildings affected vary between the ranges of values obtained for different scenarios. However, the maximum number of residential buildings affected can be the highest value obtained from all the scenarios (the worst case scenario i.e. 100% burnt watershed). For all the floodplains, the highest number of residential buildings affected are from the 100 percent burnt watershed scenario. These value are used in estimating the potential total cost of damage. The damage costs are estimated using simple calculations. The costs provided in **Table 15** are for two different size of residential buildings.

The buildings are categorized based on their average value obtained from Hazus census data. From the data the buildings are sorted into two size sets based on their property value. All the buildings with their value less than $150,000 are sorted into group 1-size: 600sft – 1499sft. And for the buildings with their values above $150,000 are sorted into group 2-size 1500sft-2500sft. This assumption is based on average property value for specific square-footage details found on a real estate and rental marketplace website (www.zillow.com). The website provided the costs of residential houses in floodplain of Case II dam. A 1200sft residential building in Case II dam floodplain is priced approximately $120,000. The group 1 building damages due to flood are assumed to be equal to the building damages of 1000sft buildings and group 2 building damages are equal to 2000sft. A similar approach is followed to sort the residential buildings of case I and case III floodplain.

Table 38: Cost of Damage to Residential Buildings in Case I Floodplain

Size of Building(ft^2)	Depth of Flood (in)	Cost to Fix each Unit	Number of units	Percentage of units	Total Cost
1000	12	$ 27,150	65	27%	$ 1,764,750
2000	24	$ 52,220	53	22%	$ 2,767,660
1000	12	$ 33,700	65	28%	$ 2,190,500
2000	24	$ 62,880	54	23%	$ 3,395,520
Total Cost of Damage			**237 units**		**$ 10,118,430**

Table 39: Cost of Damage to Residential Buildings in Case II Floodplain

Size of Building(ft^2)	Depth of Flood (in)	Cost to Fix each Unit	Number of units	Percentage of units	Total Cost
1000	12	$ 27,150	210	43%	$ 5,701,500
2000	24	$ 52,220	34	7%	$ 1,775,480
1000	12	$ 33,700	215	44%	$ 7,245,500
2000	24	$ 62,880	30	6%	$ 1,886,400
Total Cost of Damage			**489 Units**		**$ 16,608,880**

Table 40: Cost of Damage to Residential Buildings in Case III Floodplain

Size of Building(ft^2)	Depth of Flood (in)	Cost to Fix each Unit	Number of units	Percentage of units	Total Cost
1000	12	$ 27,150	632	41%	$ 17,158,800
2000	24	$ 52,220	139	9%	$ 7,258,580
1000	12	$ 33,700	632	41%	$ 21,298,400
2000	24	$ 62,880	139	9%	$ 8,740,320
Total Cost of Damage			**1542 units**		**$ 56,880,380.00**

For simplicity purposes, the sorted buildings are split equally between the two depths (individual building location within each census block is not available in Hazus census data). From **Table 38** to **Table 40** we can observe that the cost of damages to the residential buildings for different floodplains and as expected the highest cost of damages is observed in case of Case III floodplain due to its high floodplain occupancy compared to Case I and Case II.

4.4.2. Infrastructure under Risk:

From the interpolation of WMS flood polygon and Hazus inventory data, the essential infrastructures such as schools, fire stations, roads, and hospitals among others under the influence of flood (those within the floodplain) are identified. The interpolated maps for each dam are presented below from **Figure 26** to **Figure 28**. The figures show, various essential infrastructures located within the floodplain. This indicates that the infrastructures might experience partial to complete damage depending on the flood depth at their respective physical locations.

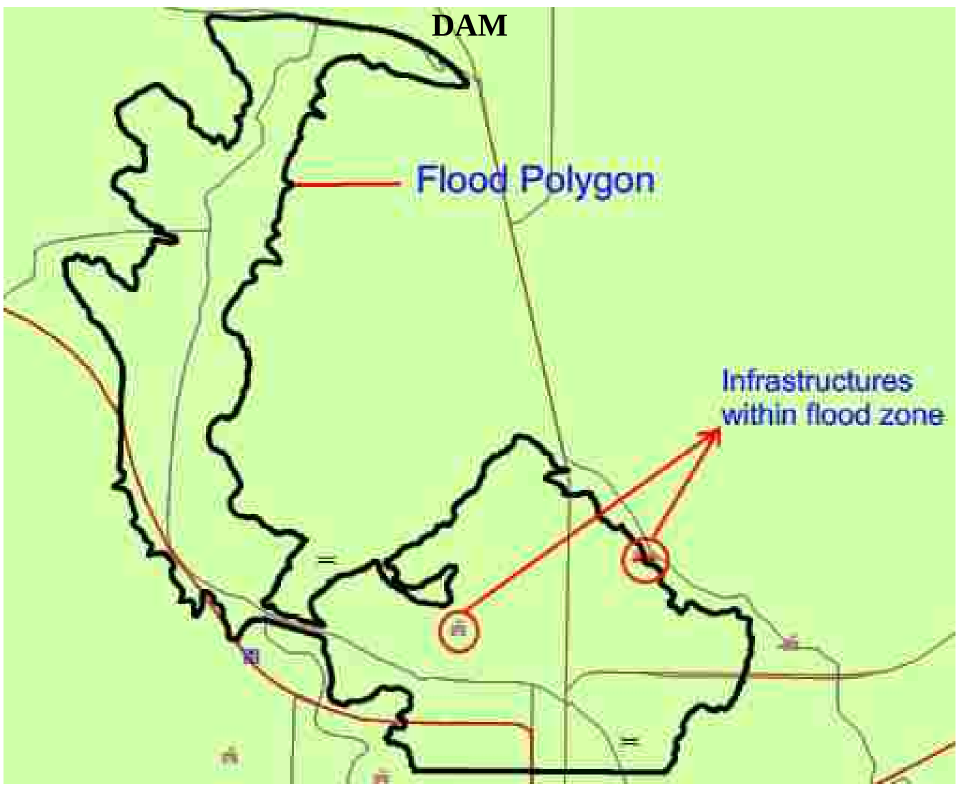


Figure 26: Case III Flood Polygon Overlaid on Hazus Inventory Data
[scale 1in = 0.7mile]

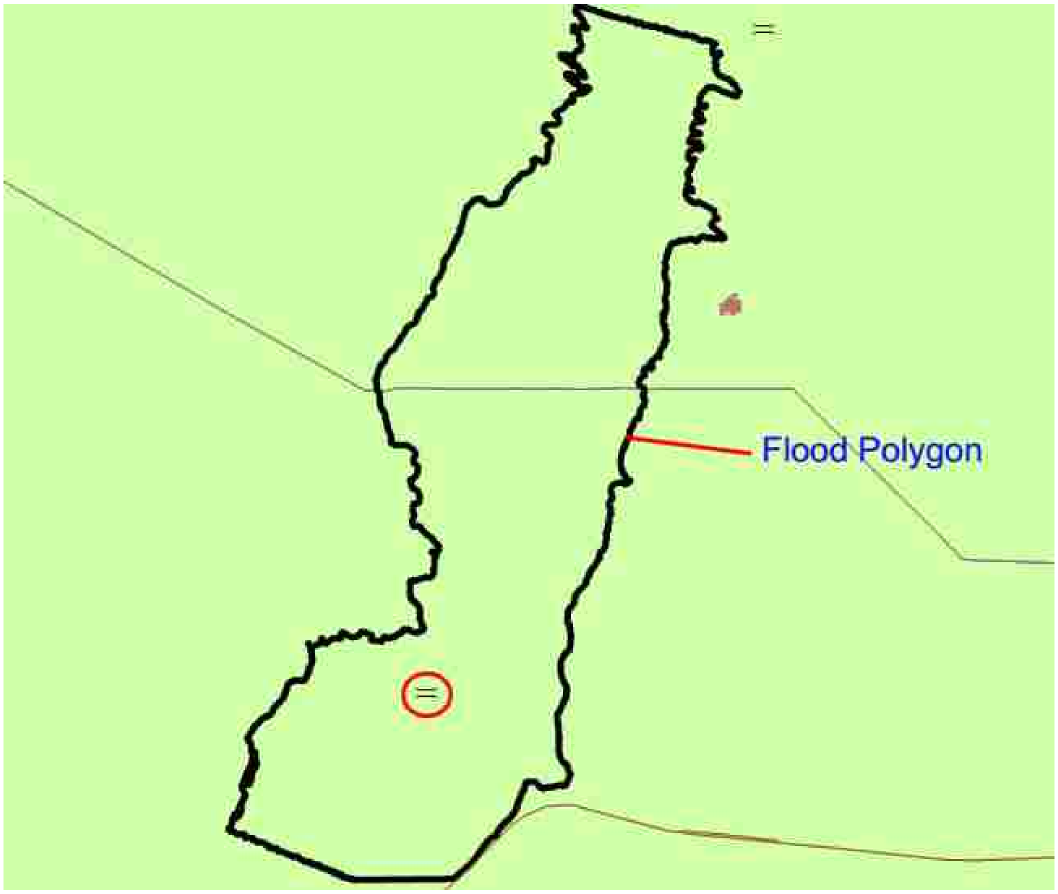


Figure 27: Cased II Flood Polygon Overlaid on Hazus Inventory Data
[scale 1in = 0.7mile]

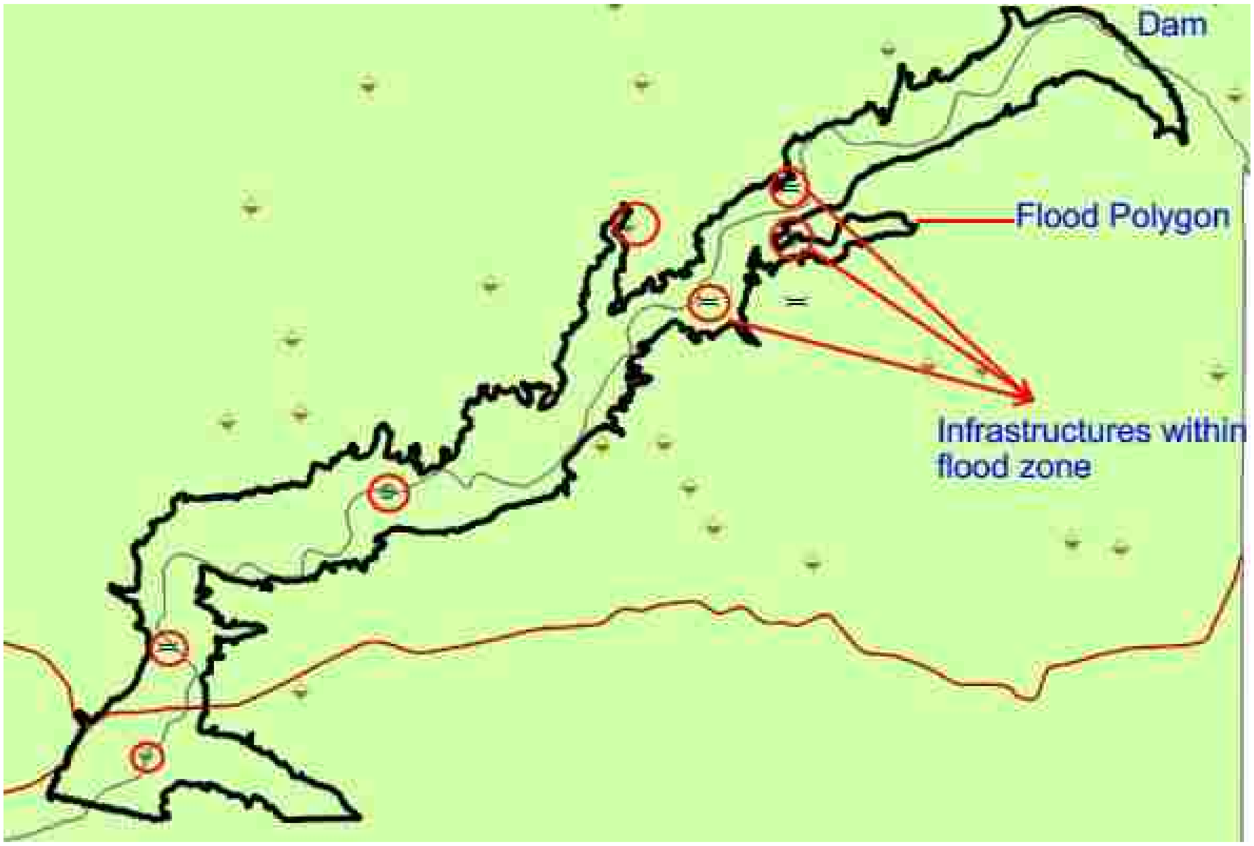


Figure 28: Case I Flood Polygon Overlaid on Hazus Inventory Data
[scale 1in = 1mile]

In **Figure 26**, **Figure 27**, and **Figure 28** the flood polygon can be seen in the black line and in each map, red circles in the flood polygon indicate various essential structures that are within the flood zone. The symbols legend is given in **Table 41** which shows the symbols of the structures used in the map along with its name (note: table consist symbols of structures within the flood zone only). **Table 42** lists the infrastructures under impact of flood for each dam's floodplain.

Table 41: Symbols Legend

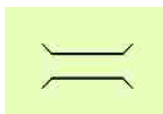
Symbol Shown in the Map	Structure Represented
	School
	Fire Station
	Bridge
	Waste Water Treatment Plant
	Natural Gas Facility
	Rail-Road (Brown line)
	Road (Red line)

Table 42: Infrastructures within the Flood Zone at Each Dam

Dam	50% Watershed Burnt	75% Watershed Burnt	100% Watershed Burnt
Case I	Bridges - 3 Waste water facility - 1 Natural Gas Facilities - 3	Bridges - 3 Waste water facility - 1 Natural Gas Facilities - 3	Bridges - 3 Waste water facility - 1 Natural Gas Facilities - 3
Case II	Bridges - 1 Road Network	Bridges - 1 Road Network	Bridges - 1 Road Network
Case III	Schools - 1 Fire Stations - 1 Bridges- 2 Road Network Rail Road Network	Schools - 1 Fire Stations - 1 Bridges- 2 Road Network Rail Road Network	Schools - 1 Fire Stations - 1 Bridges- 2 Road Network Rail Road Network

The inundation of these infrastructures listed in **Table 42** can cause a partial damage or complete failure which can increase the intensity of flood, dam-break and thereby the impact of post-fire events. For instance, a portion of road network in Case III floodplain shown in **Figure 26** is within the flood zone and has a chance of inundation up to 8ft of flood (the depth at this location is obtained from WMS:SMPDBK output map). Similarly, the railroad passing through the town has a chance of inundation up to 12ft. In both the cases, the flood can damage the road, resulting in reduced capacity for the traffic flow and disturbs any evacuation, rescue measures underway (Santella et al. 2009). In **Figure 26** a bridge can be seen within the flood polygon. The water depth at the location of this specific bridge is 26ft and here the height of the bridge can play a crucial role. If the height of the bridge is above the flood depth, the bridge might stay intact, else it might fail or experience a partial damage cause a disruption in traffic flow (Santella et al. 2009).

The damage in the infrastructure such as a bridge can propagate its impact to another infrastructure (road network) because of their interdependency (geographic interdependency: explained in **Table 4**). This can disrupt the operation capacity of the entire road network leading to increased impact of the flood. Similar cases can be observed in Case I and Case II floodplain maps, where natural gas facilities are within the inundation zone in Case I floodplain shown in **Figure 28**. The inundation of natural gas facilities can be lethal and may be life threatening. It may also lead to the disruption of natural gas supply to the locality causing inconvenience to the stakeholders. Inundation of a waste water treatment plant (as in case of Case I flood map **Figure 28**) can pollute the river water that reaches the downstream areas. The pollutant can contaminate the water, affect the aquatic life and cost additional money to contain the pollutants and restore the water quality. To better understand the nature of these disruptions, the impacts (population affected, residential buildings damaged, and infrastructure failures) are categorized into social, economic and environmental impacts.

4.4.3. Impact Categorization:

4.4.3.1. Social Impacts:

Social impacts of a flood are associated with the discomfort faced by people residing the floodplain (Levy et. al. 2007). Some of the most studied social impacts of floods are loss of life, population affected, evacuation, property loss, public health, social activity hot-spots and recreations among others are listed in **Table 14**. From **Table 14** we observed that the post-fire flood has similar or higher impacts compared to normal flood event. From this hypothesis, we assume the social impacts associated with flood event can be associated with a post-fire flood event resulting due to a wildfire.

From the available Hazus inventory data, the social impacts that are evaluated for each dam are: (1) population affected/evacuated, and (2) social hot-spots (schools). The maximum potential population affected in each scenario of dam are presented in **Figure 29** to **Figure 31**. The population is estimated as explained in section 4.4.1 using Hazus inventory data and WMS flood extent map. As expected the figures below (**Figure 29** to **Figure 31**) indicate that the population affected increase with increase in percentage of burnt watershed and Case III dam floodplain has highest impact in terms of population affected (3494 for 100% burnt watershed scenario). This population under the flood impact need to be relocated to temporary shelters. And only Case III floodplain **Figure 26**, indicates the presence of a school within the inundation zone.

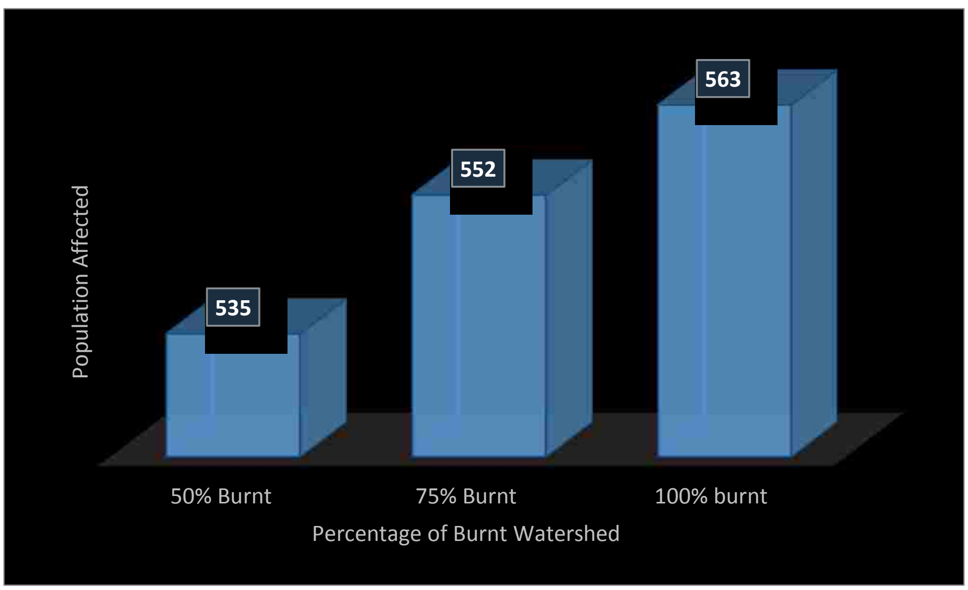


Figure 29: Population Affected in the Case I Floodplain

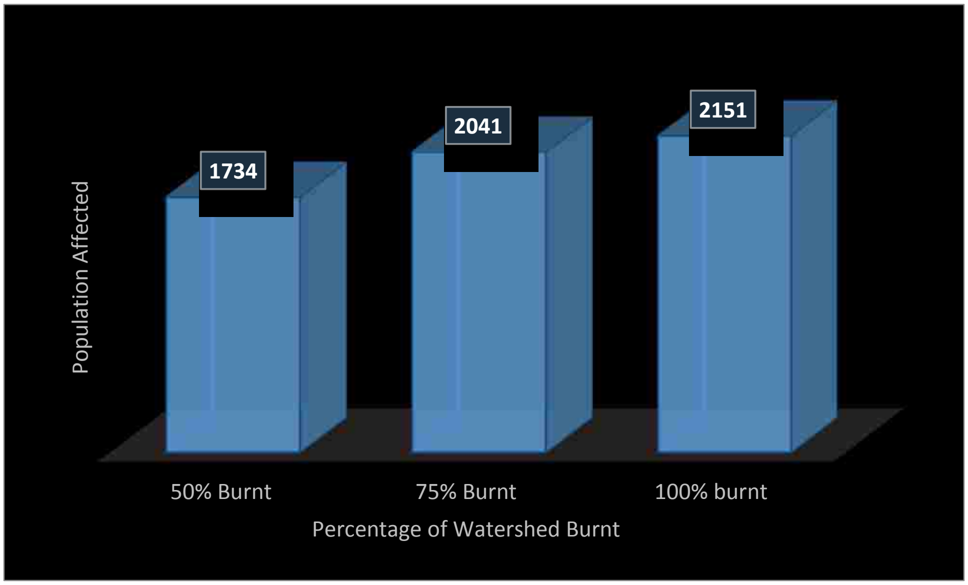


Figure 30: Population Affected in Case II Floodplain

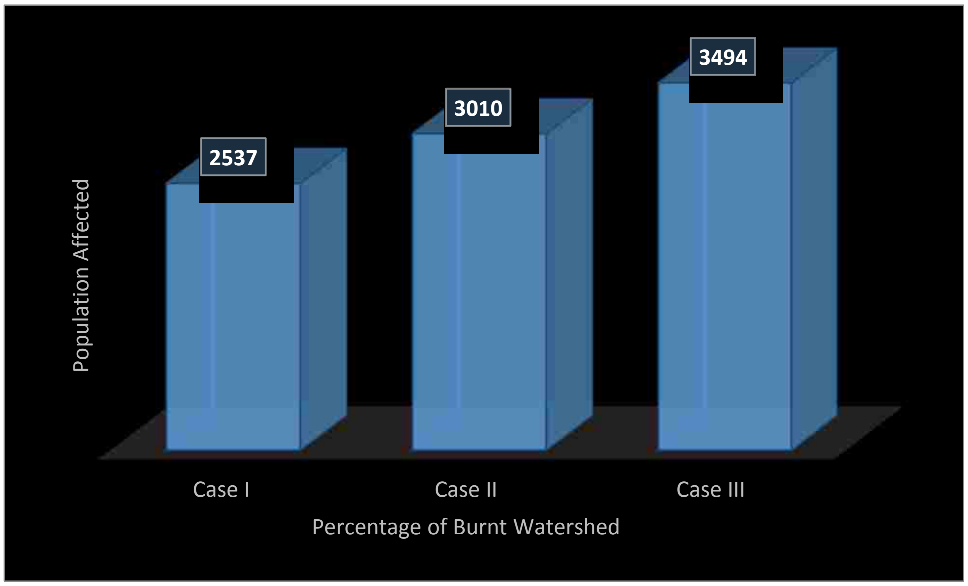


Figure 31: Population Affected in Case III Floodplain

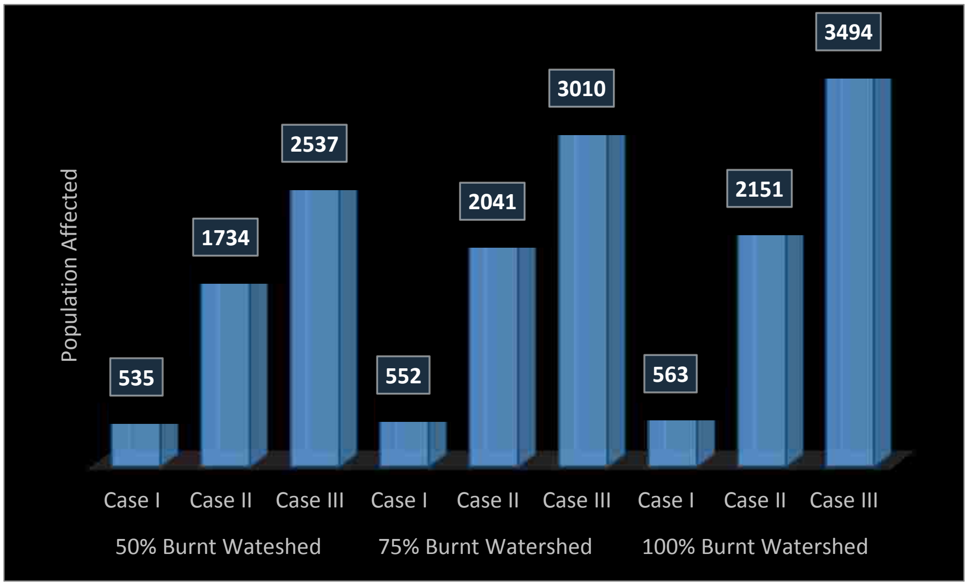


Figure 32: Comparison of Population Displaced in all Scenarios for Each Dam

Figure 32 shows the population displaced for different watershed burnt scenarios. As expected, with increase in area affected by wildfire, there is increase in population affected in the floodplain of all dams.

4.4.3.2. Economic Impact

The cost of damage to a building is considered as economic impact (Tkach and Simonovic 1997). The cost of damage to residential and infrastructures is considered in this study as economic criteria. The total number of households (residential buildings) under the flood impact are given in **Table 37**. The cost of damages for each dam are estimated and shown in **Table 38** to **Table 40**. **Figure 33** shows the cost of damage to residential buildings at each floodplain due to dam-break flooding in which Case III floodplain has the highest cost of damage. Case III dam's floodplain occupancy is much higher compared to Case I floodplain and Case II floodplain. Hence the higher impact in terms of cost of damages.

Table 42 shows different infrastructures under impact in each dam's floodplain. The cost of damages to these infrastructure might depend on the depth of flood and the extent of damage.

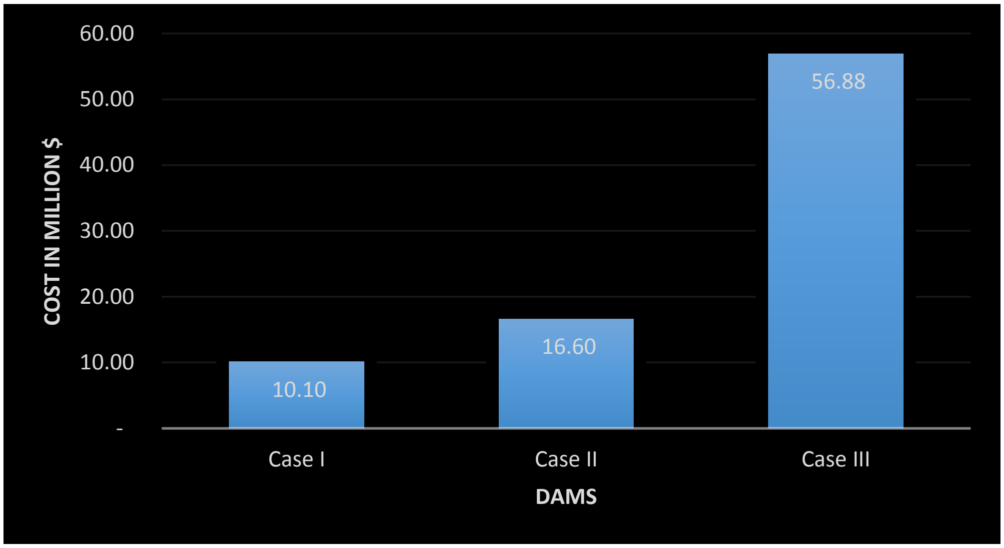


Figure 33: Cost of Damage to the Floodplain Residential Buildings

To estimate the cost of damage to infrastructure, the percentage of damage for each infrastructure is identified. To identify the percentage of damage, Hazus Multi-hazard Loss Estimation Manual is used. This manual provided the percentage of damage to various infrastructures based on the depth of flood. Therefore, depth of flood at the location of each infrastructures identified in **Table 42** are presented along with the percentage of damage due to flooding in **Table 43**. **Table 43** presents the level of criticality of the infrastructure provided by Hazus along with depth of flood at its location and the extent of damage (percentage of damage, cost of damage, and functionality depending on the availability of data).

Table 43: Cost and Extent of Infrastructure Damage

Dam	Infrastructure	Depth (ft.)	Criticality	Damage Extent
Case I	Bridge 1	16	High	Partial damage
	Bridge 2	40	High	Significant damage
	Bridge 3	45	High	Significant damage
	Waste Water Facility 1	10+	High	40% Damage
	Natural Gas Facility 1	10+	Low	40% Damage
	Natural Gas Facility 2	10+	Low	40% Damage
	Natural Gas Facility 3	10+	Low	40% Damage
Case II	Bridge 1	30	High	Water Flows over the bridge
	Road	4	High	Damage Cost of $5,000,000 per km
Case III	School 1	3	-	Closed for flood above 0.5ft
	Fire Station	3	-	Closed for flood above 2ft
	Bridge 1	15	High	Water Flows over the bridge
	Bridge 2	6	High	Partial damage
	Road	7	High	Damage cost $10,000,000 per km
	Irrigation canal (bridge)	16	High	Damaged canal
	Rail Road	8	High	Damage cost $1,500,000 per km

The damage costs for governmental buildings (general services and emergency responses) and educational buildings (schools and universities) provided by Hazus (2006) are \$.95/ft^2. To estimate the approximate cost of damages of the infrastructures, area of each infrastructure is necessary. As the SMPDBK flood extent polygon imported to ArcMap does not contain flood depth data, the cost of damage estimation could not be performed in Hazus. Therefore the cost of damage per square-foot of governmental buildings is provided.

4.4.3.3. Environmental Impacts:

Sediments discharge from reservoir due to dam-break can cause damages to the agricultural lands and drainage systems. The increased sedimentation due to post-fire rainfall along the river channels can trigger number of morphological changes in river channels and valley floors (Benda et al. 2003). The post-fire sedimentation leads to alluvial fan alterations, changes in channel gradients, and irregularly spaced tributaries lead to new riverine habitats (Benda et al. 2003). Apart from sediment deposits, debris flow can have adverse effects on agricultural lands and native species habitats (Cannon and DeGraff 2009). The maximum possible sediment discharge from each dam is given in **Figure 34** for the maximum watershed affected scenario (100% burnt watershed). As expected, the increased percentage of watershed affected by wildfire resulted in increased sediment yields.

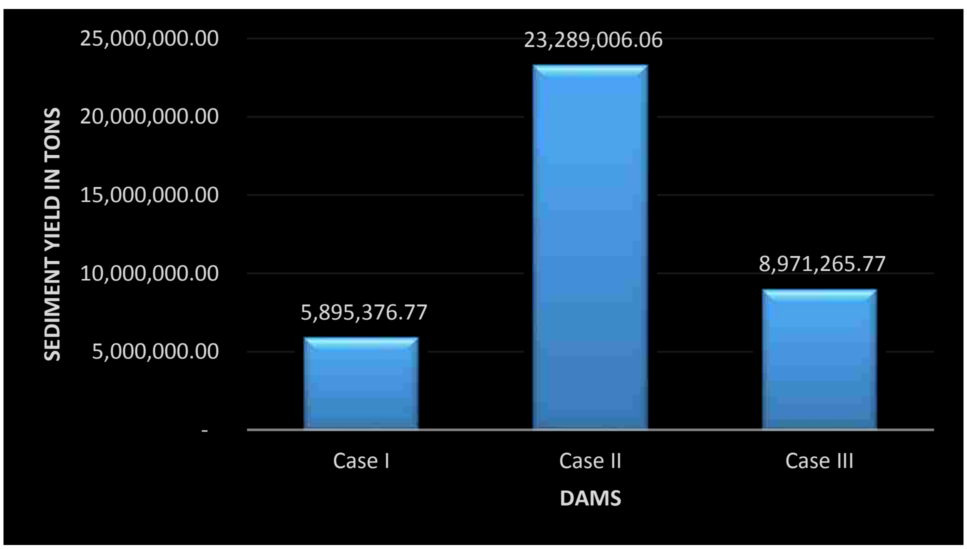


Figure 34: Sediment Yield at Each Dam

Case II floodplain has higher potential to be affected by major sediment flow (approximately 23,289,006tons). The higher runoff generated by a 25 year storm in Case II watershed resulted higher sediment yield. The increased sediment yields results in higher environmental impacts. The wastewater facility affected in Case I floodplain can pollute the water and the river ecology. The irrigation canal (listed in **Table 43**) disruption and sediment flow can reach the agricultural lands resulting loss of cultivated crops and fertility of the soils.

4.5. Risk Due to No-Dam Break Event:

According to a dam Safety Manager at a local dam in New Mexico, even though the excess runoff generated due to post-fire rainfall does not result in a dam failure, the post-fire runoff and sediment yields can have adverse effects on dams and reservoirs. As mentioned in section 4.2, there are four instances in which an overtopping effect is not observed at dam's crest which might not result in dam failure. However, there is significant amount of sediment yield at the reservoir due to post-fire rainfall which might fill-up the reservoir and result in the reduced storage capacity (Robichaud (2005) Hossain et.al. (2010)). When the runoff volume from a post-fire flood do not exceed the reservoir capacity the outcomes (impacts) are different at the reservoir according to the dam safety manager. These outcomes/impacts are categorized into social, economic and environmental impacts.

4.5.1. Social Impacts

The dams are usually designed with sediment pools with a lifetime of 75 years (approximate) according to the dam safety manager. However, there is increased sediments flow with post-fire rainfall event. This can fill up the sediment pool and reduce the storage capacity of the dam. The reduced capacity might not store enough water to serve the design purpose of the dam. This can cause discomfort for the floodplain residents who depend of the reservoir water on daily bases. As in the Case III dam, the dam height was increased twice in 1912 and 1936 due to sedimentation of reservoir (Bureau of Reclamation). For Case II reservoir, 970 acre-ft. of sediments are added annually (US Army Corps of Engineers 2015).

4.5.2. Economic Impacts

From the interview with the dam safety manager, an increased runoff inflow from a post-fire flood is recorded at Case II Dam. If the runoff is not high enough to create an overtopping effect it could still bring enough water to the reservoir which can set a record pool level. According to safety manager, this record pool elevation is a special condition for a given dam. Case II dam had a record pool elevation in 1987 (which is close to 25 year time period which is the rainfall storm (25yr rainfall) considered in this study). The record pool elevation of the reservoir puts the dam in an untested water elevation enforcing a round the clock inspections. The performance of the dam is inspected on daily basis apart from annual comprehensive inspection and a periodic 5 year inspection.

However the record pool elevation forces much comprehensive physical inspection of the spillways, dam structure, and banks of the reservoir to make sure the dam is performing as expected. These set of inspections are laborious and expensive. According to safety manager, the cost of inspections can vary depending on the flood intensity. If the inspections conclude that the dam structure might fail for the record pool level, an Emergency Action Plan (EAP) will be implemented immediately (evacuating the floodplain residents). According to safety manager, the EAP is exercised on annual bases to make sure the downstream stakeholders are evacuated in time to minimize loss of life and property.

4.5.3. Environmental Impacts:

The record pool elevation, and the excess sediment inflow due a post-fire rainfall lead to specific scenarios that can create environmental impacts. According to the dam safety manager, if the inspections conclude that the dam might not hold at the new water level, excess water is released to the downstream floodplain to inundate agricultural lands. This might result in loss of crop and erode the top fertile soil of the agricultural lands. The excess sediment deposition might result in filling up the reservoir's sediment pool faster than the design life period. In such scenario, two options are available to implement to restore the dam storage capacity, (1) Drain the reservoir and remove sediments, and (2) Raise the height of the dam. The decision between these two options are made based on their environmental impacts. Draining of the reservoir decision will be monitored by Reservoir Control Branch and raising the height of the dam is monitored by Dam Safety team. According to safety manager the draining of the reservoir inundates the floodplain and the agricultural lands on the downstream which has major environmental impact, and special clearances and permissions need to be taken to procced. And to raise the dam height specific processes need to be followed to get the required funds. Both the teams suggest the options to the District Manager and he makes the final decision based on the consequences and impacts.

4.6. Decision-Making Matrix

The outcomes presented in sections 4.4 and 4.5 are used to form the decision-making matrix given in **Table 17**. The decision-making matrix is a list of possible impacts of a post-fire flood and its impact on earth dams and their floodplains. This can help decision makers to identify the intensity of a wildfire due to a post-fire rainfall events and make decisions to protect the infrastructures and minimize stakeholder's losses by allotting funds to the highest hazardous zone (the collective set of watershed-dam-floodplain with highest impacts due to wildfire and post-fire rainfall). The findings of this study are summarized in **Table 44** where the impacts in each scenario are shown for the three dams. The matrix shows impacts in terms of total population affected, total residential buildings damaged, sediment yields and infrastructures at risk. Along with the impacts, the critical percentage of area affected by wildfire and post-fire rainfall are presented. The critical percentage of area indicate that critical area to be affected to result in an overtopping affect at the dam. As we consider overtopping failure as the only failure criteria of an earth dam, if there is no overtopping phenomenon at the dam, there will be no failure. Based on this consideration, burnt scenarios which are below the critical burnt percentages are marked 'Green' indicating no dam failure. And in scenarios which exceed the critical conditions indicated in 'Red' dam failure occurs and their consequent impacts are listed in the **Table 44**. From the critical percentages area of watershed affected and the hypothesis explained in 3.1.1.1 (Q_{crit}), Case III watershed needs little burnt percentage compared to Case I and Case II to produce V_{crit}. And in case of Case I, the percentages indicate that the entire watershed need to be burnt and experience rainfall to cause an overtopping effect which is highly unlikely. From this we can understand that Case I dam is safe for any burnt scenarios below 96%, similarly, Case II dam is safe for any burnt scenario below 75%.

Case III's low percentage of watershed affected can be attribute to its huge watershed area compared to Case I and Case II. Case III watershed is 6.89 times the size of Case I watershed and 1.89 times the size of Case II watershed. Therefore, for lower burnt percentages, Case III watershed generates enough runoff to cause an overtopping effect. However, earlier from section 4.4.1 and **Figure 17** we observed that even for lower burnt percentages, Case I floodplain experienced maximum impact in terms of it population affected (provided the dam fails due to other failure criterion apart from overtopping). Summarizing the observations form the table we can understand that Case III dam-watershed has higher chance of failure compared to Case I and Case II dams. Based on this Case III's watershed and floodplain can be categorized as high-hazard zone where the authorities can implement mitigation methods to prevent impacts on stake holders. In case of no-dam failure, the consequences are listed in **Table 45**.

Table 44: Decision-Making Matrix

<table>
<tr><th>Dam</th><th>Impacts in Floodplain</th><th>50 % watershed burned scenario</th><th>75 % watershed burned scenario</th><th>100 % watershed burned scenario</th><th>Critical watershed burnt (%)</th><th>Critical watershed affected by rainfall (%)</th></tr>
<tr><td rowspan="5">Case I</td><td>Rainfall Intensity Ranges (in)</td><td colspan="3">1.37-2.23</td><td rowspan="5">96%</td><td rowspan="5">98%</td></tr>
<tr><td>Population affected</td><td>No Dam Failure*</td><td>No Dam Failure*</td><td>563</td></tr>
<tr><td>Household impacted</td><td>No Dam Failure*</td><td>No Dam Failure*</td><td>237</td></tr>
<tr><td>Sediment Yield (Tons)</td><td>No Dam Failure*</td><td>No Dam Failure*</td><td>5,895,377</td></tr>
<tr><td>Infrastructures at risk of inundation</td><td>No Dam Failure*</td><td>No Dam Failure*</td><td>Bridges - 3
Waste water facility - 1 Natural Gas Facilities - 3</td></tr>
<tr><td rowspan="5">Case II</td><td>Rainfall Intensity Ranges (in)</td><td colspan="3">1.64-2.21</td><td rowspan="5">75%</td><td rowspan="5">85%</td></tr>
<tr><td>Population affected</td><td>No Dam Failure*</td><td>2041</td><td>2151</td></tr>
<tr><td>Household impacted</td><td>No Dam Failure*</td><td>461</td><td>489</td></tr>
<tr><td>Sediment Yield (Tons)</td><td>No Dam Failure*</td><td>17,647,583</td><td>23,289,583</td></tr>
<tr><td>Infrastructures at risk of inundation</td><td>No Dam Failure*</td><td>Bridges - 1
Road Network</td><td>Bridges - 1
Road Network</td></tr>
<tr><td rowspan="5">Case III</td><td>Rainfall Intensity Ranges (in)</td><td colspan="3">2.47-3.15</td><td rowspan="5">20%</td><td rowspan="5">36%</td></tr>
<tr><td>Population affected</td><td>2537</td><td>3010</td><td>3494</td></tr>
<tr><td>Household impacted</td><td>1161</td><td>1338</td><td>1542</td></tr>
<tr><td>Sediment Yield (Tons)</td><td>4,628,164</td><td>6,798,107</td><td>8,971,268</td></tr>
<tr><td>Infrastructures at risk of inundation</td><td>Schools - 1
Fire Stations - 1
Bridges- 2
Road Network
Rail Road Network</td><td>Schools - 1
Fire Stations - 1
Bridges- 2
Road Network
Rail Road Network</td><td>Schools - 1
Fire Stations - 1
Bridges- 2
Road Network
Rail Road Network</td></tr>
</table>

Note: * the consequences of no-dam-break are listed in **Table 45**.

Table 45: No-Dam Break Impacts Summary

No Dam Break	
Impact	**Consequences**
Sediment Deposition	1. Reduced reservoir capacity 2. Reduces life time of the dam as the increased sediment level reduces the reservoirs major functionality of storing water 3. Leaves the dam vulnerable to the future floods as the reservoir might not hold enough flood water 4. Causes economic burden to remove the sediment deposits from the reservoir
Dam at Record flood level	1. Round the clock physical inspections of all dam components 2. Close monitoring of dam systems 3. Implementation of EAP(Emergency Action Plan) to evacuate floodplain occupants in case of dam malfunction at record flood level

From the decision matrix (**Table 44**) and the economic impacts in residential zones (section 4.5.2), a decision making process can be developed. This decision making process is intended to help the decision makers to allot funds appropriately. The decision making flow chart evaluates the decision making based on profits and losses (in this case, we want minimum losses due to the wildfire event). The decision making flow chart is provided in **Figure 35**. The acronyms used in this flow chart are explained in **Table 46**. The decision making process starts with a wildfire event. Consider a wildfire event in a given watershed, the first step shown in **Figure 35** is a chance (probabilistic event) i.e. the chance of wildfire reaching a critical burnt area or not. For demonstration purpose, the chance of reaching the critical burnt area is assumed be 6% (an approximate values assumed considering Case I watershed). This leaves the chance of not reaching the critical burnt percentage as 94%. Based on this we have couple of decisions to make 1) apply mitigation strategies 2) not apply mitigation strategies.

Table 46: Acronyms for Decision Flow Chart

Acronym	Expanded Form
A_W	Area of watershed burnt in a wildfire
A_{wcrit}	Critical watershed burnt area
A_R	Area of watershed affected by rainfall
A_{RCrit}	Critical Area of watershed affected by rainfall
Q	Runoff inflow
Q_{crit}	Critical runoff inflow

In both cases (A_w>=A_{wcrit} and A_w<A_{wcrit}) mitigation and no-mitigation decisions can lead to another set of chances. In case of mitigation strategies implemented in watershed we might have benefit from them or we might not. The benefits in this case are avoiding excess flooding during a post-fire rainfall (in other words, Q<Q_{crit}) which avoids a dam overtopping and failure and thus the inundation of floodplain. All these outcomes avoided are considered as benefits of mitigation (in this decision making section). In case of no-mitigation strategies applied, the dam may experience excess sedimentation and record flood level which have potential economic impact. As the decision tree needs certain values (profits and losses incurred in each decision) to make decisions, the benefits are assumed as profits (expenditure avoided at dam and floodplain, for example, avoiding sedimentation, and downstream flooding, are considered as profits) and the expenditure (money spent on mitigation, money spent in removing sediments in a reservoir among others) is assumed as losses. For instance, if no-mitigation strategies is applied to A_w>=A_{wcrit} case, we can have a two probabilistic events, A_R >= A_{RCrit} or A_R < A_{RCrit}. The probability of A_R >= A_{RCrit} is assumed to be 2% and A_R < A_{RCrit} is assumed to be 98% (considering Case I watershed). Both cases (A_R >= A_{RCrit} and A_R < A_{RCrit}) can lead to Q<Q_{crit} or Q>=Q_{crit} however, the probabilities satisfying this condition vary differently in each case of A_R >= A_{RCrit} and A_R < A_{RCrit}.

In case of A_R >= A_{RCrit}, $Q<Q_{crit}$ and $Q>=Q_{crit}$ were given equal probabilities but in case of A_R < A_{RCrit}, $Q<Q_{crit}$ was assigned higher probability (90%) than $Q>=Q_{crit}$ (10%) (These assumed probabilities are not accurate, however, the probabilities can make sense when we think in case of $A_R<A_{RCrit}$ the chance of Q reaching a critical limit is very low). If $Q>=Q_{crit}$ condition is satisfied, the dam fails due to overtopping causing, floodplain inundation, implementation of emergency action plan and property loss. All these events were given equal probability and the same can be observed in **Figure 35**. Each of these events result in losses depending on floodplain occupancy of the given dam. In **Figure 35** some sample values (money spent due to inundation of buildings) were assigned for each event to allow the decision making process. For the given set of profit and loss values, the decision tree chose to implement mitigation strategies after a wildfire event to minimize the losses. Similar approach is followed in each decision making node in the decision tree. This flow chart of multiple decision making can help us evaluate the losses in floodplain and the expenses of mitigation strategies and its benefits to make a decision in an event of wildfire.

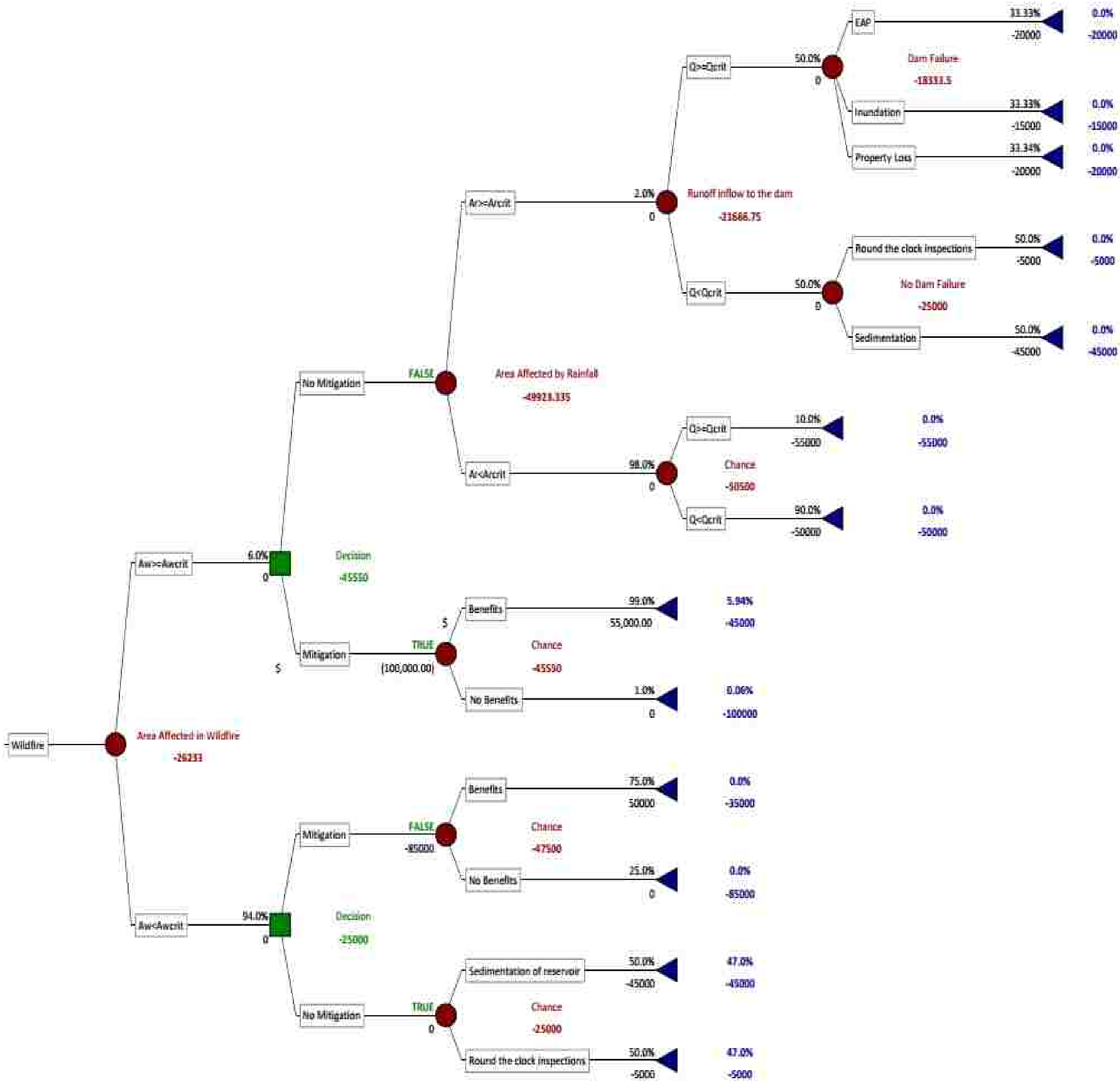


Figure 35: Decision Tree

4.6.1. Mitigation Alternatives:

Some of the mitigation alternatives that can be implemented in the watershed are discussed here. Mitigation alternatives are necessary where fires are closer to wildland-urban interface as the risk on stakeholder is high in these zones (Robichaud et al. 2000). Different mitigation alternatives can be implemented at different locations within the zone (anywhere from watershed, river channels, at the dam and in the floodplain). The effectiveness of the mitigation method is crucial as the implementation of each method could be expensive. In the last decade the spending on mitigation/rehabilitation process to reduce the threat of increased runoff and sediments has increased to over $48 million (Robichaud et al. 2000). The latest spending could be much higher than the value provided here. Some of the potential mitigation alternatives are provided in **Table 47** along with their area of focus.

Table 47: Mitigation Alternatives for Post-fire Flood

Order of Mitigation	Mitigation Method	Area of focus	Source
Post-fire Mitigation	Contour Felled Logs	Hillside treatment for immediate watershed protection	(Robichaud et al. 2000).
Post-fire Mitigation	Seeding grass	Reduce erosion at burnt sites, hillslopes	(Robichaud et al. 2000).
Pre-fire Mitigation	Mulching and installed barriers	Hillside protection to reduce sedimentation	(Robichaud, 2005)
Pre-fire Mitigation	Rolling dips, water bars, and culvert reliefs	Reduce damage to roads	(Robichaud et al. 2000).
Pre-fire Mitigation	Check dams	Reduce sedimentation	(Robichaud et al. 2000).
Pre-fire Mitigation	Raising of Dam Height	Increase dam capacity to avoid flooding	Dam Safety Manager(NM)
Pre-fire Mitigation	Different fuel reduction techniques employed in watershed	Reduce fire intensity	(Strom and FulÃ© 2007)

However, the mitigation methods provided in **Table 47** have their limitations. The effectiveness of any treatment method is limited to small quantity (Robichaud et al. 2000). Contour-felled logs are effective in immediate watershed protection (the first post-fire year) (Neris et al. 2013). Seeding grass and mulching have low effect as the benefits of grass can be observed after initial runoff events (Robichaud et al. 2013). Most importantly, onsite sediment control programs (barriers, and contour-felled logs among others) are effective than offsite sediment control programs (check dams) (Robichaud et al. 2000). Based on mitigation alternatives and their effectiveness, appropriate measures need to be taken to the high hazard zones to reduce the impact on stakeholders. This research framework helps to identify the high hazard zones to help decision makers in prioritizing and allotting funds. Allotting funds based on the priority might help in effective management of taxpayer’s money in reducing the impacts on stakeholders.

4.7. Chapter Summary:

In this chapter, the proposed framework was applied to the case-study. A Decision-Making Matrix was proposed that summarized the impacts and prioritizes hazardous zones with a goal to assist decision makers. First, the post-fire runoff and sediments generated from each watershed were estimated for three different scenarios (i.e. 50% burnt watershed, 75% burnt watershed and 100% burnt watershed). Q_{crit} for each watershed was computed. The runoff volumes were used in modeling the dam-break using WMS: SMPDBK. The flood extent polygon generated from the program was interpolated with Hazus inventory data to estimate the impacts in each floodplain. The trends in floodplain impacts were investigated based on the topography of the floodplain.

The damage costs of residential buildings under the dam-break flood impact were estimated. Infrastructures within the flood extent were identified at each floodplain. From the runoff estimates, few scenarios did not result in overtopping of dam and hence a no dam-break scenario was evaluated to identify the potential impacts. A telephone interview with Dam Safety Manager, at a local dam in New Mexico, provided valuable information regarding dam-break and no dam-break scenario and details of Emergency Action Plans. The total population affected, residential buildings damaged and infrastructures under inundation are considered in evaluating the impacts of floodplain. The post-fire flood and dam-break impacts were categorized into social, economic and environmental impacts. These impacts were summarized in a matrix to help decision makers. The decision matrix and critical percentage area affected were used to build a decision tree and make decision based on profit (money saved by avoiding damages/impacts) and loss (money lost due to damages). In the end a set of mitigation alternatives were proposed that can potentially reduce the impacts of wildfire and post-fire rainfall events on earth dams and their floodplains.

Chapter 5: Research Summary and Conclusions

5.0. Introduction:

The changing climate is responsible for the increased frequency of natural disasters such as wildfires, post-fire rainfall and floods. The impacts of these events on urban areas can be significant in terms of social, economic and environmental categories. It is important to understand the potential severity of such events and their impacts on urban centers and communities. The problem that any decision maker faces is limited funds and tight budgets. Prioritizing the high hazard zones can help the decision makers to identify the vulnerable zones and can act to minimize the risk of damage and protect essential infrastructure. This research focuses on proposing a decision making model capable of identifying and prioritize the high hazard zones to help the decision makers allot funds to minimize the impacts on stakeholders.

5.1. Summary of Research:

The objective of this study was to propose a framework capable of prioritizing high hazard zone (watershed-dam-floodplain). From the review of previous works, it was found that studies incorporated post-fire floods are limited to the study of runoff, sediment and debris increments. Additionally, it was found that the literature on dam-break flooding is limited to specific case studies and to reduce the computational time of dam-break modeling. In this thesis, the impacts of post-fire flood are extended to earth dams and their floodplains.

A risk-based framework is proposed to identify high hazard zones (watershed-dam-floodplain with highest impacts) and prioritize to assist decision makers.

Three main research questions were formulated and researched throughout the study to achieve this objective.

1. *What criteria can be considered to evaluate the severity of a post-fire rainfall event?*

In this study, post-fire runoff and sediment yield from watershed are estimated for different burnt scenarios where each scenario is based on the percentage area of watershed burnt. Three scenarios were considered: (1)50% of watershed burnt in wildfire, (2) 75% of watershed burnt in wildfire and (3) 100% watershed burnt in wildfire. With increase in percentage of watershed burnt, an increase in runoff and sediment yield is observed for a given rainfall intensity. This can justify that the criteria considered to evaluate the severity of post-fire rainfall is valid.

2. *What are the impacts of post-fire flood on Earth Dams and Reservoirs?*

The post-fire rainfall flood generated excess runoff and sediments from the watershed compared to a normal rainfall flood. These excess runoff and sediment yields resulted in adverse effects on earth dams. In the considered case studies majority of the scenarios predicted an overtopping effect at the dam which leads to dam failure and flooding. The impacts of dam failure are measured in terms of population, residential buildings and infrastructure affected. In scenarios where there is no dam failure observed, the impacts are in terms of reduced reservoir storage capacity, and increased maintenance costs.

3. *How can the dam-break impacts be incorporated in decision making?*

The two responses of an earth dam to a post-fire flood are (1) a dam-break event due to overtopping, (2) no dam-break event. In case of dam-break event, the impacts of floodplain are evaluated in terms of population affected, residential buildings damaged and infrastructure at risk of inundation. In a no dam-break scenario, impacts are observed in terms of reduced reservoir capacity, increased maintenance and inspection costs. The impacts were estimated for each watershed burnt scenario and considered as major criteria in prioritizing the zone (watershed-dam-floodplain) as high hazard zone. From the decision matrix, based on the critical percentage of watershed affected Case III watershed is identified as high-hazard zone. The impacts from the decision matrix can be used in the decision tree which helps the decision-makers to allot funds appropriately to minimize the impacts.

An interview with Dam Safety Manager at local dam in New Mexico, provided justification of the findings for all the questions. He provided with valuable information for majority of no dam-break scenario outcomes. Based on these inputs (dam-break and no dam-break impacts and outcomes) a Decision-Making Matrix is proposed to prioritize the watershed-dam-floodplain zones. The matrix consists of values indicating the potential population affected, residential buildings damaged and infrastructures under the risk of inundations.

5.2. Summary of Results:

The proposed framework was illustrated with the case-studies of three different dams in New Mexico, USA. First, runoff and sediments were estimated for a 25year post-fire rainfall storm with 95% confidence intervals for three different scenarios: (1) 50% burnt watershed, (2) 75% burnt watershed, and (3) 100% burnt watershed scenarios. The runoff estimates were used in dam-break modeling with WMS: SMPDBK. The flood extent polygon is imported to ArcMap where it was interpolated with Hazus inventory data (census data, residential and essential infrastructure data). Population affected, residential buildings and infrastructure damaged due to downstream flooding are listed out for each scenario.

Some of the scenario considered did not result in dam overtopping phenomenon and hence no dam-break event. However, these scenarios can result in record reservoir level enforcing round the clock inspections and the sediments inflow could reduce the reservoir storage capacity. Based on all the findings, the study zones were prioritized and Case III (watershed-dam-floodplain) was noticed to have higher vulnerability to wildfire and post-fire rainfall events. And potential pre-fire mitigation alternatives such as mulching, installed barriers, check dams and fuel reduction among others and post-fire mitigation alternatives such as contour felled logs and seeding grass were proposed to minimize the impacts of post-fire rainfall.

5.3. Research Contributions

This research contributed in few fields of interest. The research framework considered the evaluation of potential impacts of post-fire rainfall.

5.3.1. Contribution to the Body of Knowledge

The major contribution of this research is the development of a framework to evaluate the impacts of post-fire rainfall on an earth dam including a dam-break event and evaluating the impacts of dam-break on its floodplain in terms of population affected, residential and essential infrastructure at risk of inundation. The proposed Q_{crit} can serve as a major factor for a given watershed, wildfire and rainfall events. The Q_{crit} can be a major decision making variable based on which the critical watershed burnt and watershed affected by rainfall area can be determined. The study proposes a method to incorporate post-fire rainfall impacts in a dam-break event and the impacts of dam-break event in decision-making. Using these inputs, a decision-making matrix and a decision tree is proposed to quantify the impacts on the floodplain to prioritize the study zones.

5.3.2. Contribution to the Body of Practice

The frequency of wildfires have increased over the last decade and so does the likelihood of post-fire flood and respective impacts. However, there is a lack of work done focusing on the impacts of post-fire rainfall runoff and sediments on dams and their floodplain occupants (stakeholders and infrastructures). Prior research related to post-fire rainfall focused on watershed erosion, runoff and sediment yields. Most research related to dam-break event focused on types of earth dam failures with a data base approach, studies related in minimizing the computation time of dam-break modeling. Additionally most of the studies focused on a specific cases.

This study sheds light on the importance of incorporating post-fire flood evaluation and its impacts on earth dams and their floodplains. The framework is capable of estimating the impacts of post-fire flood and integrate those estimates in an earth dam response scenarios. The decision-making matrix included the impact criteria (population affected, residential and essential infrastructure damaged) considered in each response. Based on the impacts, the study zones are priority to assist decision makers in allotting funds to minimize the risk on stakeholders. A set of potential pre-fire mitigation alternatives such as mulching, fuel reduction, installed barriers and check dams and post-fire mitigation alternatives such as contour felled logs and seeding grass among others were proposed. The effectiveness of these mitigation alternatives was also discussed briefly.

5.4. Research Limitations:

Data availability and data quality is one of the major limitation for this study. For instance, the runoff and sediment yield coefficients are obtained from previous studies but not from the study regions. The distribution allotted to the area affected by wildfire and post-fire rainfall are uniform distributions, which in reality is highly unlikely. The damage costs of residential buildings for post-fire flood are not available and hence damage costs for a normal flooding event are considered to estimate minimum damage cost for residential buildings. A qualitative data on cost of building damages based on their sizes can provide better analysis in economic impact evaluation. The WMS: SMPDBK does not have any inventory data to analyze the floodplain impacts. Hence, Hazus inventory data is used to evaluate the floodplain impacts which did not account for detailed floodplain occupancy. The WMS flood polygon does not contain flood depth data that can be imported to ArcMap which is crucial in estimating the cost of damage to various infrastructures located in the floodplain.

The dam-break modeling with WMS: SMPDBK does not account for backwater effects created by channel constraints like bridge embankments. The DEM obtained for the study region had a resolution of 10 meters. This elevation data represents single elevation for a cell sized 10m x 10m which might not result in detailed delineation of dam-break flood. The debris flow and its impacts on earth dam are not focused in this study which is one of the limitation in evaluating post-fire rainfall event.

5.5. Recommendation of Future Research:

Given the limitations of this study, there are numerous areas in which the study can be expanded. For example, a floodplain stakeholder interview could provide better details and understanding of social impacts (such as discomfort, recreation, health and safety among others) due to dam-break flooding. A comprehensive data of floodplain can help in identifying detailed impacts of dam-break. A much detailed study of infrastructure interdependency can provide better insight of floodplain damage severity and propagation of disruptions from one infrastructure to another infrastructure. Sampling of burnt and unburnt soils at the watershed could provide accurate details of runoff excess and sediment yield values for a post-fire rainfall. The incorporation of mitigation alternatives into the framework can help in decision making process over reduce the impacts of post-fire rainfall and reducing the severity of wildfire events.

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Appendix:

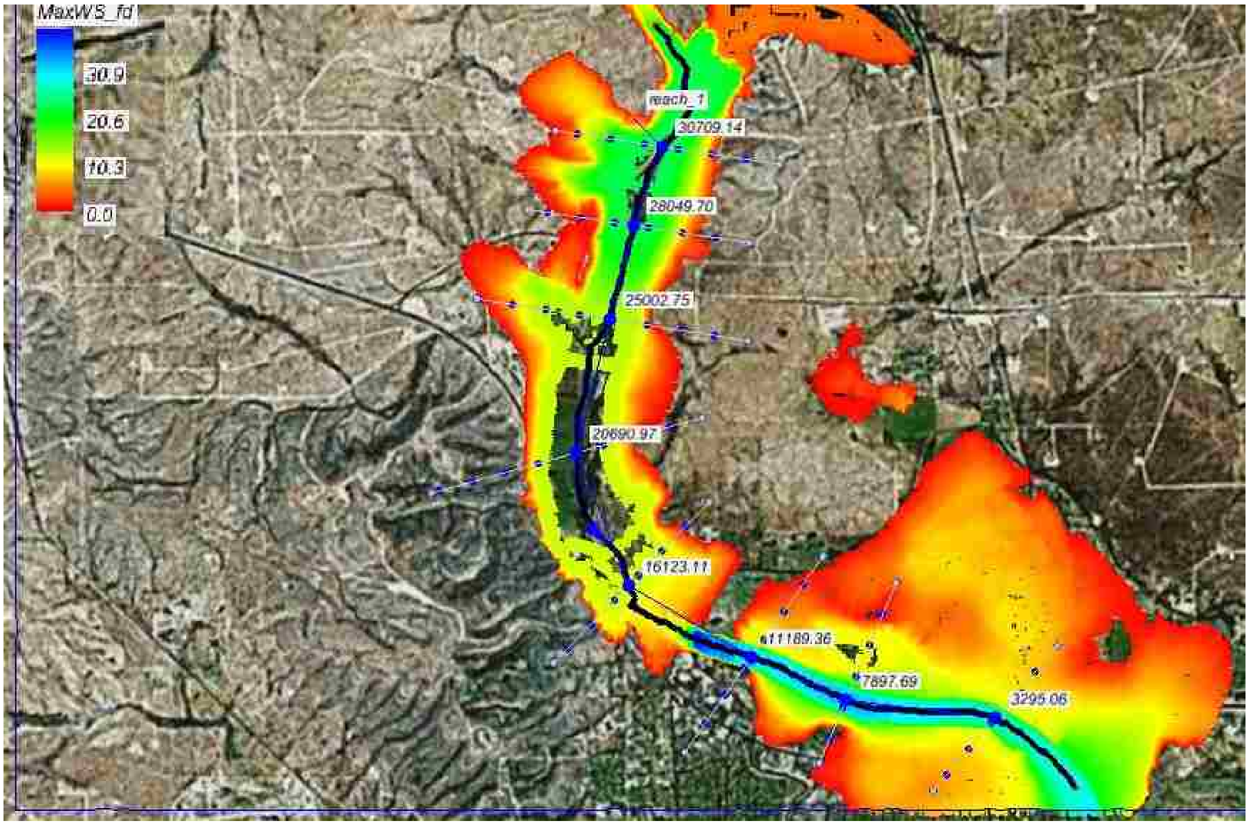

Figure 36: Case III Dam Flood - 50% drainage burnt

[Scale: 1 inch – 1 mile]

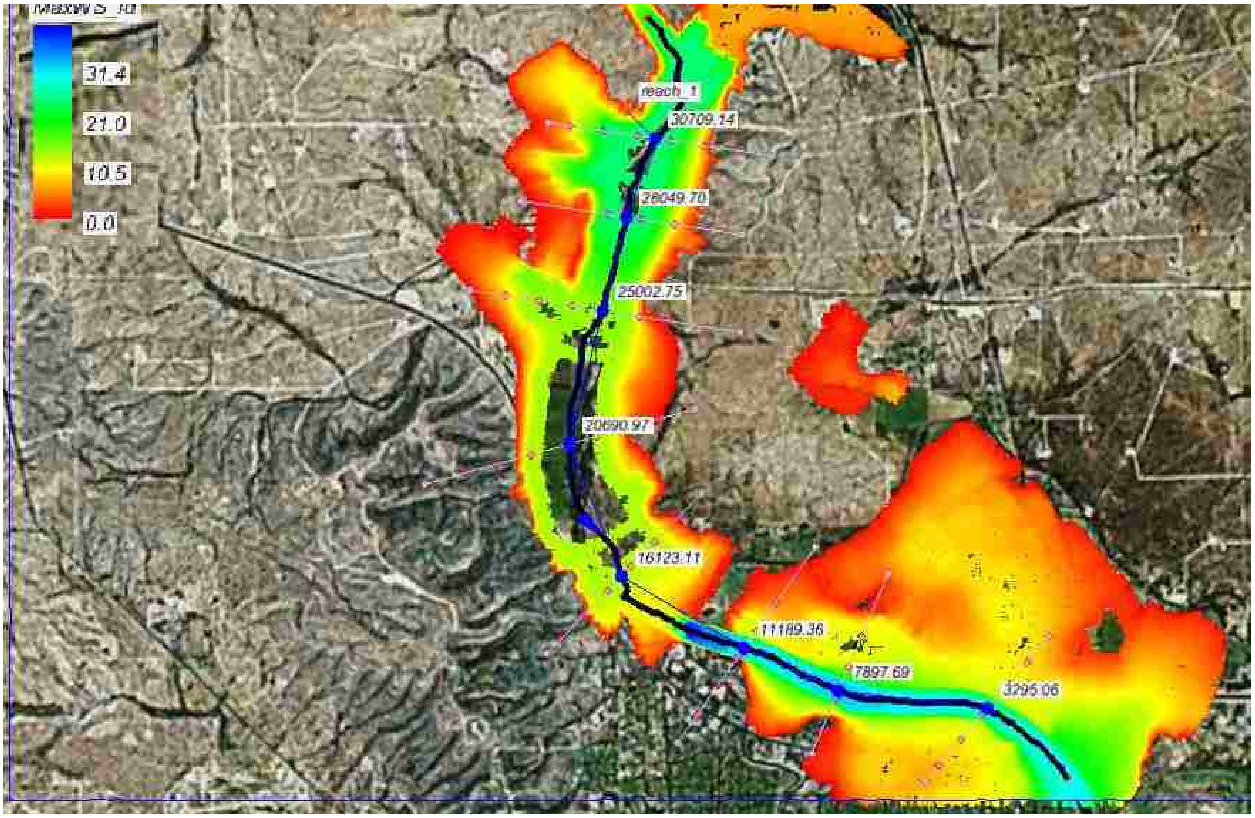

Figure 37: Case III Dam Flood - 75% drainage burnt

[Scale: 1 inch – 1 mile]

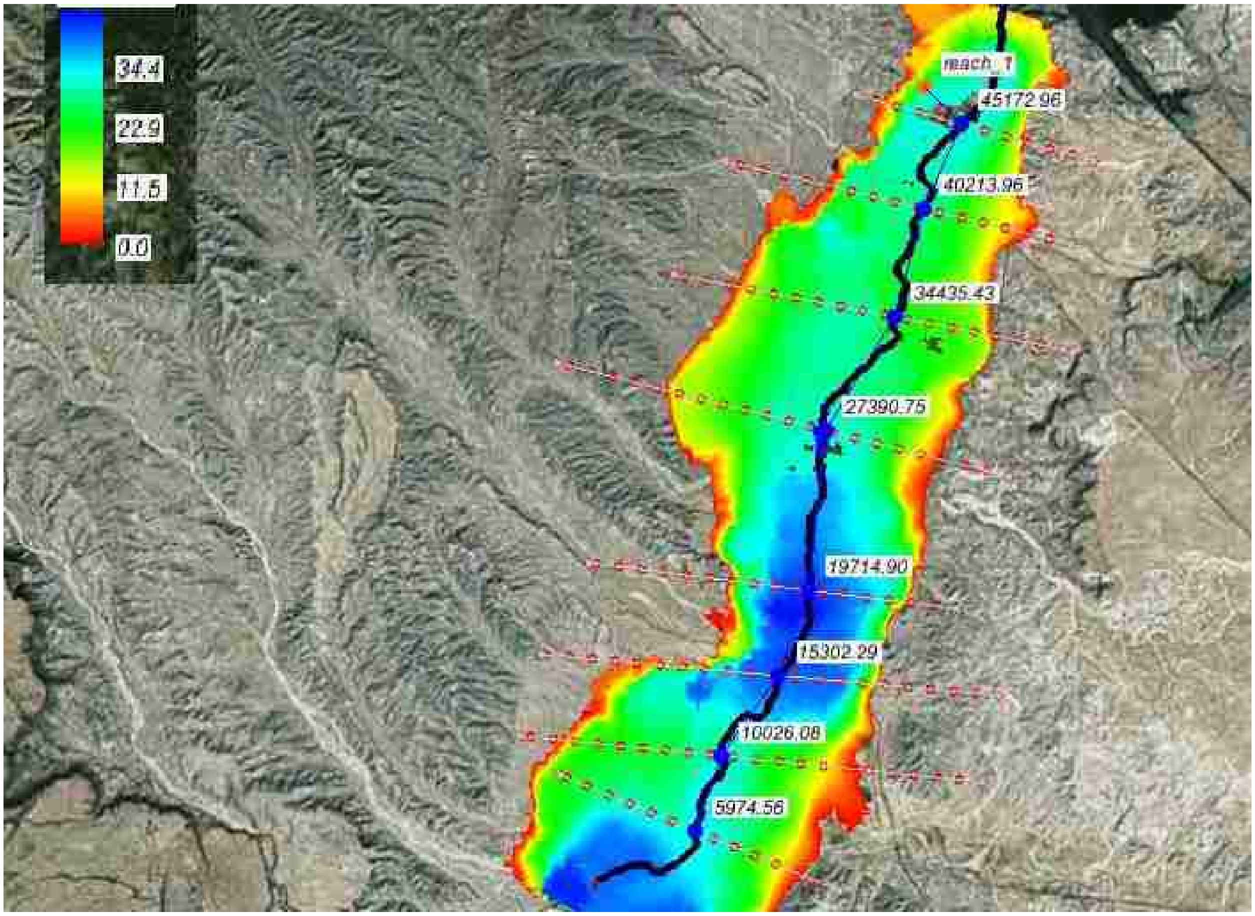

Figure 38: Case II Dam Flood - 50% drainage burnt

[Scale: 1 inch – 1 mile]

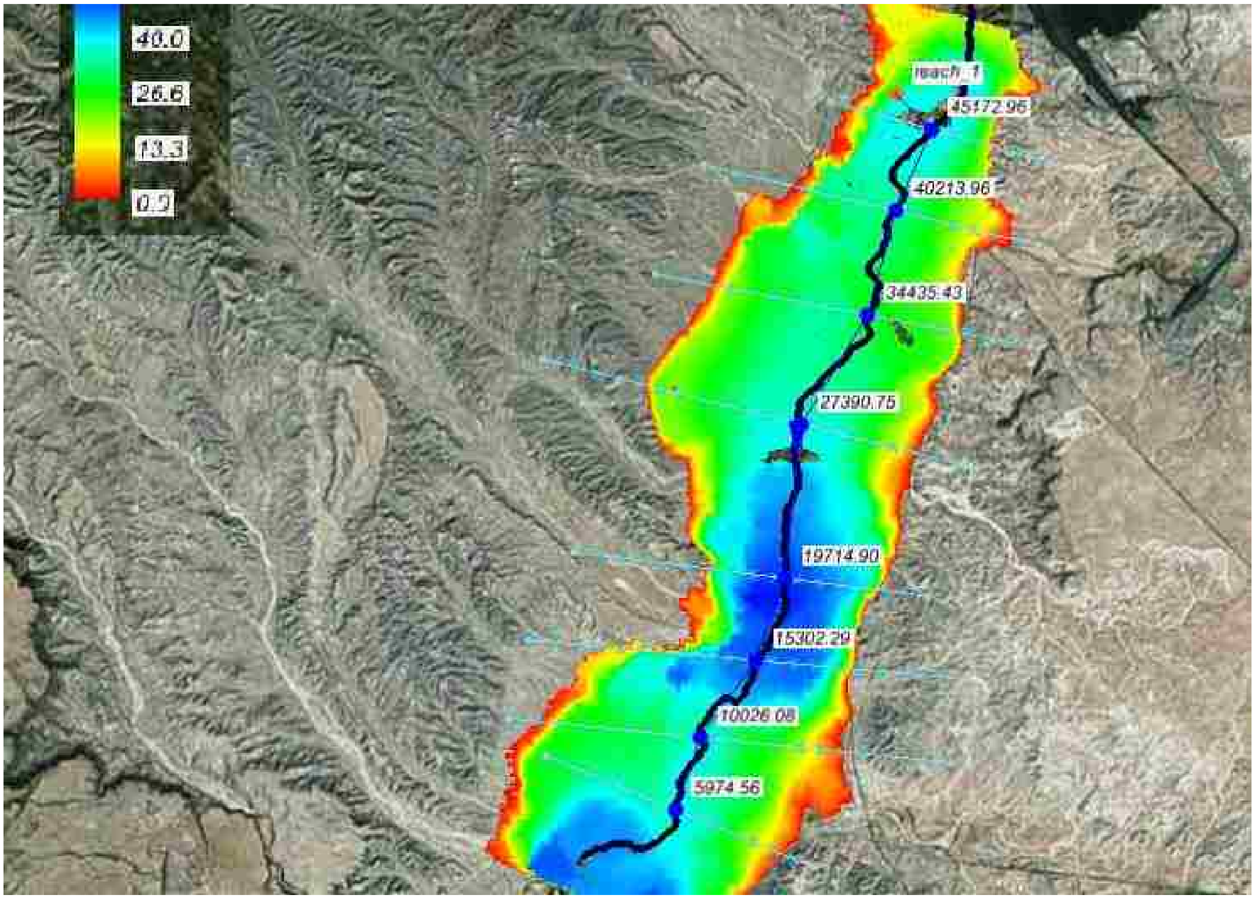

Figure 39: Case II Dam Flood - 75% drainage burnt

[Scale: 1 inch – 1 mile]

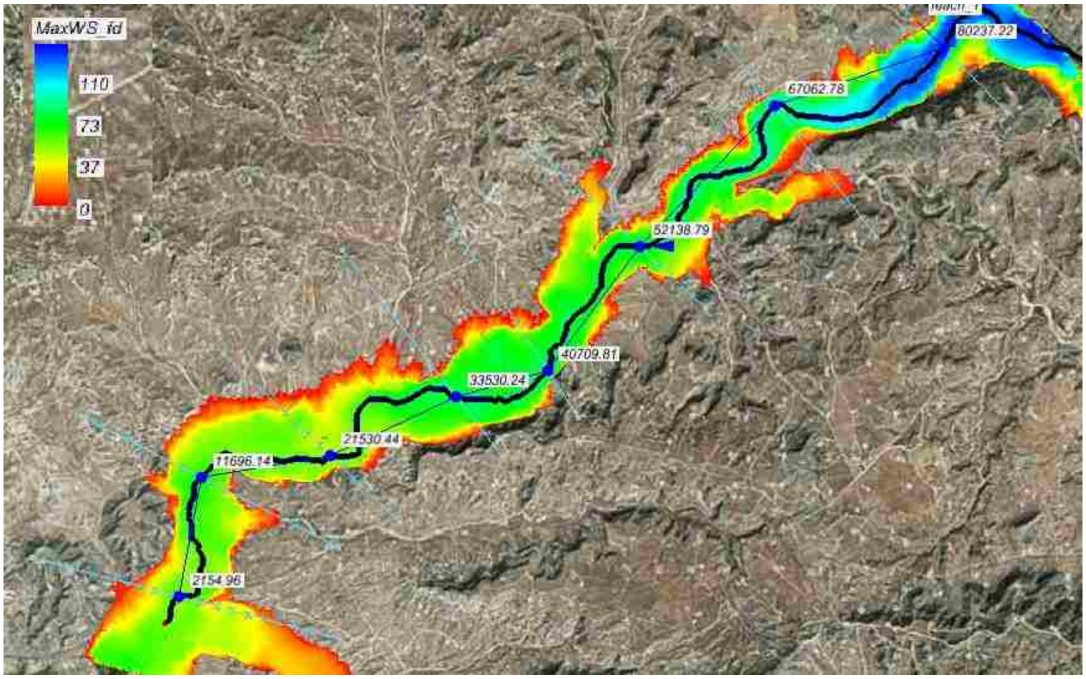

Figure 40: Case I Dam Flood - 50% drainage burnt

[Scale: 1 inch – 1 mile]

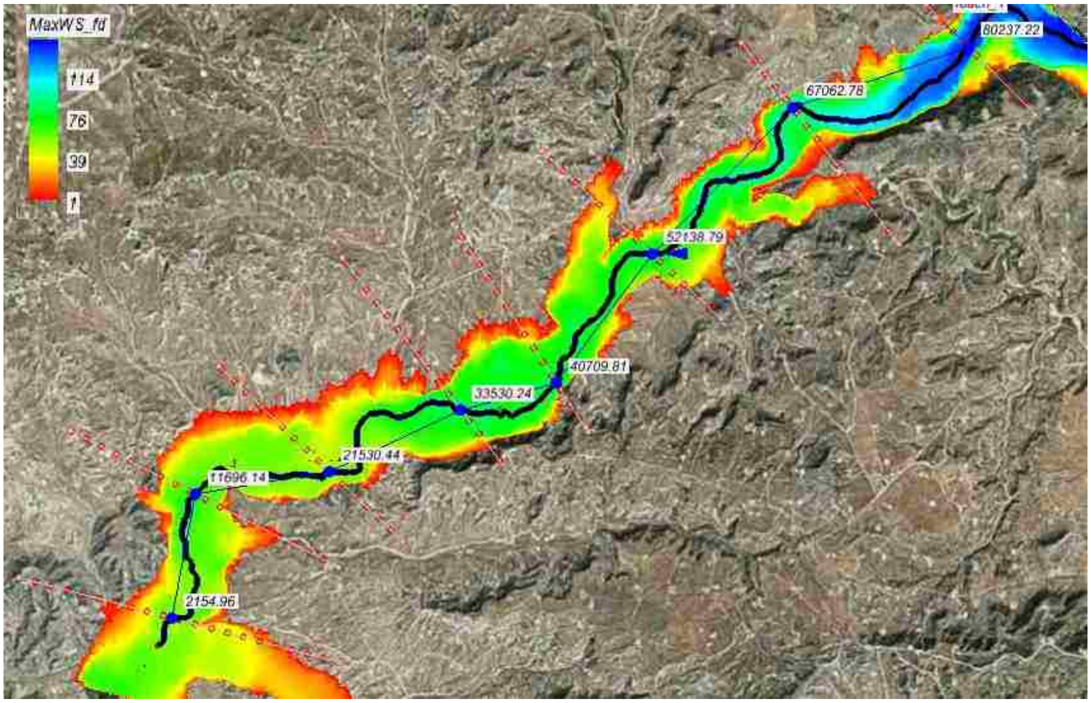

Figure 41: Case I Dam Flood - 75% drainage burnt

[Scale: 1 inch – 1 mile]