The relationship between regional climate and post-fire debris flows

in Glacier National Park

by

Steven Larcom

A directed research report submitted to the Geography Department of

Texas State University in partial fulfillment

of the requirements for the degree of

Master of Applied Geography

with a specialization in Geographic Information Science

May 2018

Committee Members:

Dr. David R. Butler

Dr. Nathan A. Currit

Table of Contents

Abstract

Debris flows often occur on burned hillslopes in mountainous areas, which can damage infrastructure and pose hazards to people and wildlife. Glacier National Park, Montana, has a well-documented history of wildfires across its 400,000 hectares, making it especially vulnerable to these mass wasting events. This project focused on two fires in particular: the Trapper Creek fire from 2003, and the Red Eagle fire from 2006. The goal was to compare and contrast debris flows from a burn scar on the east side of the park with those from a burn scar on the west side of the park in order to understand the relationship between these events and the prevailing climate systems on opposite sides of the Continental Divide. Post-fire debris flows were digitized from aerial imagery (2-3 years post-fire) using ArcGIS, and parameters such as frequency and runout length were measured. At-risk infrastructure was identified based on the location of past flows and current roads and trails. Burned areas in western Glacier contained a higher frequency of debris flows due to higher annual precipitation. Conversely, burned areas in eastern Glacier produced debris flows with longer runout lengths due to the nature of the precipitation and greater sediment availability. By holding all other variables constant, this study has identified a relationship between climate and post-fire debris flows.

Introduction

Background

A debris flow is a moving mass of loose mud, sand, soil, rock, water, and air that moves downslope under the influence of gravity (King 2017). A post-fire debris flow is one that occurs on a burn scar where a recent wildfire has removed vegetation, which in turn decreases slope stability. These phenomena in mountainous areas have been well studied for some time, but far less research has been done on the effects of a particular region's environment on debris flow occurrences. Specifically, one environmental factor that deserves a closer look is regional climate: How do differences in annual temperature and precipitation affect these burned hillslopes? And in knowing the answer to this question, how can public land managers better plan mitigation strategies or identify at-risk infrastructure? Debris flows can be very dangerous – often leading to damaged roads, trails, and occasionally loss of life. In order to better understand what affects their volume and frequency, further research is needed to identify the role that regional climate systems play in post-fire debris flow occurrences.

Glacier National Park is located in northwestern Montana in the northern Rockies section of the western United States. It is part of the larger Waterton-Glacier International Peace Park, which was created in 1932 and combines the two national parks across the US-Canada border. Glacier National Park itself was established on May 11, 1910, and encompasses over 400,000 hectares (NPS 2017c). With more than 2 million visitors per year, Glacier ranks in the top 10 of national parks by visitation (NPS 2016). Many of these visitors come to enjoy the scenery, wildlife, outdoor activities, and relaxation that such a remote place can offer.

The park received its name from the glaciers that sculpted the landscape during the Pleistocene Ice Age, starting approximately 2 million and ending about 12,000 years ago. Since then the glaciers have slowly retreated as a result of the Earth's warming period (NPS 2017b). Photographic evidence over the last century has been used to document the dramatic changes in number and size of the remaining glaciers, and if the current post-industrial warming trend continues, scientists estimate that all of the glaciers in the park will disappear by the year 2030 (Hall and Fagre 2003). This rapid glacial retreat has produced a very visible climate change indicator for scientists and the general public.

Glacier National Park's unique geography is well-suited to the study of mass wasting, and post-fire debris flows in particular. The western Continental Divide runs directly through the park, separating it into eastern Glacier and western Glacier. The rivers on the west side of the Continental Divide drain into the Pacific Ocean, whereas the rivers on the east side drain into the Hudson Bay and Gulf of Mexico. This feature is important because it creates two unique climates for the park. West Glacier, a town on the western side of the park, is much wetter, with an average annual precipitation of 729 mm (US Climate Data 2017a). Babb, a small community in eastern Glacier, is much drier, with an average annual precipitation of 451 mm (US Climate Data 2017b).

In addition, since 1964 is the only year on record in which Glacier National Park did not encounter a wildfire, it serves as an ideal research location for post-fire conditions (NPS 2017a). When vegetation is burned, bare earth is exposed to sun, rain, and snow with no plant root structure to hold it in place. This makes it easier to initiate debris flows. Debris flows have been known to move downslope quickly and inundate lower elevation areas with little to no warning (King 2017). The goal of this project is to understand the relationship between the various wildfire locations on both sides of the Continental Divide and the debris flows that occur there, and to describe the observed differences in those areas. By drawing conclusions based on debris flow runout length and frequency, the findings will better define the locations of the most hazardous areas for post-fire debris flows in Glacier National Park. This will, in turn, assist park managers in preparing mitigation and prevention strategies. The project will also add to the body of knowledge regarding the role of regional climates on the aforementioned processes.

Research Questions

The research questions for this project are:

- Question 1 – How do the runout length and frequency of post-fire debris flows differ across climate regions in Glacier National Park?
- Question 2 – What infrastructure is most at risk of being affected by post-fire debris flows?

The hypotheses are as follows:

- Hypothesis 1a – Burned areas in western Glacier will have a higher frequency of debris flows than burned areas in eastern Glacier. This is because of the higher annual precipitation in western Glacier, with more frequent rainfall events leading to more frequent debris flows. By investigating quantity of debris flows over time, a good estimate of frequency can be determined.
- Hypothesis 1b – Burned areas in eastern Glacier will produce debris flows with longer runout lengths than burned areas in western Glacier. The study will look for an inverse relationship between debris flows frequency and runout length, so if Hypothesis 1a is supported by the findings, debris flows would have longer runout lengths in eastern Glacier.
- Hypothesis 2 – The infrastructure most at risk will include roads and trails at the lowest elevations in Glacier National Park. The study will look to determine

whether infrastructure at lower elevations will have the likeliest chance of being affected by debris flows because the larger the upslope area above a trail or road, the higher the probability that a debris flow will inundate that infrastructure due to the increase in potential initiation points.

Study Area

The study area is comprised of two past wildfires, the extents of which are displayed in Figure 1 below. The Trapper Creek fire occurred in July of 2003 and burned an area of 174 square kilometers. The Red Eagle fire occurred in July and August of 2006 and burned an area of 301 square kilometers. These specific fires were chosen for this study for the following reasons:

- Size – both of the selected sites represent major fires in the park's history.
- Age – each fire occurred recently enough to be relevant in today's rapidly changing climate, but they are also old enough to have sufficient aerial imagery of the site.
- Proximity to Continental Divide – although the Red Eagle burn scar exhibits a more linear shape that extends into low relief areas outside Glacier National Park, both of the fires reached into the upper portions of the park's glacial valleys, adjacent to the Continental Divide.

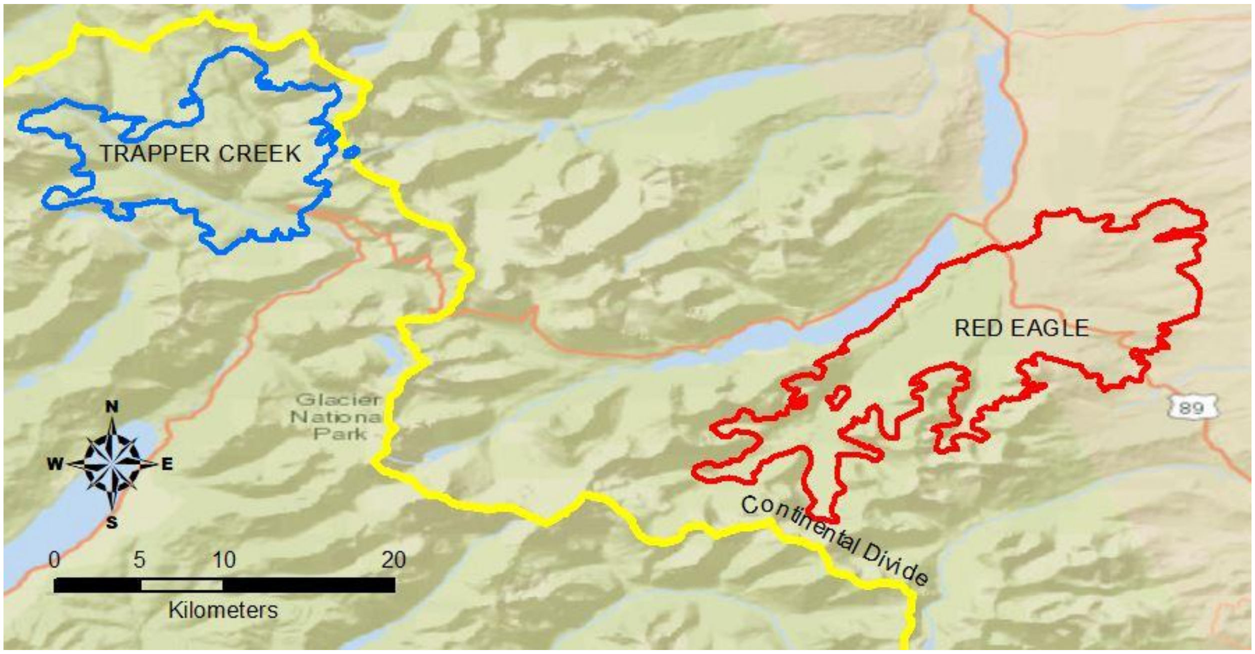

Figure 1. Trapper Creek and Red Eagle wildfire extents, separated by the Continental Divide.

Literature Review

The three bodies of literature that contribute to this project are: fire-related debris flows, non-fire-related debris flows, and debris flow climate studies. Although this paper will directly contribute to the knowledge base in the first and third bodies listed, non-fire-related debris flow research is still vital to understanding the processes involved in mountainside mass movement as a whole.

Fire-Related Debris Flows

The relationship between wildfires in mountainous areas and subsequent debris flows has been studied in depth and is well documented in the literature. Recent studies have indicated that 85% of post-fire debris flows occur within 12 months of the fire (DeGraff et al. 2015). This demonstrates the power of erosion control that plants provide to a hillslope; once they are removed, surficial material is immediately at the mercy of gravity and only in need of a trigger such as a heavy or persistent rainstorm. In order to understand how the soil, rocks, plant matter, and other debris transition from a stagnant position on a hillslope to a torrent racing down a mountain, we must identify the two main processes or types of debris flow initiation: runoff-dominated and infiltration-dominated (Gabet & Bookter 2008, Parise & Cannon 2012). Runoff-dominated erosion is characterized by overland flow of material in response to a rainstorm, whereby soil is carried into nearby channels where it gradually builds into a slurry of water and debris. This is the most common type and is responsible for the formation of most debris flows in burned areas (Parise & Cannon 2012). Infiltration-dominated debris flows occur when rain soaks into the ground and produces a shallow slope failure; then, a discrete, more massive quantity of debris sloughs off and descends the hillslope. Post-fire debris flows are often generated by the first major rainfall event after the fire, but storms of the magnitude associated with a 2-year recurrence interval are generally considered to reach the threshold necessary for debris flow initiation as well (Cannon et al. 2008). This is not always the case, however, since other factors come into play, such as soil types and vegetation burn severity (Staley et al. 2013). Because of this, there is no absolute formula for determining when and where a debris flow will occur on a burned hillslope.

Despite the difficulty associated with predicting these events, there are examples in the literature where research has been done to predict post-fire debris flows and identify the hazards they may pose. Models assessing the runout of debris flows have been created with the help of Geographic Information Systems and a program called LAHARZ in an attempt to meet 10-day post-fire deadlines in the United States for identifying risk and proposing mitigation strategies. Burned Area Emergency Response crews know that these 10-day deadlines are unique to post-fire debris flows (as opposed to landslide-generated debris flows or large rock avalanches) and require different strategies and methods (McCoy et al. 2016).

GIS models for assessing spatial probability of post-fire debris flows have also been developed. These help accelerate the process of defining the extent of susceptibility regions, which had previously been done manually, a time-intensive task (Gartner et al. 2015). Detailed methods done remotely using satellite imagery are also available for those who do not have access to funds needed for obtaining "ground-truth data." Ground-truth data are data collected in the field, and are used to calibrate remotely-sensed data. By using functions in GIS to evaluate terrain attributes, it is possible to construct post-fire debris flow hazard maps to inform local planners and land managers of the most at-risk areas using a hazard rating system (Bisson et al. 2005).

Non-Fire-Related Debris Flows

As mentioned before, this body of literature is only tangentially related to this research, but is necessary for understanding this topic nonetheless. Many of the important papers that have been published in this body of literature deal with how to define, classify, and analyze debris flows in a complex earth system. Debris flows are one of numerous types of mass movement that fall along a continuum that includes phenomena such as landslides, rockfalls, earth flows, soil creep, etc. It is important to be able to distinguish one type from another. One proposed method of making that distinction is by focusing on the parameters of solid fraction and material type. Taking into account the range of possible solid fraction and material type combinations, the two extremes identified are muddy debris flows and granular debris flows (Coussot & Meunier 1996). Other methods of classifying debris flows include bringing out parameters such as total volume, peak discharge, and inundation area (Jakob 2005), although this method is more oriented toward ranking debris flows based on size rather than distinguishing them from other forms of mass movement.

Based on this fundamental understanding of what a debris flow is and how it behaves, we can turn our attention to identifying these features on the landscape, analyzing their characteristics, and assessing the hazard potential. Aerial photographs are one of the primary sources for identifying debris flow locations, although satellite imagery is also effective (Metternicht et al. 2005). Outlining and/or digitizing the extents of the debris flows and compiling them in GIS is the easiest way to perform analyses on variability across space and time. In fact, this process has been applied to non-fire-related debris flows in eastern Glacier National Park (Wilkerson & Schmid 2008). Numerous statistical analyses can be performed to tease out the relationships and patterns within the park in order to better understand the effects that variables such as temperature, rainfall, elevation, and sediment supply have on debris flows in mountainous regions. This project will utilize these same methods and processes developed for non-fire-related debris flows and apply them to post-fire debris flows in order to uncover similar relationships.

Debris Flow Climate Studies

Since this project will focus on the effects of regional climate on debris flow occurrences and their characteristics, the third body of literature described here is the interplay of climate and debris flows. Unfortunately, most of the research in this area has so far focused on measuring the effects on debris flows caused by a changing climate. Instead, I argue that it is critical to first understand what roles a specific regional climate plays on a given landscape before analyzing the effects of changes to that particular climate. After all, every region on Earth will not be impacted evenly by climate change. Some areas may see increased precipitation whereas others see decreases; most areas will see a rise in temperature, but others may see a drop.

However, given the aforementioned objections, debris flow climate change research is still very commonplace. One prominent theme in the literature is that a recent increase in temperatures and extreme precipitation events have led to, and will continue to lead to, an increase in debris flows (Stoffel et al. 2014, Pavlova et al. 2014). The drying of summers and the wetting of shoulder seasons (fall and spring) are the leading contributors to the increased ease of likelihood of debris flow initiation (Stoffel et al. 2014). In addition to natural variations having a direct impact on the environment, population growth is also a factor. Human-caused fire ignitions are the most common. During the record-setting 2000 wildfire season, 43% of the fires were caused by humans (Cannon and DeGraff 2009). The resultant burn scars increase the susceptibility for future debris flows.

One way to determine scenarios for the impact of a changing climate on debris flow activity is through the use of meteorological proxies. When rainfall measurements are sparse or incomplete in mountainous areas, variables such as temperature, specific humidity, and Convective Available Potential Energy (CAPE) can be used as proxies. This is especially applicable to those debris flows that are triggered by intense convective rainfall (Turkington et al. 2016). This relationship gives researchers and climate scientists the ability to predict the increase in the frequency of debris flows in the coming decades with respect to a baseline in the recent past.

However, in contrast to these examples, there are areas where temperature and precipitation can be accurately recorded. In these cases, proxies are not necessary, and scientists are able to discern probabilities for coincident timing of exceeding both temperature and precipitation thresholds (van den Heuvel et al. 2016). The probabilities can be calculated based on projections of these parameters for future climate change. It should be noted that there are many factors that contribute to debris flow occurrences worldwide. This project, while mindful of the changing climate, will focus on the effects of regional climates in Glacier National Park on debris flows. Then, with this added knowledge, predictions on changes to mass wasting in the park with respect to climate change can be made more accurately.

Methodology

Approach

The study of post-fire debris flows in Glacier National Park and the role regional climate plays on those processes is best defined by the paradigm of spatial science. As a physical geographer and a geologist, I viewed this study from a positivist point of view. That is, through the use of the scientific method, the hypotheses I have set forth can be rationally justified or rejected. Conducting simple, straightforward research is the best way to provide applicable results to decision-makers in a timely manner. Through the lens of this quantitative approach, we can better understand the natural phenomena occurring on the slopes of the study areas.

Throughout the literature, the causes of post-fire debris flows are fairly well-defined, but how important each cause is to debris flow initiation is rather nebulous. Since the relationship between regional climate and mass movement has not been well studied, the methods used in this project did not follow specific protocols set forth by previous studies. Instead, these methods were developed to identify parameters for characterizing post-fire debris flows across climate zones. The parameters measured were then used to compare and contrast the different environments in order to extract a defining relationship.

The primary technique used in this project was landscape analysis via aerial photographs. This approach allowed for detailed identification of the characteristics of post-fire debris flows. By calculating statistics of these flows, a quantitative comparison was made which allowed the two study areas to be objectively differentiated. Although I did not actively engage in remote sensing data acquisition, remotely sensed data was utilized for all of the analyses of the study. Because of this, the project will only be reproducible in areas that have similar data coverage, although the results can be applied to other regions that share similar topography.

Selection of Study Areas

Two study areas within Glacier National Park were identified for detailed evaluation: the Trapper Creek fire and the Red Eagle fire. The Trapper Creek fire is located on the west side of the park and occurred in 2003. The Red Eagle fire is located on the east side of the park and occurred in 2006. These burn scars were chosen based on similarities in size, age, and proximity to the Continental Divide. The debris flows located within were compared to determine if the prevailing climate systems in each area contribute to the size or frequency of mass wasting in the park.

It was important to select two burn scars that were as similar as possible in order to minimize the impact of variables that may contribute to differences in the collected data. In addition to the criteria mentioned above, other similarities such as mean elevation, slope, and latitude were taken into account. By reducing the differences as much as possible between the study sites, the results are a better indicator of the specific climate regimes that govern the park's two halves.

A few topographical characteristics were required of both study sites in order to be selected for analysis. They included:

- Steep slope – without a steep enough slope, gravity does not have enough pull to overcome the friction between surficial sediment/debris and the ground.
- Channelized slopes – debris flows occur when sediment and water moving downhill are concentrated into a channel. Without these wrinkles on a hillside, sediment-rich sheet wash generally will not become concentrated enough to form a debris flow.
- Presence of roads and/or trails – for the purpose of testing the second hypothesis, burn scars were only eligible for analysis if they contained park infrastructure.

Data

Data for the project came from several sources. Governmental agencies provided most of the data, but one of the key files came directly from Glacier National Park's Richard Menicke, the park geographer. The shapefile containing the park's trails and boundary was obtained through email correspondence with Mr. Menicke, and this piece of data was vital for identifying at-risk infrastructure within the selected burn scars.

The DEM (digital elevation model) was downloaded from the USGS (United States Geological Survey) website. This allowed for the creation of new rasters to display physical terrain features such as slope and aspect. These parameters were important for understanding the topography of the area, and how that played a role in debris flow occurrences.

A roads layer was downloaded from US Census "Tiger/Line" data to visualize surface infrastructure within Glacier National Park. Due to the remote nature of the park, few roads were located near the study areas. No roads ran through either the Trapper Creek or Red Eagle burn scars. The "Going to the Sun" road was the closest to the study sites, but it was not intersected by any of the identified debris flows.

Historical wildfire data was obtained from the National Park Service via download through Glacier National Park's website. A shapefile containing the extents of all recorded wildfires in Glacier's history was very useful in identifying and ultimately deciding on the two burn scars that would be studied in detail. The Trapper Creek and Red Eagle fire extents were selected out and new shapefiles were created using only their features.

The most important data used in this project came from the state of Montana's Geographic Information Clearinghouse. Through this website, NAIP (National Agricultural Imagery Program) data was downloaded for the appropriate times and study areas. Two different images were downloaded and used for the project: one that satisfied the time and location requirements for the Trapper Creek fire and one that satisfied the requirements for the Red Eagle fire. For Trapper Creek, the "Flathead East" image from 2005 was selected. For Red Eagle, the "Glacier" image from 2009 was selected. These image dates were chosen for this study because they represent the necessary elapsed time for debris flows to occur, recalling that 85% of post-fire debris flows occur within 12 months of the fire (DeGraff et al. 2015). At Trapper Creek, two years passed between fire and imagery. At Red Eagle, the elapsed time was three years. NAIP imagery's high resolution (1 meter accuracy) was essential to the identification of mass movement features on the surface.

Research Methods

This study was conducted with the intention of using only GIS techniques to view data, analyze images, make measurements, and study correlations. The benefits of doing an entire research study remotely are threefold:

- Cost – this study was completed without spending any money. This was made possible by taking advantage of already-purchased software licenses (provided by university) and readily available imagery and data (provided by state and federal governments). Funding for fieldwork-related costs such as travel, food, and supplies was also not necessary.
- Time – using remotely sensed data allows the researcher to cover large areas in a short period of time. Field data collection is much slower due to the difficulty of traversing rough terrain by foot.
- Reproducibility – the process for collecting data in the field will change for each study area depending on its unique topography and accessibility. GIS workflows are much

more repeatable and can easily be utilized for different locations as long as the imagery is available.

However, there are some aspects of fieldwork that cannot be replicated without actually going into the field. This study relies on some assumptions that will be discussed later, but the one major drawback of an entirely remote sensing-based research study is the lack of ground-truth data for verification of results. With that in mind, the methodology laid out herein was designed to maximize accuracy and consistency while minimizing errors and omissions.

Analysis

The first step in the analysis process was to understand the physical characteristics of the landscape through the creation of new rasters for slope and aspect. With the DEM that had already been acquired, the Slope and Aspect tools in ArcToolbox were used to further characterize the topography. This allowed for visual interpretation of the study sites. Which areas contained steep slopes? Did the direction of the slope face matter? The answers to these questions formed the start of the search for debris flows.

Identifying the debris flows evolved into the most important and time-consuming task of the study. Initially, the plan was to use a supervised classification to train an algorithm to locate and return the debris flows within each wildfire extent. But after the first attempt, it became clear that this was not the most accurate nor the most timely method for the job. How many iterations of a classification would be required to achieve the desired accuracy? A classification that could discern the difference between the brown earth of hiking trails versus the same brown earth left behind as debris flow paths would be more time and labor-intensive than manually identifying them. So the study shifted to relying on the high resolution of the NAIP imagery in concert with the strategy of creating a new polyline feature in ArcMap for each manually-identified debris flow. Canvassing the steep slope areas first, debris flows were identified and marked, and the resulting sets were exported as their own shapefiles. On occasion, two debris flows merged into one on their way down a slope. Two strategies for determining where one began and another ended were adopted. The first strategy, which resulted in two debris flows coming together to form a third, was chosen when the following criteria were met:

1. The two primary debris flows merged to form a secondary debris flow that was significantly larger in width.
2. The two primary debris flows merged at such an angle to each other that the secondary debris flow was determined to be a new flow, rather than a continuation of one of the primary flows.

The second strategy, which resulted in one debris flow joining the path of an existing debris flow, was chosen when the following was true:

1. The two primary debris flows merged, but the width of the combined debris flow did not significantly change.
2. One of the primary debris flows appeared to join the path of an existing debris flow, in which the angle of movement of only one flow changed.

Once the debris flows had been identified for both the Trapper Creek and Red Eagle fires, some basic statistics were calculated. The following data was collected and/or calculated from the debris flow shapefiles created in this study: frequency, minimum length, maximum length, mean length, and standard deviation. In addition to these, the number of trail crossings and the distribution of debris flows across different slope aspects were noted. These details formed the critical basis for determining the role of regional climate systems on the post-fire debris flows in this study.

The last step in the analysis was to identify the park infrastructure at risk of post-fire debris flows. As previously mentioned, few roads transect the park. The "Going-to-the-Sun Road" comes near the wildfire extents, but is not within the study area. Because of this, the Glacier trail system was chosen as the main type of infrastructure for investigation. Several trails ran through the burn scars being studied, and the occurrences where debris flows intersected these trails were tallied and recorded. Based on the location of these intersections and what was learned by studying the length, location, and frequency of the debris flows themselves, recommendations about potentially hazardous areas can be made to park administrators. This information can then be passed down to park visitors during periods in which weather and landscape conditions are favorable for debris flows to occur.

Results

Trapper Creek

The debris flows at Trapper Creek were found in a cluster on the eastern side of the wildfire extent. In total, 36 flows were identified. Below is an image of the location within the study site where the debris flows were found.

Figure 2. Site of debris flows at Trapper Creek.

The larger debris flows are visible in this image, even at this scale. By zooming in and examining the imagery up close, the finer details of the paths were able to be traced and recorded. Figure 3 shows the same photo with the debris flow paths superimposed in blue. Trails in the area are also labeled and displayed with an orange dashed line.

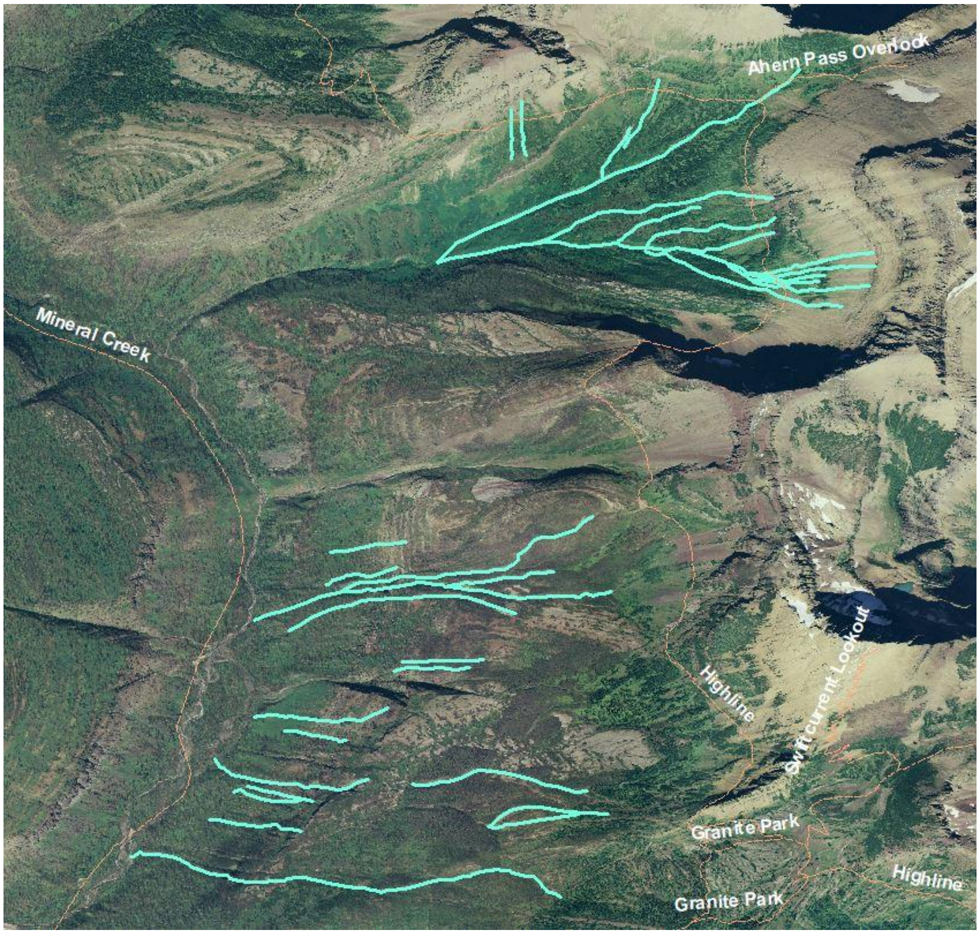

Figure 3. Debris flow paths and trails at Trapper Creek.

Figure 3 shows that there can be a significantly wide range of debris flow runout lengths within a relatively small area. This variance can likely be attributed to differences in slope and availability of loose material. Also visible are the 15 trail crossings that occur on the Ahern Pass Overlook and Highline trails. All 15 crossings are found in the northern half of the image where the debris flows begin higher up on the slope. The debris flows in the southern half of the image initiate below the Highline trail and terminate before the Mineral Creek trail, resulting in zero trail crossings.

By calculating the runout length statistics of the debris flows identified in blue, comparisons can be made between the two study sites. Table 1 outlines the statistics calculated for the debris flows in this burn scar. Number of debris flows and mean length are the primary comparators between the two study sites. Table 2 is useful in determining whether slope aspect plays a role in debris flow initiation. Does a southern-facing slope in the northern hemisphere produce more or fewer debris flows? According to the data gathered at Trapper Creek, southwestern-facing slopes account for the highest number of debris flows.

Number of Debris Flows	Minimum Length	Maximum Length	Mean Length	Standard Deviation	Trail Crossings
36	298 m	2176 m	686 m	477 m	15

Table 1. Trapper Creek debris flows statistics.

N	NE	E	SE	S	SW	W	NW
-	-	-	-	5	14	13	4

Table 2. Number of Trapper Creek debris flows per slope aspect direction.

Red Eagle

The debris flows at Red Eagle were more widespread than those at Trapper Creek. Figure 4 shows a high percentage of ridges oriented in the east-west direction, which results in a surplus of south-facing slopes. These south-facing slopes are responsible for most of the debris flows in the Red Eagle burn scar. All of the debris flows were found in the western half of the study site. The wildfire extent for Red Eagle extended into an area of little to no relief well east of the Continental Divide which did not meet the slope steepness requirements for debris flow initiation. That area is not pictured in Figure 4.

Figure 4. Site of debris flows at Red Eagle.

In total, 17 debris flows were identified at Red Eagle. Table 3 shows that the mean length for debris flows at Red Eagle was 746 m. This is 60 m longer than the average Trapper Creek debris flow. Apart from the southeastern corner of Figure 5, where there is a series of debris flows along the same slope, the flows in the Red Eagle burn scar were distributed throughout the area with very little spatial clustering. The Triple Divide trail is the primary trail running through the study area, but none of the debris flows intersected it. The trail runs through the bottom of the valley, and none of the debris flows were long enough to reach it.

Figure 5. Debris flow paths and trails at Red Eagle.

The statistics show that debris flows at Red Eagle had a higher minimum length and a lower maximum length. However, they still exhibit a 1,400 m range, suggesting that the runout lengths are far from consistent within even a single burn scar. A more consistent response was found in the location of debris flows in relation to slope aspect. Of the 17 debris flows identified, 13 (76.5%) were located on south-facing slopes. No debris flows occurred on north, northeast, or east-facing slopes.

Number of Debris Flows	Minimum Length	Maximum Length	Mean Length	Standard Deviation	Trail Crossings
17	315 m	1729 m	746 m	393 m	0

Table 3. Red Eagle debris flows statistics.

N	NE	E	SE	S	SW	W	NW
-	-	-	1	13	1	1	1

Table 4. Number of Red Eagle debris flows per slope aspect direction.

Discussion

Hypothesis 1

The first hypothesis of this study was divided into two parts, a and b, as follows:

a) Burned areas in western Glacier will have a higher frequency of debris flows than burned areas in eastern Glacier.

b) Burned areas in eastern Glacier will produce debris flows with longer runout lengths than burned areas in western Glacier.

Hypotheses 1a and 1b are both supported by the analysis of data collected in this study. Debris flows found in the Trapper Creek study site outnumbered those found in the Red Eagle study site 36 to 17. This is likely due to the higher annual precipitation on the west side of the Continental Divide. In addition, it is not just the amount of rain but the number of rainfall events that may contribute to the increased number of debris flows. Climate data from West Glacier indicates that the western side of the park receives consistent rainfall throughout the year, and is especially wet during the winter months (US Climate Data 2017a). The eastern side of the park receives less precipitation, and that precipitation typically comes in the form of high-intensity, short-duration convective thunderstorms produced by orographic lifting during the late spring and early summer months. However, the rest of the year is very dry due to the rain shadow caused by the Rocky Mountains (US Climate Data 2017b). This disparity in number of rainfall events likely plays a role in the two-to-one ratio of debris flows at Trapper Creek versus Red Eagle.

The debris flows in eastern Glacier at Red Eagle were, on average, 60 m longer than those in western Glacier at Trapper Creek. One potential cause for this finding is the likelihood of increased sediment availability on the eastern side of the Continental Divide. As a result of lower annual precipitation and a smaller number of rainfall events, slopes in eastern Glacier are more likely to retain sediment and other debris than their western Glacier counterparts. The erosion of surficial material due to precipitation, especially on steep slopes, is exacerbated by the effects wildfires have on soil stability. This means that more material is readily caught up in debris flows in areas where there have been fewer rainfall events to remove sediment, which may lead to longer runout lengths. However, the accumulation of sediment on a slope is a relatively slow process. The nature of the rainfall events may have a greater influence over the debris flow runout lengths than sediment availability. As a result of the locally heavy, brief downpours in eastern Glacier, more energy is put into these mass wasting events. By subjecting the hillslopes to substantial amounts of water all at once, the process of debris flow initiation is intensified. It is possible that a debris flow that forms in this manner is more capable of using its speed and momentum to pick up a large quantity of debris, and will cover more ground before losing its energy. More study into the literature surrounding debris flows dynamics is needed to support this possibility.

Hypothesis 2

The second hypothesis of this study was: "The infrastructure most at risk will include roads and trails at the lowest elevations in Glacier National Park." The idea was that despite precipitation generally increasing with elevation in the park, infrastructure at lower elevations will have the likeliest chance of being affected by debris flows. The larger the upslope area above a trail or road, the higher the probability that a debris flow will inundate that infrastructure due to the increase in potential initiation points. In other words, if a trail is high up on a slope, it is more likely for a debris flow to begin beneath it than above it, which would not result in an intersection of the two features.

After analysis of the data, it was determined that trails in the middle of slopes are most likely to be affected by debris flows. The flows identified in this study do not necessarily run all the way to the bottom of the valley. This means that trails such as the Triple Divide trail at Red Eagle are much safer than trails like the Highline trail at Trapper Creek. However, a trail's mid-slope location does not necessarily condemn it to inundation by debris flow. Not all of the identified flows started at the very top of the slope. There seemed to be little correlation between debris flow beginning and ending points, which is why there is such a large range of runout lengths throughout both of the study areas.

A trail's vertical position on the slope is not the only parameter that factors into its risk of intersection with a debris flow. The slope aspects identified in Tables 2 and 4 show a considerable preference for debris flow initiation on south, southwest, and west-facing slopes. As a result, trails in these areas are more at risk than those on north and east-facing slopes. Figure 3 shows the Ahern Pass Overlook trail, which is a mid-slope trail on a south-facing slope, and there are several intersection points where debris flows have crossed the trail. While it is unlikely that anyone would be directly in the path of a debris flow when it crosses a hiking trail, it's not impossible. In addition, it is not only the potential direct hazard to humans that matters. Debris flows can damage or completely wash out trails, which take time and money to repair. This negatively affects the recreation opportunities for park visitors.

Limitations

The primary concern of this study was the reliance on assumptions where ground-truth data was not available. For example, one general trend is an increase in precipitation as elevation increases, but without rain gauges at these locations, this assumption cannot be verified. Another assumption was that the debris flows identified via aerial imagery occurred after the fire, rather than before. And any differences between the quantifiable characteristics of post-fire debris flows in eastern versus western Glacier were assumed to be a result of regional climate; in reality, it is not feasible to hold all other variables constant. However, it is more likely than not that the regional climate contributed significantly to the frequency, distribution, and size of debris flows in the park, whether directly or indirectly. The particular climate that characterizes each side of the park is responsible for the soil type and abundance, vegetation type, precipitation amount, temperature, and evapotranspiration – all of which affect debris flows occurrences. The goal of this study was to determine if the prevailing climate systems did, in fact, have an effect on the debris flows. This premise was supported by the findings of the analysis conducted in this study.

Conclusion

Study Review

The current literature showed that there had not been any previous studies on the effects of regional climate on post-fire debris flows. This project capitalized on the opportunity provided by the unique geography of Glacier National Park to study these phenomena from a different perspective. The resulting differences between the pacific maritime and continental semi-arid climates in relation to post-fire debris flows have provided answers to the following research questions proposed at the beginning of this study:

- Question 1 – How do the runout length and frequency of post-fire debris flows differ across climate regions in Glacier National Park?
- Question 2 – What infrastructure is most at risk of being affected by post-fire debris flows?

Through analysis of the data, this study was successful in answering these questions. Using image and statistical analysis, it was determined that debris flow parameters such as frequency and runout length do differ across climate regions in Glacier National Park. They were found to be more frequent at Trapper Creek in western Glacier and longer at Red Eagle in eastern Glacier. When determining the risk to humans and man-made infrastructure, roads were excluded because they did not transect any of the fire boundaries. The hiking trails that were found to be most at risk were those vertically positioned in the middle of south, southwest, and west-facing slopes. Only two burn scars were studied in depth, but these findings should allow for application of the results in other areas throughout the park.

Recommendations

Despite its remote location, over 2.9 million people visited Glacier National Park in 2016 alone, the largest number of visitors for any one year in the park's history (NPS 2016). What many of these people do not know is that they may be placing themselves in harm's way when they visit. Debris flows can strike at any time, giving little warning when they do. And as more and more people visit the area, the National Park Service should bear the responsibility of becoming more knowledgeable about post-fire debris flows and actively engaging in public awareness.

By taking advantage of recent improvements in remote sensing and GIS, we are able to better understand the conditions under which post-fire debris flows occur and what to expect from them when they do. The results of this project should be used by park officials to inform visitors of the hazards that debris flows pose. The hiking trails at highest risk of being affected by post-fire debris flows (mid-slope, south-facing hillsides) should be clearly marked with warning signs. Ideally, rain gauges would be installed in and around burned areas to measure precipitation and monitor the exceedance of intensity-duration thresholds. Data of this nature could help park managers with real-time threat monitoring and emergency warning dissemination.

References

Bisson, M., M. Favalli, A. Fornaciai, F. Mazzarini, I. Isola, G. Zanchetta, and M. T. Pareschi. 2005. "A rapid method to assess fire-related debris flow hazard in the Mediterranean region: An example from Sicily (southern Italy)." *International Journal of Applied Earth Observation and Geoinformation* 7 (3):217-231.

Butler, David R., and Stephen J. Walsh. 1994. “Site characteristics of debris flows and their relationship to alpine treeline.” *Physical Geography* 15(2), 181-199.

Cannon, Susan H., and Jerry DeGraff. 2009. "The increasing wildfire and post-fire debris-flow threat in western USA, and implications for consequences of climate change." In *Landslides – Disaster Risk Reduction*, 177-190.

Cannon, Susan H., Joseph E. Gartner, Raymond C. Wilson, James C. Bowers, and Jayme L. Laber. 2008. "Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California." *Geomorphology* 96 (3–4):250-269.

Cannon, Susan H., Robert M. Kirkham, and Mario Parise. 2001. "Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado." *Geomorphology* 39 (3–4):171-188.

Coussot, P., and M. Meunier. 1996. "Recognition, classification and mechanical description of debris flows." *Earth-Science Reviews* 40 (3–4):209-227.

Degraff, Jerome V., Susan H. Cannon, and Joseph E. Gartner. 2015. "The timing of susceptibility to post-fire debris flows in the western United States." *Environmental & Engineering Geoscience Journal* 21 (4):277-292.

Environmental Systems Research Institute, 2017. “What is GIS?” *ESRI.* Retrieved March 20, 2017, from ESRI. http://www.esri.com/what-is-gis (Last accessed 20 March 2017)

Friedman, E. Q., and P. M. Santi. 2014. "Debris-flow hazard assessment and validation following the Medano Fire, Great Sand Dunes National Park and Preserve, Colorado." *Landslides* 11 (6):1093-1113.

Gabet, Emmanuel J., and Andy Bookter. 2008. "A morphometric analysis of gullies scoured by post-fire progressively bulked debris flows in southwest Montana, USA." *Geomorphology* 96 (3–4):298-309.

Gartner, J., P. Santi, and S. Cannon. 2015. "Predicting locations of post-fire debris-flow erosion in the San Gabriel Mountains of southern California." *Natural Hazards* 77 (2):1305-1321.

Hall, Myrna H. P., and Daniel B. Fagre. 2003. “Modeled climate-induced glacier change in Glacier National Park, 1850-2100.” *Bioscience* 53 (2): 131-140.

Hürlimann, Marcel, Brian W. McArdell, and Christian Rickli. 2015. "Field and laboratory analysis of the runout characteristics of hillslope debris flows in Switzerland." *Geomorphology* 232:20-32.

Jakob, Matthias. 2005. "A size classification for debris flows." *Engineering Geology* 79 (3–4):151-161.

King, Hobart. 2017. “What is a debris flow?” *Geology.com.* Retrieved March 20, 2017, from Geology.com. http://geology.com/articles/debris-flow/ (Last accessed 20 March 2017).

McCoy, Kevin, Vitaliy Krasko, Paul Santi, Daniel Kaffine, and Steffen Rebennack. 2016. "Minimizing economic impacts from post-fire debris flows in the western United States." *Natural Hazards* 83 (1):149-176.

Metternicht, Graciela, Lorenz Hurni, and Radu Gogu. 2005. "Remote sensing of landslides: An analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments." *Remote Sensing of Environment* 98 (2–3):284-303.

National Park Service. 2016. "Annual park recreation visitation." Retrieved March 20, 2017, from National Park Service. https://irma.nps.gov/Stats/SSRSReports/Park%20Specific%20Reports/Annual%20Park%20Recreation%20Visitation%20(1904%20-%20Last%20Calendar%20Year)?Park=GLAC (Last accessed 20 March 2017).

National Park Service. 2017a. "Fire history." *Glacier National Park.* Retrieved March 20, 2017, from National Park Service. https://www.nps.gov/glac/learn/nature/fire-history.htm (Last accessed 20 March 2017).

National Park Service. 2017b. "Geology." *Glacier National Park.* Retrieved March 20, 2017, from National Park Service. https://www.nps.gov/glac/learn/education/geology.htm (Last accessed 20 March 2017).

National Park Service. 2017c. "Fact sheet." *Glacier National Park.* Retrieved March 20, 2017, from National Park Service. https://www.nps.gov/glac/learn/news/fact-sheet.htm (Last accessed 20 March 2017).

Parise, M., and S. H. Cannon. 2012. "Wildfire impacts on the processes that generate debris flows in burned watersheds." *Natural Hazards* 61 (1):217-227.

Pavlova, I., V. Jomelli, D. Brunstein, D. Grancher, E. Martin, and M. Déqué. 2014. "Debris flow activity related to recent climate conditions in the French Alps: A regional investigation." *Geomorphology* 219:248-259.

Riley, Karin L., Rebecca Bendick, Kevin D. Hyde, and Emmanuel J. Gabet. 2013. "Frequency–magnitude distribution of debris flows compiled from global data, and comparison with post-fire debris flows in the western U.S." *Geomorphology* 191:118-128.

Santi, P., and L. Morandi. 2013. "Comparison of debris-flow volumes from burned and unburned areas." *LANDSLIDES* 10 (6):757-769.

Staley, D. M., J. W. Kean, S. H. Cannon, K. M. Schmidt, and J. L. Laber. 2013. "Objective definition of rainfall intensity-duration thresholds for the initiation of post-fire debris flows in southern California." *Landslides* 10 (5):547-562.

Stoffel, M., T. Mendlik, M. Schneuwly-Bollschweiler, and A. Gobiet. 2014. "Possible impacts of climate change on debris-flow activity in the Swiss Alps." *Climatic Change* 122 (1/2):141-155.

Turkington, Thea, Alexandre Remaître, Janneke Ettema, Haydar Hussin, and Cees Westen. 2016. "Assessing debris flow activity in a changing climate." *Climatic Change* 137 (1/2):293-305.

US Climate Data. 2017a. “Climate West Glacier.” Retrieved March 20, 2017, from US Climate Data. http://www.usclimatedata.com/climate/west-glacier/montana/united-states/usmt0352 (Last accessed 20 March 2017).

US Climate Data. 2017b. “Climate Babb.” Retrieved March 20, 2017, from US Climate Data. http://www.usclimatedata.com/climate/babb/montana/united-states/usmt0013 (Last accessed 20 March 2017).

van den Heuvel, Floor, Stéphane Goyette, Kazi Rahman, and Markus Stoffel. 2016. "Circulation patterns related to debris-flow triggering in the Zermatt valley in current and future climates." *Geomorphology* 272:127-136.

Wilkerson, Forrest D., and Ginger L. Schmid. 2008. "Distribution of debris flows in Glacier National Park, Montana, U.S.A." *Journal of Mountain Science* 5 (4):318-326.