RECREATIONAL TRAILS AND GEOMORPHIC HAZARDS IN GLACIALLY CONDITIONED BASINS: A CASE STUDY OF MANY GLACIER VALLEY, GLACIER NATIONAL PARK, MONTANA

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ABSTRACT

RECREATIONAL TRAILS AND GEOMORPHIC HAZARDS IN GLACIALLY CONDITIONED BASINS: A CASE STUDY OF MANY GLACIER VALLEY, GLACIER NATIONAL PARK, MONTANA

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Glacially conditioned, high mountain environments are prone to high energy geomorphic processes because of the abundance of water, steep slopes, high relief, and the frequent occurrence of freeze-thaw events. Geomorphic processes pose significant hazards to recreationalists in the Many Glacier Valley of Glacier National Park, MT. A total of 394 mass wasting landforms were identified from airphotos and 34 additional geomorphic events were identified from written historical documents. This research suggests geomorphic hazards occur in every basin and along every trail in the study area. Mass wasting and flooding are tied to wet weather events and wet periods in the climate record. The glacially conditioned landscape provides the potential, while water provides a triggering mechanism. In order from the most to least hazardous, the trails with the highest potential for injury to people and/or property are Cracker Lake, Iceberg Lake, Ptarmigan Tunnel, Swiftcurrent Pass, Grinnell Lake/Glacier, and Piegan Pass Trail.

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CHAPTER I

INTRODUCTION

Research Problem

Mountains represent ~22% of the total land area of the earth (Huddleston et al. 2003). Mountain environments differ from region to region but share complexity in topography that results in rapid changes in temperature and precipitation over short distances (Lieb, Kellerer-Pirklbauer, and Avian 2007). Sharp transitions in mountain topography allow for small changes in average temperature to have magnified impacts on the locations of these transitions (Beniston 2003). Mountains across the world are experiencing a general warming trend (IPCC 1996, 2007)

Glacier retreat is occurring in mountain environments across North America with increased average annual temperatures (Holm, Bovis, and Jakob 2004). Alpine glaciers are sensitive to small changes in temperature making them good indicators of climate change (Hall and Fagre 2003). The warming trend is responsible for an upward shift of snowlines resulting in a significant amount of ice loss in alpine glaciers (Evans and Clague 1994, IPCC 1996, 2007).

Contemporary ice cover characterizes *glacierized* landscapes. In contrast to glacierized landscapes, *glaciated* landscapes show evidence of being occupied by ice sometime in the past (Slaymaker and Menounos 1999). Glacierized and glaciated landscapes lie within *glacially conditioned* landscapes. Glacially conditioned landscapes are characterized by glacial landforms that commonly include U-shaped valleys, cirques, arêtes, moraines, tarns, paternoster lakes, hanging valleys and overall landscapes dominated by glacial till (Figure 1) (Slaymaker and Menounos 1999).

Figure 1. Glacially conditioned, U-shaped Many Glacier Valley, Glacier National Park. View looking east. From bottom to top: Lower Grinnell, Josephine, and Sherburne Lakes. Photo by author.

As glaciers recede, over-steepened slopes are left behind subsequently causing instability (Evans and Clague 1994). As mountain environments shift from glacierized to glaciated landscapes, a profound change occurs in geomorphic systems because of the combination of over-steepened slopes and increased sediment supply (Evans and Clague 1994). Glacially conditioned, high mountain environments are prone to high energy geomorphic processes because of the abundance of water, steep slopes, high relief, and the frequent occurrence of freeze-thaw events. Some geomorphic processes associated with glacially conditioned mountain landscapes include rockfalls, debris flows, snow avalanches, landslides (translational and rotational), and flooding (Gerrard 1990, Moore et al. 2009). Geomorphic processes that potentially cause harm to people or property are geomorphic hazards (Gares, Sherman, and Nordstrom 1994).

Glacier National Park is located in the Northern Rocky Mountains along the Continental Divide in northwest Montana of the northwestern United States (Figure 2). Glacier National Park is composed of glacierized and glaciated basins; however, glacierized basins are declining and glaciated basins are growing because of increased average annual temperatures. The park is predicted to be glacier-free by 2030 (Hall and Fagre 2003). Given the prediction of a completely glaciated landscape in the near future, it is increasingly important for park managers to be aware of the hazards associated with this transition.

With ample, high energy, geomorphic processes and over 2 million visitors per year, a clear potential exists for geomorphic hazards in Glacier National Park. Indeed, hazards are part of the Glacier National Park environment (Wilkerson and Schmid 2003). Geomorphic processes pose a hazard to visitors using recreational trails in Glacier National Park; however, the degree of susceptibility of trails to geomorphic hazards is unclear (Thornberry-Ehrlich 2004).

The Many Glacier Valley, located in the northeastern portion on the park, is known for its dense network of trails and spectacular, glacially conditioned landscape. Previous research by Butler (1979, 1986, 1990, 2001), Butler and Malanson (1985), Butler and Walsh (1990, 1994) Butler, Malanson, Wilkerson, and Schmid (1998), Oelfke and Butler (1985), Wilkerson (2004), and Wilkerson and Schmid (2003, 2008) have explored rockfalls, debris flows, snow avalanche track location, snow avalanche dams,

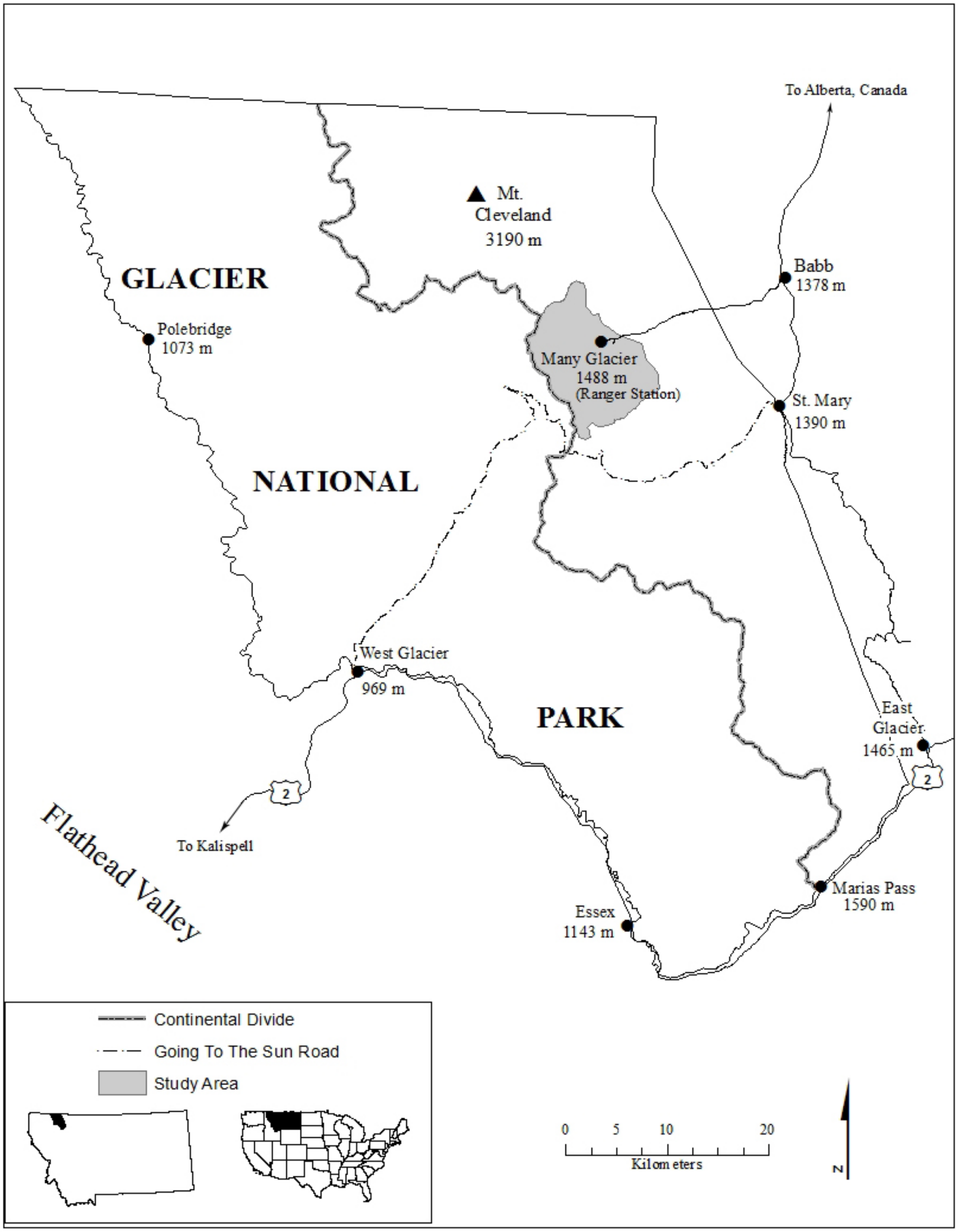

Figure 2. General map of Glacier National Park. Note location of Many Glacier study area.

landslides, and potential flooding throughout Glacier National Park, including the Many Glacier Valley. However, the holistic relationship between geomorphic hazards and recreational trails in the Many Glacier Valley has not been well defined prior to this study.

Research Objectives

This research explored the spatial and temporal patterns of geomorphic hazards and their implications for recreational trails in the Many Glacier Valley. Specifically, I focused on four main objectives: 1) identifying and mapping spatial and temporal patterns of past hazardous geomorphic events; 2) determining the main spatial and temporal variables resulting in geomorphic events; 3) creating a series of geomorphic hazard maps that incorporate recreational trails with past and potential future geomorphic events based on variables found in objective 2; and 4) making a management recommendation to the National Park Service regarding trail management and hazards for the Many Glacier Valley. The trails examined included Cracker Lake, Piegan Pass, Grinnell Lake/Glacier, Swiftcurrent Pass, Iceberg Lake, and Ptarmigan Tunnel.

Research Significance

With approximately 734 miles of trails, its ability to attract over 2 million visitors annually, and the presence of ample high-energy geomorphic processes, the National Park Service is confronted with significant management issues regarding trails in Glacier National Park. An opportunity for research exists because of the popularity of the park, location of the hiking trails, geomorphic processes, and the transitional landscape.

Park personnel rely on continuing research to better understand natural systems and manage humans in these systems as landscapes change over time. This study will be beneficial to Glacier National Park managers regarding the temporal and spatial occurrence of geomorphic hazards as glaciers recede and ultimately disappear. A geomorphic hazard map incorporating trails in the Many Glacier Valley will provide park managers with information that indicates places and times of increased potential geomorphic hazard, forming a baseline for future research to be measured against as the landscape becomes fully glaciated. This report will help the National Park Service educate and warn hikers of the hazards associated with geomorphic processes. Education and subsequent safety of recreational visitors is of high value to the National Park Service (Thornberry-Ehrlich 2004).

The National Park Service is dedicated to allowing natural processes to proceed while keeping visitor safety a top priority (NPS 2011). With the reality of global climate change more prominent in alpine areas, it is important to gain insight as these alpine areas transition from glacierized to glaciated landscapes (Holm, Bovis, and Jakob 2004). Alpine areas are temperature sensitive and small changes in average temperature to have large impacts on alpine areas (Beniston, 2003). As glaciers recede and mountains become more accessible, more people will visit mountain environments, increasing their chances of being affected by geomorphic processes. This study adds to the greater understanding of geomorphic processes in glacially conditioned landscapes. Continued research is important and needed to gain a better understanding of how these environmental systems will change and function over time.

CHAPTER II

LITERATURE REVIEW

Mountains are important to human and natural systems worldwide. They are an important part of ecological and social health to adjacent lowlands providing water, energy, minerals, timber, agricultural products, and recreational areas (Beniston 2003). As the reality of climate change is globally recognized, it is increasingly important to understand how mountain environments react to increased average annual temperatures and how these adaptations will affect our human and natural systems. This chapter provides insight on mountain climate, climate change in mountains, glaciation, alpine glacier retreat in the 19th, 20th, and 21st centuries, geomorphic processes and hazards, mountain recreation, and hazard management.

Mountain Climate

In alpine areas, climate changes quickly with elevation gain over short horizontal differences (Beniston 2003). Generally, temperature decreases, and precipitation and windiness increase with increased elevation (Bach and Price 2013). Mountains influence climate of surrounding lowlands depending on latitude, size, orientation in relation to moisture sources, and global circulation patterns.

Climate Change in Mountains

Worldwide

Mountain areas across the world are experiencing a warming trend that is expected to continue well into the future (IPCC 2007). Temperature and precipitation are the main variables used to monitor climate change, globally. Precipitation projections in mountains are generally unreliable and vary considerably depending on latitude and elevation (IPCC 2007). Worldwide, temperatures have increased 0.74 °C ± 0.18°C, with temperatures warming at double the rate in the last 50 years (IPCC 2007). In the Northern Hemisphere, precipitation increased over land masses north of 30° latitude and decreased between 10 and 30°N (IPCC 2007). Extreme weather follows precipitation trends with more heavy precipitation events at latitudes higher than 30°N and more droughts between 10 and 30°N (IPCC 2007).

Considerable loss of snow and ice because of general warming has been documented in mountains worldwide (IPCC 2007). Glaciers and seasonal snowpack act as a bank releasing water gradually throughout the summer. Snow and ice are key components to the hydrologic cycle, with increased importance on the volume and timing of spring melting. Snowpack is generally melting earlier in the spring and summer, and accumulating later in the fall and winter, leading to an upward migration of flora and fauna. As warming continues, water stored in glaciers and snowpack is expected to decline.

North America

North American mountain temperatures are expected to increase more than the global average during this century. Trujillo et al. (2012) indicates mid-elevation mountains, 2,000 to 2,500 m, are the most sensitive to climate change with larger upward shifts of vegetation expected in the western United States. The climate in North America is highly variable, but has warmed considerably in the last century and is expected to increase at a faster rate in the next century. Warming is expected to be magnified over elevated areas as a result of snow-albedo feedback (IPCC 2007).

Temperatures in the western U.S have risen 0.5°C – 2.0°C in the past century (Hall and Fagre 2003, Pederson et al. 2010). These trends are more evident in the cool season with an earlier onset of spring, and more precipitation falling as rain instead of snow, resulting in earlier snowmelt (Pederson et al. 2010). Less snow coupled with higher absorption of insolation and resulting heating, is causing an environment where alpine glaciers are receding.

Glacier National Park has experienced a 1.66°C increase with 10% more precipitation in the last century (Hall and Fagre 2003). A combination of natural (emergence from the Little Ice Age) and anthropogenic (carbon emissions) factors indicate a 3.3°C increase in temperature by 2050 (Hall and Fagre 2003, Mearns et al. 2009).

Glaciation of Glacier National Park

Landscapes of Glacier National Park are a direct result of late Pleistocene glaciation. Most of northwestern Montana was covered by glaciers. To the east and west of present day Glacier National Park were the Laurentide and Cordilleran Ice sheets, respectively (Alden 1953, Carrara, Short, and Wilcox 1986, Carrara 1987). In the area between the ice sheets, along the Continental Divide, alpine glaciers formed and are responsible for much of the current landscape of Glacier National Park (Figure 3) (Carrarra 1987).

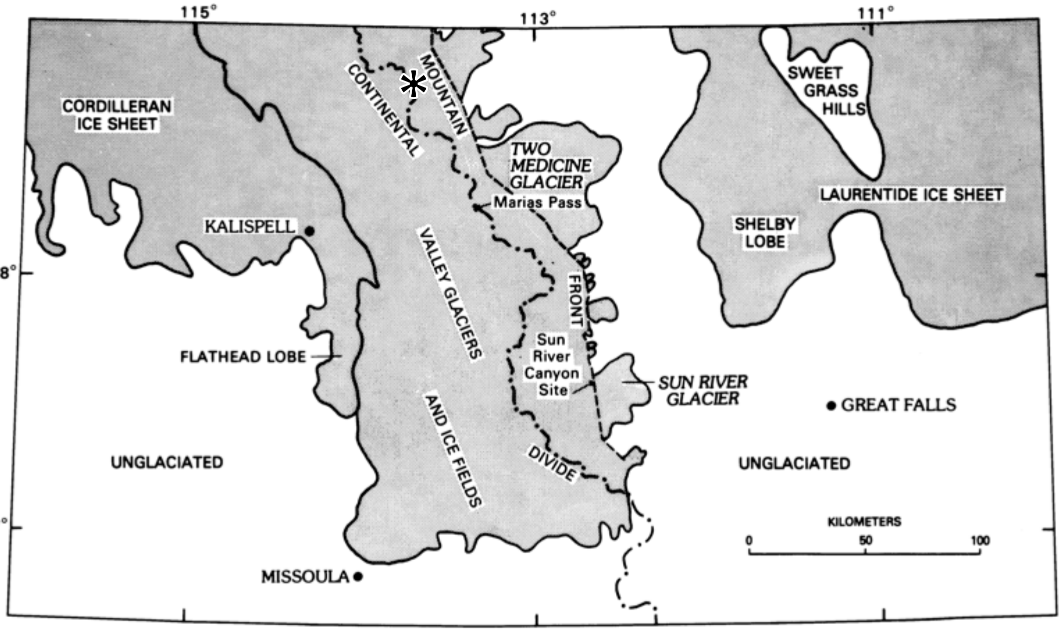

Figure 3. General map showing late Pleistocene glacier limits in Glacier National Park. Asterisk indicates study area. From Carrara, Short and Wilcox (1986).

Alpine Glacial Retreat in the 19th, 20th, and 21st Centuries

Worldwide

In the 1800s, Swiss naturalists established the general idea of an ice age. Louis Agassiz was the first to scientifically propose the idea, although it came from years of research of the Swiss landscape by German and Swiss naturalists. They combined knowledge from their own experiences, local communities, and scientists to explain the existence of glacial landforms (Orlove, Wiegandt, and Luckman 2008). As research further developed, scientists found evidence of multiple glaciations, linking them to the earth’s natural climate fluctuation patterns. The most recent period of glacier advance is known as the Little Ice Age and occurred between ~1400 and 1850 AD (Nesje and Dahl

2002). Warming during the second half of the 19th century ended the Little Ice Age and caused a retreat of alpine glaciers. Mountains worldwide are currently experiencing an increased rate of glacier retreat because of increased average annual temperatures (Holm, Bovis, and Jakob 2004).

North America

Alpine glaciers in North America are following the same general pattern of glaciers worldwide. Glacier retreat was strong into the first half of the 20th century, followed by a period of stabilization, and in some cases, advance until ~1980. This coincided with a cool phase, characterized by mild summers (Pederson et al. 2004). Since this time, glaciers have generally retreated (Moore et al. 2009). General circulation models indicate the warming trend will continue and is likely to increase in magnitude over the next century. As a result, glaciers will continue to recede (IPCC 2007).

Glaciers present in Glacier National Park today are remnants of the Little Ice Age that ended between 1850 and 1900 AD (Mathes 1940). Glacier National Park was established in 1910 to preserve its wilderness character and mountain scenery, ensuring recreation to future visitors (Buchholz 1976). Upon creation, it contained approximately 150 glaciers and perennial ice fields. When Carrara and McGinley conducted research in 1981, they reported that over two thirds of the glaciers present in 1910 had disappeared. As an example, Grinnell Glacier is one of the most studied glaciers within the park and was approximately 2.33 km² in 1850. By 1993, Grinnell Glacier had fragmented into six perennial snow and ice fields with a combined area of only 0.88 km², a 62% loss (Key, Fagre, and Menicke 2002). Small cirque glaciers, such as ones found in the Many

Glacier Valley, are important to the hydrologic cycle because they experience a more significant amount of ice loss, relative to the area and volume, compared to larger glaciers (MacDonald et al. 2010). A simulation model created in 2003 infers a visible ecosystem-wide change in Glacier National Park. The model predicts that mean summer temperatures will continue to rise and mean annual precipitation will remain constant through 2100. It further predicts that glaciers within the park will be gone by 2030 (Hall and Fagre 2003).

Impacts of Glacier Retreat

Glacier retreat impacts human and natural systems. Orlove, Wiegandt, and Luckman (2008) name four broad categories of glacier retreat impacts: global environmental change, economic resources, cultural landscapes, and hazards.

Global environmental change refers to issues such as sea level rise and changes in the spatial and temporal occurrence of biota. The International Panel on Climate Change (IPCC) (2007) estimated that approximately 27% of the rise in sea level is attributed to glacier melt in the last few decades of the twentieth century. With expectations of continued retreat, melting glaciers will continue to cause sea level to rise. The change in spatial and temporal occurrence of biota is attributed to the absence of snow and availability of water at higher elevations. For every 1°C increase, the snowline is expected to rise by 150 m (IPCC 2007).

Alpine glaciers have historically acted as water banks, holding water for future use. According to Basagic, Fountain, and Clark (2004), two major localized effects of glacier retreat include the: 1) release of water from ice storage leads to an increase in overall stream discharge during spring months and 2) shrinking of glaciers reduces the moderating effect on stream flow in summer dry climates, especially in late summer, shifting peak runoff to earlier in the summer, and enhancing the possibility of localized drought during late summer months.

The Many Glacier Valley is located within the St. Mary River Watershed with its tributaries emptying into the St. Mary River. The release of water from glaciers in the Many Glacier Valley provides water for the St. Mary River Watershed, especially during spring and summer months (MacDonald et al. 2010). A GENESYS hydrometeorological model indicates that the rise in annual temperatures will likely cause the storage of water as ice/snow to decrease with an earlier onset of spring in the St. Mary Watershed (MacDonald et al. 2010). Earlier snowmelt will result in an increase in overall stream discharge during spring months and an earlier date of a snow-free landscape, reducing the moderating effect on stream flow in late summer, when water is needed most. The increased demand for water in late summer months, when water supply is low, enhances the possibility of water shortage (Schindler and Donahue 2006).

The economic impacts of glacier retreat mainly affect users in the lowlands although impacts to tourism and recreation do occur on a smaller scale at high elevations (Orlove, Wiegandt, and Luckman 2008). Power generation, irrigation, and urban consumption rely on seasonal melt of snowpack. Without a reliable source of water to streams, the potential for negative economic impacts is high to users in a watershed with declining glaciers. Often, basins with glaciers also receive economic benefits from tourists who come to alpine areas to see glaciers and/or recreate. Without glaciers present, the economic impact of glacier retreat is unclear with regard to tourism but is likely negative (Orlove, Wiegandt, and Luckman 2008).

Glacier National Park is the headwater for its region thus snowpack is an important economic aspect to both the park as well as surrounding communities. The St. Mary Watershed is going through a profound change that will influence hydrology and geomorphology throughout the basin (MacDonald et al. 2010).

The natural occurrence of spring runoff is important to the physical environment of streams and rivers. The water supplied by St. Mary Watershed to users in the United States and Canada is fully allocated throughout the basin (MacDonald et al. 2010). The highest average annual discharge occurs in June and is heavily dependent on winter snowpack and spring weather (Boner and Stermitz 1967). As the climate warms, snow water equivalent (SWE) is expected to decline, therefore impacting all users throughout the basin (MacDonald et al. 2010).

Cultural impacts of glacial retreat include attachment to place through scenery. Glaciers are part of the identity of a region with many members of the community caring and creating a sense of place with glaciers (Orlove, Wiegandt, and Luckman 2008). Many people seek alpine environments for recreation. Skiing, snowboarding, snowshoeing, and hiking contribute to the cultural identity of an area. The Many Glacier Valley is known as the heart of Glacier National Park, where visitors can see active glaciers and how they impact the landscape via horseback, foot, boat, or automobile (NPS). Glaciers are an important part of the identity of the glacially conditioned Many Glacier Valley landscape in their past (glaciated) and present (glacierized) form.

Geomorphic Processes in Glacially Conditioned Landscapes

The predominant geomorphic processes active in Glacier National Park include rockfalls, debris flows, snow avalanches, landslides, and flooding (David Butler personal communication March 2012). Glacially conditioned landscapes are prone to mass wasting because of the abundance of water combined with steep slopes. As glaciers retreat, the exposed landscape is weathered and eroded, causing instability (Figure 4) (Evans and Clague 1994, Moore et al. 2009). The largest controlling variables to mass wasting are topography, lithology, climate, weather, seismicity, and root strength through vegetation cover. These controlling variables cause the slope to fail based on increased shear stress or decreased shear strength. Increased shear stress is caused by the removal of lateral support through undercut slopes, loading of the slope with increased weight (i.e. precipitation), lateral pressure from the expansion and contraction of water during freeze-thaw events, and seismicity which causes shaking. Decreased shear strength is caused by physical and chemical weathering, increased pore-water pressure, weak rock structure, and loss of vegetation and associated root strength (Roering et al. 2003).

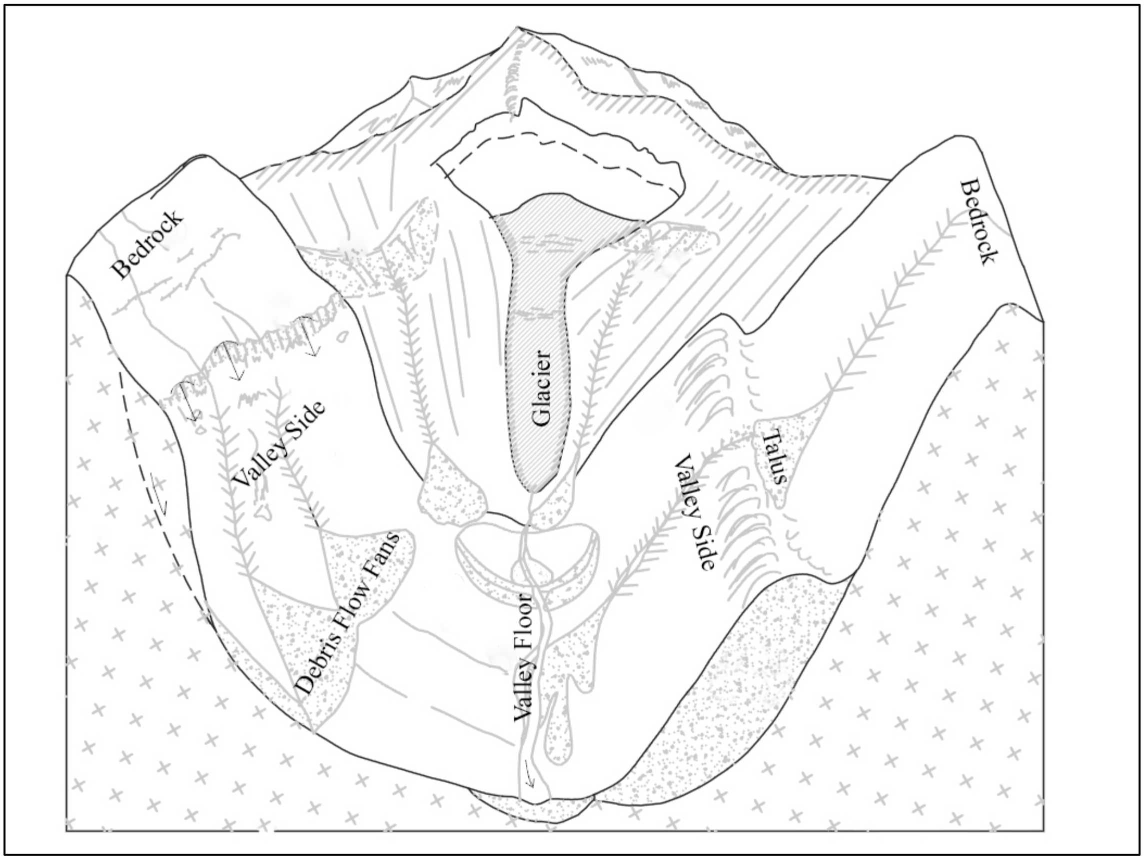

Figure 4. Diagram depicting a typical glacially conditioned landscape. Note over steepened valley walls and abundance of material available for transport. Adapted from Moore et al. (2009).

Rockfall

Rockfall occurs when individual blocks become detached from cliff faces and fall freely through the air, bouncing or rolling down the slope (Easterbrook 1999). Rockfall often occurs where relatively weak sedimentary rocks underlie stronger rock. Rockfall in alpine areas are associated with freeze-thaw cycles in spring, late summer, and fall as well as short duration, intense rainfall throughout the year (Butler 1990). Freeze-thaw cycles result in the expansion and contraction of water within joints in bedrock. This leads to wider jointing and ultimately the detachment of blocks of bedrock from the slope or cliff face (Hungr et al. 2001). Intense rainfall can trigger secondary rockfall events by displacing large rocks that are already detached (Krautblatter and Moser 2009).

Landforms associated with rockfalls are talus cones, talus aprons, and protalus ramparts. Talus cones are cone-shaped features that accumulate at the foot of rock faces (Krautblatter and Dikau 2007). Talus aprons are a series of overlapping talus cones occurring in close proximity forming a long apron shaped landform. Protalus ramparts are ridge-like accumulations of talus located at the foot of snow covered talus aprons and bedrock slopes. Protalus ramparts are a result of talus bouncing or sliding across snow (Ono and Watanabe 1986). Talus cones, talus aprons, and protalus ramparts act as intermediate storage locations for regolith and are often the locations where debris flows originate.

Rock avalanches or sturzstroms are extreme forms of rockfall. They are usually wider than they are tall, and are sheets of rockfall occurring at one time. They can travel great distances with higher energy, often travelling over 100 km per hour with run-outs exceeding several kilometers (Hsü 1975).

Alpine areas in the Rocky Mountains show a peak in rockfall activity during the spring thawing period. Daily rockfall activity is dependent on site characteristics such as aspect and sun exposure (Luckman 1976). South-facing slopes receive more sun exposure than north-facing slopes resulting in a larger fluctuation of temperature throughout the day, more freeze-thaw cycles, and subsequently more talus.

Rockfall in Glacier National Park is common in spring and fall months when temperatures fluctuate between freezing and non-freezing temperatures, and in summer months when the park experiences short, heavy rainfall ("Glacier Glimpses" 1989, Butler 1990). Rockfall in Glacier National Park is not dependent on slope aspect; rather it is the product of steep, nearly vertical slopes, seasonality, and weather (Butler 1990). Butler et al. (1998) found late Holocene sturzstroms concentrated along the Lewis Overthrust Fault in Glacier National Park. There is no evidence of sturzstroms occuring in the study area.

Debris Flows

Debris flows are mass movements of wet mixtures of clays, sands, silts, and gravels combined with water and air (Thomas and Goudie 2000). A clear scarp (initial failure point), a channel (transport and erosion zone), and a lobate toe deposit (deposition zone) are the three distinct landforms associated with debris flows (Dikau, Cavallin, and Jäger 1996).

The initiation of debris flows typically requires a large amount of water to trigger an event. Intense rainfall, rapid snowmelt, or failures of moraine-dammed lakes are common sources of water (Butler and Walsh 1989). Soil expands and contracts with the addition and removal of water, and depending on Atterberg limits, the shear strength of the soil changes. Generally, as water is added to soil, the liquid limit of soil is approached and exceeded, decreasing its shear strength. As a result, soil begins to flow as it overwhelms the resistance to gravity (Hungr et al. 2001, Nemčok Pašek, and Rybář 1972). With movement downslope, a channel is eroded and debris is transported. The transported debris begins as a coherent mass and usually breaks apart quickly as it travels downslope. The flow can range from a rigid mass to turbulent flow (Hungr et al. 2001).

Deposition generally occurs as a lobate toe when slope angle is reduced and the debris slows and stops.

Debris flows within Glacier National Park are not random, but depend on elevation, slope angle, slope aspect, debris supply, and differences in topography (Wilkerson 2004). Debris flows there originate along the distinct break in slope often present below glaciated valley walls because of available debris supply at the base of steep valley walls. The regolith available for debris flows is dominated by accumulations of limestone and argillite of the Belt Supergroup (Wilkerson and Shmid 2008). Other debris flows occur in the weaker Cretaceous rock along the Lewis Overthrust Fault on the eastern edge of the park because of the presence of younger, weaker rock under older, stronger substrate (Wilkerson 2004). Debris flows are common during short duration, intense summer rainfall as well as winter and spring rain-on-snow events when water is able to mobilize the regolith.

Snow Avalanches

Snow avalanches are sudden, rapid movements of snow and debris downslope. They can be extremely powerful carrying boulders, trees, and other debris (Gerrard 1990). Avalanches often occur in the same places following defined paths. Snowfall, temperature, vegetation, and topography impact avalanche path location (e.g., Butler 1986). Two main types of avalanches exist in mountain environments: 1) surface (i.e. loose snow) avalanches, which do relatively little geomorphic work and; 2) slab avalanches (including slushflows), that are capable of changing the landscape on a larger scale (Gardner 1970).

Slab avalanches are most common in the winter during heavy snow fall and warming periods, and in spring during snowmelt when snow becomes saturated and heavy (Thorn 1978, Butler 1986). Weather that produces wet snow “ripens” the snowpack, ultimately saturating it to the point of failure. Wet, heavy snow results in more shear stress plus water at the base of the snowpack decreases shear strength. The more water present, the more potential for geomorphically significant slab avalanches with the most powerful avalanches associated with slushflows (Thorn 1978, Larocque Hetu, and Filion 2001).

Major geomorphic signatures associated with slab avalanches are avalanche tracks (gullies), levees, debris tails, boulder tongues, pits, and mounds. Avalanche tracks are the gullies avalanches follow and are easily visible by the absence of vegetation. Avalanche gullies may result from the erosion of material in the avalanche path. Avalanches may also follow existing gullies as they are the natural conduits (Butler and Walsh 1990). The eroded materials deposited at the sides of avalanche tracks are levees (Thorn 1978, Gardner 1983). Debris tails can be depositional or erosional, and occur because of avalanche movement around large obstacles (Butler 1979, Jomelli and Betran 2001). Upslope debris tails are depositional and are known as blunt upslope tails. Longer debris tails found downslope are depositional or erosional. Boulder tongues are asymmetrical, curved features that are accumulations of rock debris formed below avalanche gullies as the slope levels (Jomelli and Francou 2000). Pits occur at the bottom of avalanche tracks where avalanches impact the valley floor and erode material.

Mounds occur on valley floors downslope from pits where sediments from pit erosion are deposited (Smith, McCarthy, and Luckman1994).

Lithology and slope angle play large roles in avalanche track location. Approximately 50% of snow-avalanche tracks in Glacier National Park are below diorite sill intrusions that are more resistant to erosion than the surrounding, semi-metamorphosed sedimentary rock. Slope angles between 25 and 35º are most common for track location. When the slope is too high, snow is unable to accumulate to create depth and when the slope is too low, the snow is stable (Butler and Walsh 1990). Directly below diorite sill intrusions, slope angle is generally lower. Lower slope angles, coupled with weaker rock, create an environment conducive to slab avalanches.

Snow Avalanche and Debris Flow Relationships

Snow avalanches and debris flows are often related and work together. The two processes often occupy common starting areas as well as common run-out zones. Avalanche tracks often become corridors for debris flows and lead to exposed debris, removal of vegetation, and ultimately, a decrease in slope shear strength (Butler 1979, Butler and Walsh 1990). Debris flows following avalanche activity often run-out on the avalanche boulder tongue and subsequently overprint the avalanche-caused deposit. Debris flows erode gullies in the upper portions of avalanche tracks and deposit material in the middle and lower portion of the avalanche track resulting in unconsolidated material with an irregular, vegetation-free surface. This material is often moved by subsequent avalanche activity and deposited in the form of boulder tongues (Luckman

1992). The continued interaction between snow avalanches and debris flows may result in distinctive landforms that would otherwise not be present.

Landslides

Landslides occur when coherent masses of material break free and slide downslope along planar or curved surfaces. A distinct zone of weak material, where failure occurs, separates slide material from stronger, more stable material below (Cruden and Varnes 1996). Two main landslide movements occur: translational and rotational.

Translational Slides

Translational slides, also known as blockslides, are the most common slides worldwide, are generally shallow, and often related to wet weather events. Failure occurs when regolith or rock planes are parallel to the surface, and weak or jointed. Joints or bedding planes are common planar surfaces that are a source of failure for translational slides (Cruden and Varnes 1996). Translational slides create linear scarps parallel to the slope (Remondo et al. 2003). Hummocky terrain is common along the run-out zone and is caused by a wedge of slide material that overflows undisplaced material, resulting in folding (Cruden and Varnes 1996). No literature regarding translational slides in Glacier National Park exists; this may be because of the absence of weak rock planes parallel to the surface or little to no understanding of what constitutes a translational slide, leading to misclassification.

Rotational Slides

Rotational slides, also known as slumps, occur over curved surfaces when a coherent mass slides down slope. Rotational slides are generally deeper, larger, less frequent than translational slides, and mainly associated with wet climates when homogenous regolith is saturated for long periods of time. Scarps associated with rotational slides are usually curvilinear. A coherent mass rotates as it slides resulting in back-tilted blocks (Cruden and Varnes 1996). Sag ponds sometimes form at the head of the rotational slide or blocks, causing repeat failure, until a lower slope angle is formed.

Rotational slides in Glacier National Park are found on north facing slopes, where snowpack lingers and saturates the ground to the point of failure (Oelfke and Butler 1985). The United States Geological Survey (USGS) map shows large slumps, block slides, and earth flows from the Late Pleistocene and Holocene near Allen Creek along the Cracker Lake Trail in the study area. These mass wasting deposits are common in areas underlain by Cretaceous sedimentary rocks and are uncommon in areas underlain by the Belt Supergroup (NPS GRI program 2013).

Floods

Flooding occurs when water exceeds the channel’s carrying capacity and inundates the floodplain (Thomas and Goudie 2000). Depending on the amount of water, flooding can drastically alter the landscape. Generally, the more water present, the more potential for geomorphic change. Two main types of potential flooding occur in Glacier National Park: glacial outburst floods (GLOFs) and annual spring and summer flooding.

GLOFs

Water is impounded and trapped in glacially conditioned landscapes in many different ways. As glaciers recede, end moraines form from relatively weak, unconsolidated material. End moraines commonly dam valleys and/or cirques creating lakes. Snow avalanches and other mass wasting deposits (landslides, debris flows, rockfall, etc.) can also form natural dams in alpine environments and dam drainage basins. As water collects, the pressure on dams increase, sometimes to the point of failure, releasing as a GLOF (Reynolds 1992). Moraines and landslides may fail because they are composed of unstable regolith or glacial till (O'Connor and Costa 1993). Glacial meltwater often collects in crevasses within glaciers, effectively trapping water. As the ice melts, the trapped water is released. The induced flooding can happen suddenly or slowly, breaking the seal that holds water in. The possible geomorphic consequences of GLOFs are substantial, depending on the amount of water released, and have the potential to alter the valley floor landscape as well as harm humans and structures present (Butler 1989). Water naturally flows to the lowest possible point, mainly impacting valley floors.

Potential for GLOFs is high in Glacier National Park because of the frequent occurrence of mass wasting occurring in the area. Rockfall and snow avalanches cause lakes to overtop and further increase the hazard in Glacier National Park (Butler 1989). Identifying possible GLOFs is generally done by identifying glacial lakes undergoing frequent change in shape from glacial recession, as well as the existence of unconsolidated glacial till, and presence of colluvium or snow dams (Bolch et al. 2011). Butler (1989) notes the danger of morainal failure and subsequent draining of Upper Grinnell Lake, specifically in the Many Glacier Valley.

Annual Flooding

Annual flooding is prevalent in mountains worldwide, especially during late spring and early summer when snowpack is melting. Warmer temperatures, coupled with spring storms, fill lakes and streams to their capacity, resulting in overland flow and spring flooding (Figure 5).

Figure 5. Snyder Creek following flood stage near Lake McDonald Lodge in Glacier National Park, spring 1964. Note damage to the dining room from flooding. National Park Service archives, June 9, 1964, John J. Palmer photographer.

Rivers and streams are at their highest during late spring and early summer when winter snowpack is melting. Glacier National Park generally averages 9.5 cm of precipitation during the month of June, most of which falls as rain (WRCC 2013).

Steady rainfall on winter snowpack, coupled with warmer early summer temperatures, has the ability to overwhelm streams. Effects of flooding are generally focused along streams and rivers on valley floors. Many trails in Glacier National Park are located along stream banks on valley floors and are damaged yearly from annual flooding.

Mountain Recreation

Worldwide

Although mountains include a low percentage of the world's population, mountainous areas are extremely popular destinations for visitors seeking outdoor recreation experiences (Beniston 2003, Nepal and Chipeniuk 2005). Among other things, recreationists are drawn to mountains by scenery. Mountains are scenic and often viewed as temples and/or symbols of freedom. Mountain environments have become more popular to tourism and settlement because accessibility has improved. Accessibility has improved because of increased resource extraction, transportation, and tourism (Kariel and Draper 2003). Scenery and ease of access has increased pressure on mountain environments. Mountains offer a diverse array of activities ranging from visiting unique mountain lodges to hiking to climbing mountains. Hiking trails are a way for visitors to experience alpine environments inaccessible to motor vehicles.

Hiking trails in mountain environments are typically located along valley walls and on valley floors. This is also true for hiking trails in glacially conditioned valleys which have wider valleys and greater valley-side relief than fluvially formed landscapes (Slaymaker and Menounos 2000). The location of hiking trails in glacially conditioned valleys creates increased potential for geomorphic hazards because of the steep, unstable valley walls that provide material and energy for mass wasting events.

U.S.

Public interest in outdoor recreation and appreciation of natural areas continues to grow in the United States (Cordell 2008). Outdoor recreation in the United States began to rise following the Great Depression and has continued to be part of the average American's life. The Outdoor Recreation Resources Review Commission (ORRRC) conducted a study in 1958 that found an increased interest in outdoor recreation. As a result, Congress began passing acts and creating resources for the American public including the National Wilderness Preservation System, the National Wild and Scenic Rivers System, the National Trails System, and a system of National Recreation Areas (Cordel 2008). Day hiking and backpacking grew by 193% and 182%, respectively, between 1980 and 2000 (Cordell et al. 2004).

The United States government manages many alpine areas across the United States with different missions, allowing public access to alpine areas. The Bureau of Land Management, Forest Service, and National Park Service are the main federal government agencies providing access to mountain areas located on federally owned land. Hiking trails and backcountry campsites are often located in these protected alpine areas. These areas offer serene settings, where the American public can escape the stresses of everyday life.

National Park Service

The creation of the United States National Park Service by the Organic Act in 1916 laid the framework for preservation of and access to many mountain environments across the United States. The National Park Service manages over 90 national parks, national preserves, and national recreation areas, many of which are comprised of mountain regions with road and/or trail access (NPS 2013).

Recreationists are now able to access the alpine environment of Glacier National Park via 734 miles of trails from mid June to mid October. In order to meet the demands of visitors, NPS and the Great Northern Railway worked together to build trails. Accessibility in Glacier National Park greatly increased in 1932 when the Going-To-The-Sun-Road was finished, transecting the Continental Divide through mountainous terrain and allowing relatively easy access to alpine areas (Robinson 1960).

According to yearly reports issued by the National Park Service, Glacier National Park received approximately 2.2 million visitors in 2013. Over half of those visitors report going on at least one hike. Approximately 1.9 million of these visitors came between June and September. The traffic count at Many Glacier Ranger Station recorded ~275, 000 automobiles entering in 2013 (NPS 2014). If it is assumed that each automobile carries on average two people, and half of those people go on at least one hike, that puts at a minimum ~275,000 people on trails in the Many Glacier Valley each year. The Many Glacier Valley is known for its high mountain landscape and dense network of hiking trails that allows hikers to get to the center of the park with relative ease (Molvar 2007).

The popularity of Glacier National Park, its steady increase of yearly visitors, location of hiking trails, geomorphic processes, and glacially conditioned landscape leads to a great potential for trail-based, recreation hazards. Wilkerson and Schmid (2004) and Butler (1989) note the clear interaction between humans and geomorphic processes in Glacier National Park.

Geomorphic Hazards

Geomorphic processes that potentially cause harm to people or property are geomorphic hazards (Gares 1994). Development of alpine areas has exposed humans and property to hazards associated with geomorphic processes. Glacially conditioned landscapes coupled with climatic conditions conducive for mass wasting create a geomorphically hazardous environment. Glaciated landscapes are prone to mass wasting and flooding because of steep slopes, readily available material, enhanced erosion processes, and abundance of water (O'Connor and Costa 1993).

Geomorphic hazards pose a major risk to visitors of Glacier National Park and have resulted in several fatal events on recreational trails as well the Going-To-The-Sun-Road. Butler (1989) identified the major hazards associated with glacial retreat in Glacier National Park as mass wasting and flooding because of a climate conducive to frost weathering, intense summer thunderstorms, and rapid snowmelt.

The Going-To-The-Sun-Road has been closed numerous times because of geomorphic hazards during spring and summer months. Rockfalls occur in steep alpine areas daily, especially in spring and fall when temperatures are fluctuating between freezing and non-freezing. Debris flows close roads and trails during spring snowmelt and during summer thunderstorms. For example, in August of 1999, numerous debris flows occurred in the Iceberg Lake and Ptarmigan Lake drainages during an intense summer thunderstorm. A total of 13 debris flows crossed the Iceberg Lake trail and 27 debris flows crossed the Ptarmigan Tunnel trail between the trail junction and the Ptarmigan Tunnel (Wilkerson and Schmid 2003). Debris flows closed the Going-To-The-Sun-Road at least once annually during the last three years. These geomorphic processes are hazards to visitors of Glacier National Park because of the location of roads and trails beneath steep, glacially conditioned slopes.

As Glacier National Park transitions from glacierized to glaciated, geomorphic processes have the potential to increase. Higher temperatures can trigger increased movement on the active level of permafrost. The absence of ice on undercut slopes decreases slope shear strength. Increased water in proglacial lakes increases shear stress on unstable moraines. These suggest potential for increased geomorphic hazard despite the warming induced, upward migration of vegetation that has the ability to increase root strength thus increasing slope shear strength (Stoffel and Huggel 2012).

Geomorphic Hazard Mapping

Hazard mapping is done worldwide to help create an understanding of the spatial and temporal distribution of hazards relative to people and infrastructure. It is often done through remotely sensed imagery, especially in inaccessible mountainous areas (Mantovani et al. 1994). The imagery, if available in multiple time series, allows for temporally sensitive hazard inventories to be developed, showing both spatial and temporal patterns of the hazard (Soeters and van Westen 1996). Once inventories are created, Geographic Information Systems (GIS) is often used to identify spatial control variables associated with different types of hazards (e.g. Gupta and Josh, 1990, Carrara et al. 1995, Dhaki et al. 2000, Ayalew and Yamagishi 2005). The GIS allows for a fairly quick analysis of a variety of spatial control variables including elevation, slope angle, slope aspect, lithology, vegetation information, distance to surface water, and others to determine a potential relationship between hazard occurrence and spatial phenomena (Carrara et al. 1995). A variety of different methods including heuristic, statistical, and deterministic approaches are then used to create hazard zones and ultimately a hazard map (Soeters and van Westen 1996).

Hazard Management

Worldwide

Hazard management practices include pre-event measures (awareness and preparedness), disaster response, and post-event recovery to reduce the loss of life and property (Clary 1985). Pre-event prevention measures minimize the effects of natural hazards through land-use planning regulations (zoning and building codes), warning systems, and community education. Disaster response refers to rescue operations and provisions during and immediately following the event. Post-event recovery reconstructs the community, including developing future pre-event measures. Hazard management is often costly and is more common in developed countries with strong government support.

U.S.

The 1988 Stafford Act outlined the requirements for state governments to mitigate hazards. Natural hazards cannot be prevented but impacts to people and property can be reduced when proper action is taken in advance (Godschalk 1999). The Stafford Act is an amended version of the Disaster Relief Act of 1974, and seeks to ensure the development of pre-event measures, disaster response, and post-event recovery.

National Park Service

The National Park Service is committed “to understand, maintain, restore, and protect the inherent integrity of the natural resources, processes, systems, and associated values of the parks, as well as the opportunity to enjoy them” (NPS 2006). The dynamism of the natural environment is recognized and the National Park Service is charged with a duality of preserving the natural environment while giving the American public the opportunity to enjoy them.

Historically, the National Park Service has been concerned with *responding* to the safety of park visitors. However, in 2006 under a Director’s Order, it was the intent of the National Park Service to *prevent* injury and enhance park enjoyment. While the National Park Service cannot eliminate hazards, especially natural hazards, the shift in management strategy places park personnel responsible to seek reasonable measures for visitor safety (2010). The National Park Service (2006) is committed “to the greatest extent possible, allow natural geologic processes to proceed unimpeded.” Natural, geologic processes can be interrupted if there is an emergency that involves human life and/or property. This indicates that improved planning is needed to avoid emergency situations.

Hazard prevention associated with recreational experiences relies on park personnel as well as individual visitors. The shared responsibility relies on park personnel to make a reasonable effort to assess risk, mitigate and/or eliminate those risks, and communicate present hazards within the limits of their resources. Individual park visitors should be prepared for, and seek information and warnings provided by park personnel to the particular park environment in which they are recreating (NPS 2006). Currently, Glacier National Park officials rely on simple road signs to warn visitors of rockfall hazard, giving tourists no indication of frequency or the hazard itself, while literature regarding bears is given to every vehicle entering the park.

The park service spends between $675,000 and $1,000,000 annually on trails in Glacier National Park, with much of the money going to post-event recovery projects. Such projects include replacing bridges washed out by floods, reinforcing eroding edges of trails with stone, rebuilding campgrounds, and installing drainage structures for diverting water. The National Park Service moves trails in some instances to avoid future hazard. Such was the case with the Swiftcurrent Pass Trail, which made switchbacks shorter, to avoid a debris flow problem area.

CHAPTER III

STUDY AREA

Location

Glacier National Park is located in the Northern Rocky Mountains in northwestern Montana, United States (Figure 2). The park was created in 1910, designated as an International Peace Park in conjunction with Canada’s Waterton Lakes National Park in 1931, an International Biosphere Reserve in 1976, and an International World Heritage site in 1995. The park encompasses 4,082 km² and is centered along the Continental Divide. It is bordered by Waterton Lakes National Park to the north, the Blackfeet Indian Reservation to the east, and the Bob Marshall Wilderness Complex to the south. The town of Kalispell is located 55 km southwest of the West Glacier entrance with many small communities in between. Elevation varies greatly within the park. West Glacier is the lowest at 998 m, while Many Glacier is at 1488 m. The highest elevation, Mt. Cleveland, is at 3190 m (Figure 2).

The Many Glacier Valley is located in the northeastern portion of the park at roughly 48˚ N and 113˚ W (Figure 6). It lies east of the Continental Divide and west of the Blackfeet Indian Reservation. It is a remote area located 16 km west of the small community of Babb, Montana. The Babb-Many Glacier Road provides access to the Many Glacier Valley from Highway 89 (Figure 2). The Many Glacier Hotel operates from mid-June through mid-September.

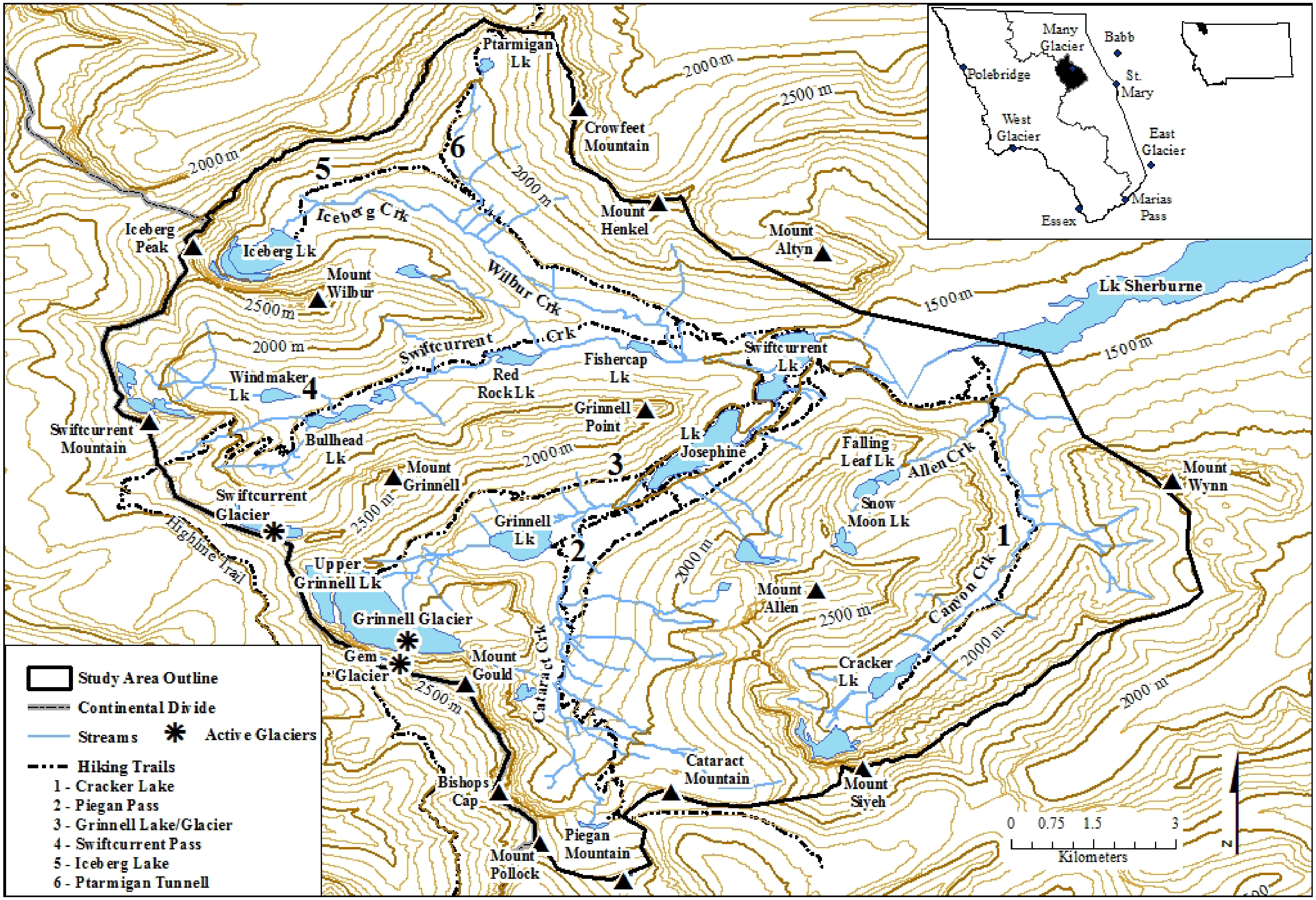

Figure 6. Many Glacier study area and key hiking trails, streams, and lakes referred to in text.

Climate

The climate of Glacier National Park is controlled by a variety of large and small scale factors. A mid-Latitude (48°N) location, prevailing westerly winds, overall elevation, physical barriers (Rocky Mountains), and location comprise the large scale factors. Small scale factors include local topography, aspect, valley and slope winds, local elevation differences, and vegetation (Finklin 1986). Large scale factors influence the amount of insolation received, temperature and moisture characteristics of air masses, and adiabatic lapse rates. Small scale factors greatly influence the climate and weather of places within a relatively short distance. For instance, a valley floor will receive winds in the evening while the elevations higher will receive more wind in the morning.

Glacier National Park's climate is characterized by cold, snowy winters, with air temperature generally below 0˚ C, and warm dry summers, that melt most snow by late June or early July. In winter months, westerly winds bring maritime cyclonic systems, and polar air masses from the north bring dry, cold air. During summer months, temperatures reflect a continental climate with large fluctuations between nightly lows and daily highs (Finklin 1986). The steep mountains within Glacier National Park result in a unique mountain climate that creates microclimates varying dramatically over small distances.

The Rocky Mountains act as a barrier for maritime air coming from the Pacific Ocean, with less annual precipitation to the east of the mountains than the west. As wet air travels east over the western slopes of the Rockies, the air cools and condenses until it reaches dew point, and clouds are formed (Finklin 1986). Precipitation, in the form of rain or snow, occurs as the air mass continues to rise and cool. Most of the moisture from air masses is lost by the time they reach the Continental Divide, resulting in little precipitation as the air mass travels down the eastern slopes. Precipitation on the eastern side of the Rocky Mountains is therefore a result of continental Polar air colliding with maritime Tropical air as well as convection heating at the earth's surface during spring and summer months resulting in thunderstorms (Finklin 1986, Bach and Price 2013). Relatively low levels of precipitation are controlled by the area's far location from a moisture source. Approximately 60-70% of the annual precipitation falls as snow at high elevations. The area receives approximately 164 cm of snow each year. The elevation of the study area is slightly higher than Babb and located closer to the Continental Divide, with varying topography. It is likely that the study area receives more precipitation and has slightly lower temperatures, but seasonal patterns should be similar.

The closest, reliable climate data for the Many Glacier Valley is from near Babb, Montana, located approximately 20 kilometers east of the study area at an elevation of 1378 m in a low relief prairie (Figures 2 and 7). The mean annual temperature there is 4.6º C with a mean January temperature of -4.9 º C and a mean July temperature of 15.9 º C. The area receives approximately 43 cm of annual precipitation, most of which falls during spring and summer months (Finklin 1986, WRCC 2012).

A SNOTEL site located at the Many Glacier Ranger Station has collected SWE data since 1977 (Figure 8). The data collected from the SNOTEL site suggests snowpack is highly variable from year to year and averages above

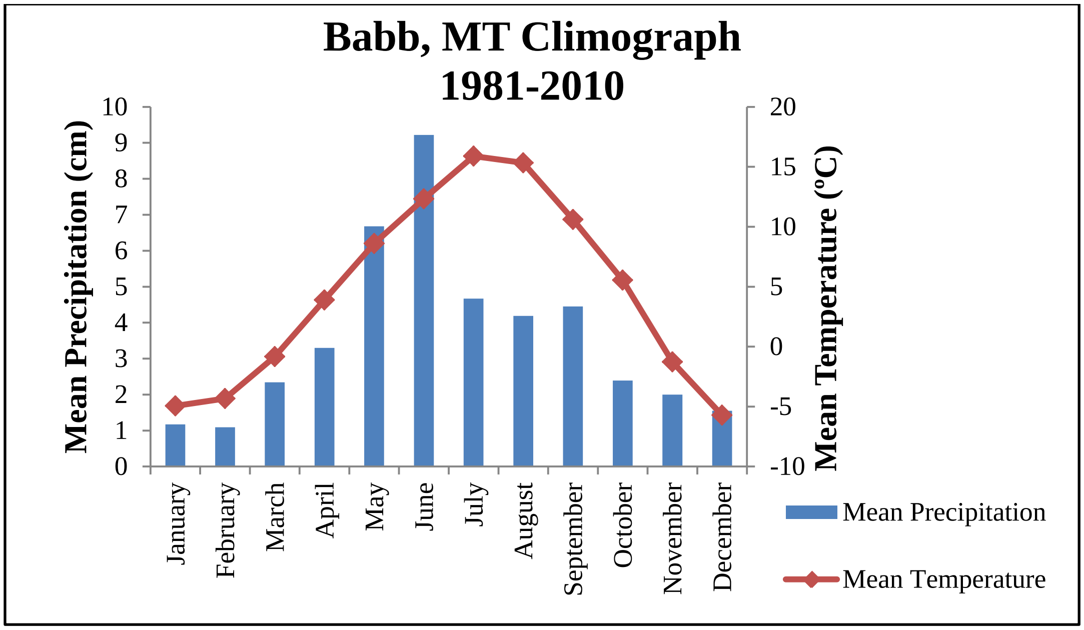

Figure 7. Climograph of Babb, MT. Compiled from WRCC data.

what is recorded in Babb. The SWE average for Many Glacier between 1977 and 2013 was 126 cm compared to 43 cm of precipitation recorded in Babb. The difference in precipitation is likely because of elevation changes, variable topography, and location along the Continental Divide.

Hydrology

Situated on the Continental Divide, Glacier National Park is the headwater for its region. Therefore, glaciers, snowpack, and resulting runoff are important to the park as well as surrounding communities. Three active glaciers, Grinnell, Swiftcurrent, and Gem, are located in the study area. The major tributaries in the Many Glacier Valley include Ptarmigan, Iceberg, Wilbur, Swiftcurrent, Cataract, and Canyon Creeks (Figure 6). Fourteen named lakes are located in the Many Glacier Valley and include

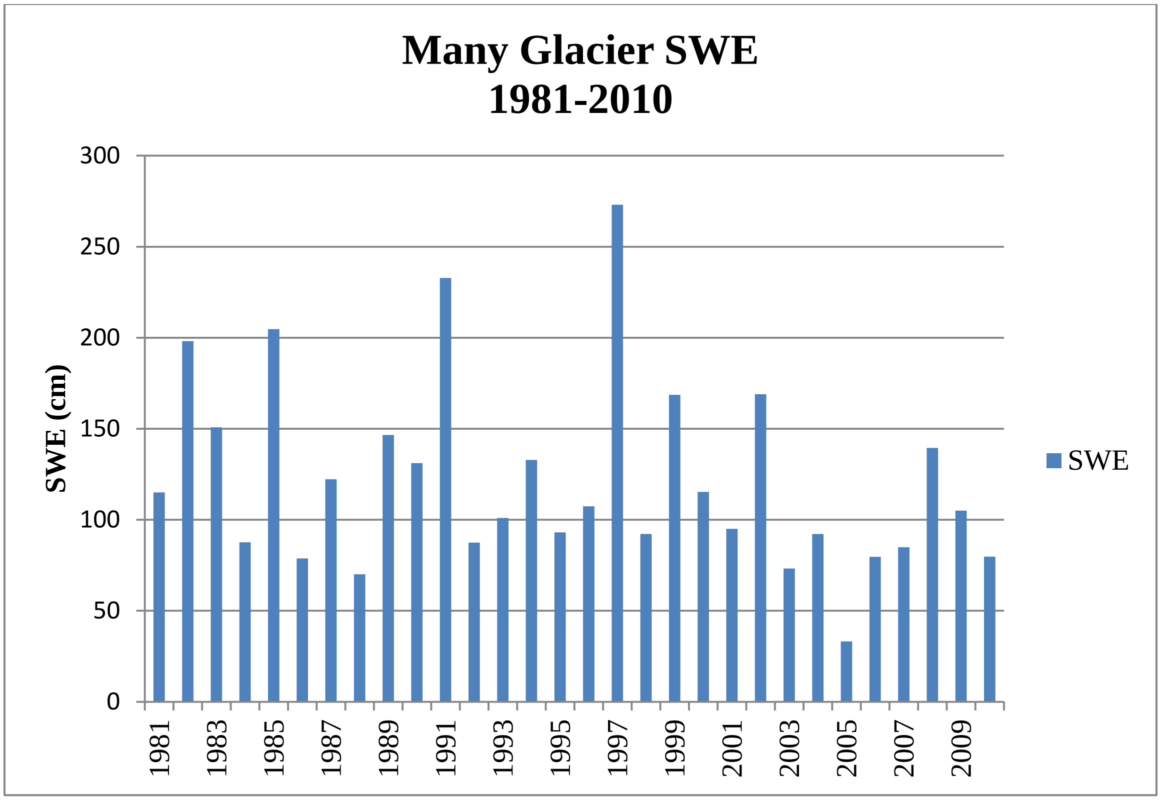

Figure 8. SWE based on water year for the Many Glacier Valley (October – September). Compiled from NRCS SNOTEL data.

Sherburne, Swiftcurrent, Josephine, Snow Moon, Falling Leaf, Cracker, Lower Grinnell, Upper Grinnell, Fishercap, Red Rock, Bullhead, Windmaker, Iceberg, and Ptarmigan Lakes (Figure 6). Annual snowpack, rain, alpine glaciers, and lakes feed streams. All tributaries in the Many Glacier Valley flow into Lake Sherburne before flowing east to the St. Mary River. The river flows northeast through northern Montana and southern Alberta to the Oldman River. Oldman and Bow Rivers join to form the South Saskatchewan River, eventually draining into Hudson Bay. The highest average annual discharge occurs in May and June, and is heavily dependent on winter snowpack and spring weather (MacDonald et al. 2010). The natural occurrence of spring runoff is important to the physical environment of streams and rivers because of the habitat provided to spawning fish and birds.

Geology

The steeply eroded cliffs of Glacier National Park are mostly composed of the Precambrian Belt Supergroup (Earhart et al. 1989). The sediments of the Belt Supergroup were deposited in a marine environment between 1600 and 600 million years ago. Approximately 144 to 65 million years ago Cretaceous shales, mudstones, siltstones and sandstones were deposited, also in a marine environment. The Cretaceous deposits are not metamorphosed and are relatively unstable and susceptible to deformation, mass wasting, and erosion (Ross 1959).

The Lewis Overthrust Fault runs north-south along the eastern edge of Glacier National Park through the eastern portion of the Many Glacier Valley (Figure 9). The presence of younger, unstable Cretaceous deposits underneath relatively older, stable Belt Supergroup results in undercut cliffs and unstable slopes due to weathering and erosion. The tilted layers of the overthrusted rock can be conducive to sliding where the weak rock dips with the slope (Alden 1932). In the Many Glacier Valley, the Altyn, Appekunny (i.e., Apekuni), Grinnell, Empire, Helena (i.e., Siyeh), Snow Slip and Shepard Formations from the Belt Supergroup are present (Figures 9 and 10). These formations were partially metamorphosed and went through a relatively short period of volcanic activity.

Because of this metamorphism, slopes made of this rock are relatively stable (Ross 1959). The Altyn is limestone, located directly above the Lewis Overthrust Fault

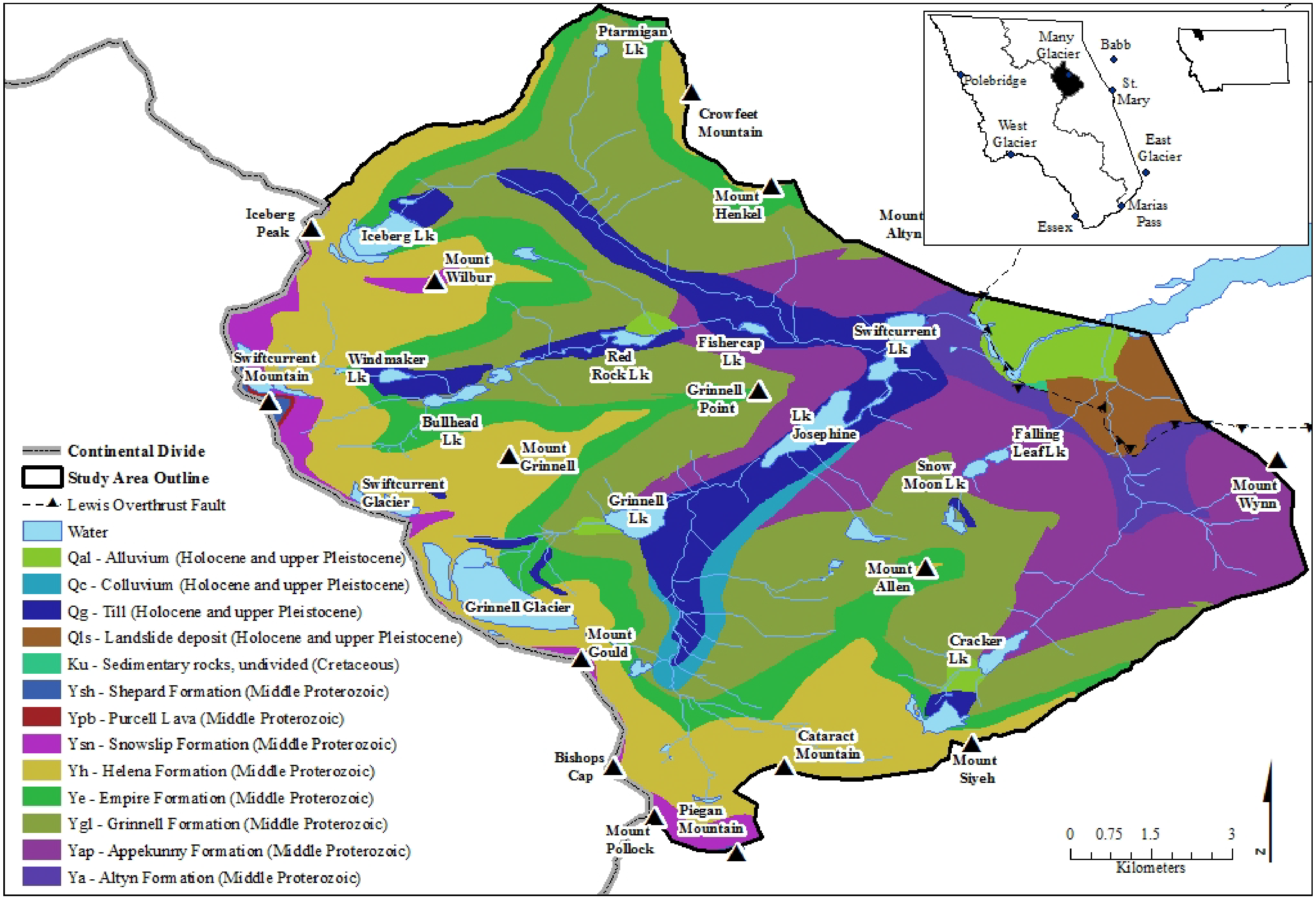

Figure 9. Geologic map of the Many Glacier Valley. Compiled from NPS GRI Program data 2013.

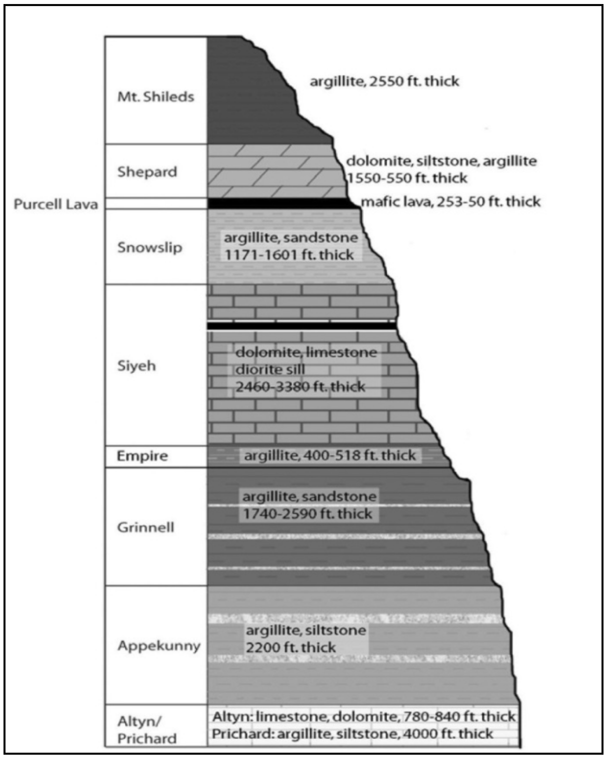

Figure 10. Stratigraphic column displaying the Precambrian Belt Formations in Glacier National Park (Hunt, 2006).

through the eastern portion of the study area (Figures 9 and 10). It is magnesium limestone resistant to weathering and forms ridges where it crosses valleys. This can be seen in the Many Glacier Valley at Swiftcurrent Falls where the Altyn Formation creates a dam, holding back Swiftcurrent Lake (Dyson 1952). Above the Altyn Formation is the Appekunny Formation, composed of green shale and extremely hard argillite (Figures 9 and 10). The Appekunny Formation is evident along the lower portion of the Grinnell Glacier Trail. Directly above the Appekunny Formation is the Grinnell Formation, a red argillite. The Grinnell Formation comprises most of Grinnell Point, Mount Allen, and Altyn Peak (Figure 9). It is evident along all trails in the study area including Ptarmigan Tunnel. Between the Helena and Grinnell Formations is a transitional formation known as the Empire (Figure 10). The Empire Formation is composed mainly of green and red argillite near the top with some quartz near the bottom (NPS GRI Program 2013). Above the Empire is the Helena Formation, a thick limestone that creates many of the steep mountain walls within the Many Glacier Valley, including Mounts Gould, Grinnell, Allen, Wilbur, and Henkel as well as portions of the Garden Wall (Dyson, 1957). The Shepard Formation sits above the Grinnell and is evident in the study area at the top of Swiftcurrent Mountain as well as the head of the Swiftcurrent Valley. The Shepard Formation is comprised of stromatolite fossils deposited in the Belt Sea and are composed of a variety of rock types including dolomite, siltstones, argillite, and quartzite (Dyson 1952, Hunt 2006). During the short period of volcanic activity in the park, submarine lava flowed over sediments while they were still in a shallow sea. The Purcell Lava is only 23 – 80 m thick, sits directly on top of the Siyeh Formation, and is evident at the top of Swiftcurrent Pass (Dyson 1952, Ross 1959).

Geomorphology

Elevation within the Many Glacier Valley varies greatly from 1479 m at the shores of Sherburne Lake to 3052 m at the top of Mount Siyeh. Topography can vary greatly within short distances, sometimes over 1000 m in 0.75 km. Areas with drastic differences in elevation are generally associated with cirques, horns, and arêtes eroded by alpine glaciers (Carrara 1987). Alpine glaciers are largely responsible for the current landscape and subsequent geomorphic agents shaping them (Figure 3). Those present in the Many Glacier Valley are not remnants of the valley glaciers primarily responsible for the landscape; rather, they occupy the same cirques as the glaciers before (Carrara and

McGimsey 1981). The three remaining glaciers in the Many Glacier Valley are retreating, exposing landscape susceptible to mass wasting.

Mass wasting and fluvial processes in Glacier National Park currently dominate the movement of material downslope. Rockfalls, debris flows, slab avalanches, landslides, and flooding are the main geomorphic processes operating within Glacier National Park. Freeze-thaw events are common during early spring and late fall and are directly linked to rockfalls. Thunderstorms that are typical during summer months are also capable of producing debris flows. Rain-on-snow events during spring can trigger snow avalanches and debris flows. Snow-melt in late spring often results in flooding which can trigger a variety of mass wasting processes.

Vegetation

The vegetation of the Many Glacier Valley is typical of a continental climate. Vegetation is often classified into belts or zones based on elevation and moisture availability. Four main vegetation belts exist within the Many Glacier Valley: alpine tundra, subalpine zone, montane forests, and aspen parklands (NPS 2011). Alpine tundra is above treeline at approximately 1800 m, mostly covered in bare rock with sparse vegetation including shrubs and forbs able to handle the harsh conditions. The subalpine zone is dominated by open meadows and islands of dwarfed trees (krummholz) stunted by high winds, heavy snowfall, and a short growing season at elevations between 1500 and 1800 m (Arno and Hammerly 1884). Common species are subalpine fir (*Abies lasiocarpa),* Engelmann spruce (*Picea engelmannii*), and whitebark pine (*Pinus albicaulis*) (Arno and Hammerly, 1984, Olin, 2005). Montane forests, at elevations between 1200 and 1500m, are dominated by Douglas fir (*Pseudotsuga menziesii*), white spruce (*Picea glauca*), limber pine (*Pinus flexilis),* and deciduous shrubs. Aspen parklands are black cottonwood (*Populus balsamifera*) forests and quaking aspen (*Populus tremuloides*) groves acting as a transition zone between 900 and 1200m. Vegetation around creeks is generally denser and consists of vegetation tolerant to variable water supply including black cottonwood and quaking aspen.

South-facing slopes are generally sparsely vegetated because of low water availability caused by high sun exposure. North-facing slopes are often more densely vegetated because of more water availability (Standley 1922). Trails in the study area are located throughout all zones and on all slope aspects. They often begin in aspen parklands and end above the treeline in the alpine tundra.

Human History and Land Use

Humans have likely been present on the landscape of Glacier National Park dating as far back as 10,000 years (Reeves 2007). The Blackfeet, Salish and Kootenai tribes were present when European explorers reached the region in the late 1700s (Buchholtz 1976). The eastern portion of present day Glacier National Park was included in the Louisiana Purchase in 1803, without full knowledge of what the purchase encompassed. The purchase marked the beginning of European-American presence in the region.

In the 1870s, the small town of Altyn, near present-day Many Glacier, drew people to the area with expectations of mineral wealth. In 1898, Altyn was declared “open” to mining and became a boomtown for mining. The area reached its peak population of approximately 1,000 residents in 1899 and had numerous stores, a post office, a hotel, a newspaper, saloons, and cabins. By 1902, most prospectors had given up hope of striking copper, silver, or gold and left the area when their efforts weren’t rewarded. Remnants of mining activity are still evident on the landscape such as an abandoned mine along the shore of Cracker Lake in the Many Glacier Valley (Figure 6).

The Great Northern Railway was completed in 1891 allowing travel between Marias Pass and the Flathead Valley (Buchholtz 1976). The creation of the railroad encouraged settlement as well as tourism in an area that had been fairly inaccessible until that point. President Taft signed the bill that created Glacier National Park as the tenth National Park in 1910. During this time, the Great Northern Railway was commissioned to build nine chalets within the park to encourage visitation. The creation of the chalets led to the development of some trails that exist today. When the chalets were built, very few roads existed within the park, so they were accessed via horseback (Robinson 1960).

Between 1910 and 1915, the Many Glacier Hotel as well as many small chalets were built on the shores of Swiftcurrent Lake. The Babb-Many Glacier Road was completed in 1915. The Appekunny, Emanon Bridges, and Swiftcurrent Bridge were built in 1930 further allowing easier access to the Many Glacier Valley (Buchholtz 1976).

In order to meet the demands of visitors, NPS and the Great Northern Railway worked together to fund and build trails. Throughout the next few decades, Eagle Scouts as well as members of the Civilian Conservation Corps from across the country came to help build and complete the trail system that exists today. In 1932, the Going-to-the-Sun road, the only road that transects the park from east to west, was completed and allowed the park to be easily accessed by visitors via automobile (Robinson 1960). The Going-to-the-Sun road transects the Continental Divide south of the study area (Figure 2).

The trails chosen for the study include Cracker Lake, Piegan Pass, Grinnell Lake/Glacier, Swiftcurrent Pass, Iceberg Lake, and Ptarmigan Tunnel (Figure 6). Although some of these trails connect to other areas of the park, the focus will be on the Many Glacier Valley side of each trail (Figure 6).

Cracker Lake Trail

The Cracker Lake Trail starts along the shore of Swiftcurrent Lake at the Many Glacier Hotel, winding along Lake Sherburne through a narrow valley, and eventually ending in a cirque below Mount Siyeh, Cracker Peak, and Allen Mountain (Figure 6). The Cracker Lake Trail is 9.8 km, one way, with an elevation gain of approximately 335 m. The relief from Mount Siyeh to Cracker Lake is approximately 1200 m and is the largest within the park.

Piegan Pass Trail

The Piegan Pass Trail connects the Many Glacier Valley to Siyeh Bend along the Going-to-the-Sun road. The Many Glacier side of the trail is 20.5 km, one way, with an elevation gain of 804 m (Figure 6). The trail follows the southern shores of Swiftcurrent and Josephine Lakes, winding into a large U-shaped valley before ascending steeply the western side of Cataract Mountain to the saddle between Piegan and Cataract Mountain known as Piegan Pass. From Piegan Pass, the trail continues east, eventually heading south to Siyeh Bend.

Grinnell Lake/Glacier

The Grinnell Glacier Trail is part of an interconnected complex of trails that travel around Swiftcurrent and Josephine Lakes leading to either Grinnell Lake or Grinnell Glacier (Figure 6). For the purpose of the study, these trails will be referred to as Grinnell Glacier for simplicity. Grinnell Lake is 3.9 km long, one way, with an elevation gain of 50 m and Grinnell Glacier is 9 km, one way, with an elevation gain of 490 m. The trails were combined for this study because of the short distance from where the trail forks and Grinnell Lake, and the locations of both destinations in the same drainage. The Grinnell Glacier Trail leaves the Swiftcurrent Picnic Area and follows the northern shore of Josephine Lake. At the head of the lake the trail splits, with Grinnell Lake to the south and Grinnell Glacier to the west. Continuing to Grinnell Glacier, the trail ascends the side of Mount Grinnell and over a terminal moraine to Upper Grinnell Lake, at the foot of Grinnell Glacier. The fork to the south leads to the foot of the cliff below Upper Grinnell Lake, where Grinnell Lake sits.

Swiftcurrent Pass Trail

The Swiftcurrent Pass Trail starts in the Swiftcurrent Valley and follows the valley floor past a chain of paternoster lakes to a headwall, where the trail switchbacks up the southeastern side of Swiftcurrent Mountain to a low saddle known as Swiftcurrent Pass (Figure 6). From Swiftcurrent Pass, the trail continues southwest where it meets the Highline Trail at the Granite Park Chalet. The Swiftcurrent Pass Trail connects the Many Glacier Valley to Logan Pass via the Highline Trail. The Many Glacier side of the trail is 10.5 km, one way, with an elevation gain of approximately 675 m.

Iceberg Lake Trail

The Iceberg Lake Trail is 7 km one way, with an elevation gain of approximately 360 m (Figure 6). The trail traverses the southern and western sides of Mount Henkel before crossing Ptarmigan Creek at Ptarmigan Falls. At a trail junction shortly after Ptarmigan Falls, the Iceberg Lake Trail turns southwest along Ptarmigan Wall and ends at Iceberg Lake in a cirque below Iceberg Peak.

Ptarmigan Tunnel Trail

The Ptarmigan Tunnel Trail is 8 km one way, with an elevation gain of approximately 750 m (Figure 6). The trail shares the first 4 km with the Iceberg Lake Trail. At the trail junction shortly after Ptarmigan Falls, the Ptarmigan Tunnel Trail heads north along the Ptarmigan Wall to the foot of Ptarmigan Lake, which lies in a small cirque. The trail switchbacks up to the tunnel, blasted in 1931, through the Grinnell formation, in the Ptarmigan Wall. The tunnel allows for easy access from the Many Glacier Valley to the Belly River area of the park. The trail continues north past Ptarmigan Tunnel into the Belly River area to the Chief Mountain Border Crossing at the U.S.-Canada border.

CHAPTER IV

METHODS

This research explored the spatial and temporal patterns of geomorphic hazards and their implications for recreational trails in the Many Glacier Valley of Glacier National Park, Montana. I identified landforms and geomorphic events occurring in or before 1940 and up to 2013. To complete this research, six steps were taken: 1) acquiring data; 2) identifying, classifying, and mapping mass wasting landforms; 3) identifying and mapping flooding; 4) identifying spatial and temporal variables; 5) creating geomorphic hazard maps; and 6) developing management recommendations for the National Park Service.

Acquiring Data

Airphotos, geographic information system (GIS) base layers, and historical records were gathered to conduct this research. Airphotos were collected from a variety of sources. A total of five sets of stereographic airphotos and one set of orthophotos were used in the mass wasting inventory (Table 1). The 1950-52, 1968, and 1999 airphotos taken by the National Park Service were acquired from the Glacier National Park archivist, Deirdre Shaw, and GIS coordinator, Richard Menicke at park headquarters in West Glacier, MT, in August 2012. The 1984 air photos were acquired through the EarthExplorer® website made freely available by the USGS in October 2012. A 2011 orthophoto created by the U.S. Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP) was obtained through the State of Montana government website in October 2012. Google Earth® images were viewed as needed as supplements to the 2011 orthophoto. The 2011 orthophoto was used as a base map to accurately digitize landforms in the GIS.

Table 1

Airphoto Datasets Used for Landform Identification

Photograph Year	Scale	Natural Color/ Panchromatic/ Color Infrared	Stereo/ Orthophoto	Source	Flight Lines (Frames)
1950-52	~1:16,000	Panchromatic	Stereo	NPS	13-(50-55) 13-(45-48) 06-(15-32)
1968	1:15,840	Panchromatic	Stereo	NPS	21B-(01-10) 22A-(21-31) 23A-(16-30) 24A-(21-32) 25A-(25-36)
1984	1:80,000	Color Infrared	Stereo	USGS	183-(187-189) 201-(043-044) 219-(030-034) 219-(046-048)
1999	1:15,840	Natural color	Stereo	NPS	23-(30-37) 24-(28-40) 25-(33-44)
2011	1:40,000	Natural color	Orthophoto	USDA	--------------

A GIS geodatabase and multiple shapefiles were acquired through the Integrated Resource Management Applications (IRMA) website made freely available through the NPS in 2013. The geodatabase included geologic and vegetation information created by Geologic Resources Inventory (GRI) program through NPS in 2013. The shapefiles acquired included boundary lines for the park, Montana, the Continental Divide, roads, trails, towns, buildings, named lakes and glaciers, and mountain peaks. Additionally, a 10 meter Digital Elevation Model (DEM) was acquired through the USGS as part of the National Elevation Dataset project in February, 2013.

A historical record aided in identifying processes that occurred before and after airphoto sets (Table 2). Geomorphic processes were sometimes noted in monthly ranger reports and less often, in the *Hungry Horse Newspaper*. Many Glacier monthly ranger reports were accessed from the park archivist in August 2012. The *Hungry Horse Newspaper* was searched online (http://www.flatheadnewsgroup.com/hungryhorsenews/) through *Hungry Horse News* Archive in July 2013 and on microfilm at the Flathead County Library in Kalispell in December 2013. Past published research was accessed via Central Washington University's Brooks Library journal databases website

Table 2

Historical Record Datasets Used for Process Identification

Year(s)	Dataset	Source
1946-1979	Many Glacier Monthly Ranger Reports	NPS
1979-2013	Newspaper Articles	*Hungry Horse Newspaper* Butler (1990)
1998,1999	Dissertation	Wilkerson (2004)

(http://www.lib.cwu.edu/), including Academic Search Complete, EBSCO, JSTOR, and Science Direct.

Additionally, daily and monthly climate data were used to identify wet weather, and potential triggers for geomorphic hazards. These data were obtained through the Western Regional Climate Center (WRCC) website for Babb (http://www.wrcc.dri.edu/Climsum.html), Natural Resource Conservation Service SNOTEL website for Many Glacier (http://www.wcc.nrcs.usda.gov/snow/), and PRISM Climate Group website for Many Glacier (http://prism.oregonstate.edu) in October 2013.

Identifying, Classifying, and Mapping Mass Wasting Landforms

Landform identification and differentiation is typically done through remotely sensed imagery (airphotos, satellite imagery, and more recently LIDAR), field survey, and archival data (agency reports, newspaper articles, past research) (Brardinoni, Slaymaker, and Hassan 2003 Soeters and van Weston 1996). Landforms are often identified based on their morphology (e.g., gullies, levees, scarps, cones, aprons etc.) and are further differentiated based on composition and vegetation patterns. Landforms and geomorphic processes were identified for this project by three different techniques: airphoto interpretation, historical records, and field survey.

Landforms were first identified on airphotos, in written historical records, and through field survey. These features were then classified by the processes which created them based on landforms and basic descriptions; and then mapped in a GIS environment.

The stereographic airphotos were viewed with a Geoscope® stereoscope along north to south flight lines and digitized in ArcMap® as shapefiles. In addition, Google

Earth® images were accessed for a 3-D view of the study area in the last decade. Historical records and newspapers identified mass wasting before and after airphoto sets. Monthly ranger reports helped identify events. Field survey allowed for the identification of landforms too small to be seen on airphotos in areas accessible by trail.

Mass wasting processes were then classified as rockfall, debris flows, slab avalanches, translational slides, or rotational slides through a decision key (Figure 11). The decision key was developed through a literature review of landforms associated with each of the processes based on morphology, vegetation patterns, drainage, and relative location (e.g., Butler 1990, Cruden and Varnes 1996). The processes were determined to have occurred before the time of the airphoto.

Classification of mass wasting processes identified through written historical data depended on descriptions and time of year given in the newspaper articles and park reports. Details in the articles and reports were inconsistent but still provided important information. They often included information regarding landforms, time of year, and weather associated with processes. Rockfall was descriptive and self-explanatory. Debris flows were classified by descriptions given. Slides were the most common description given and classified as debris flows based heavy rainfall recorded. Often weather events were noted in written historical data.

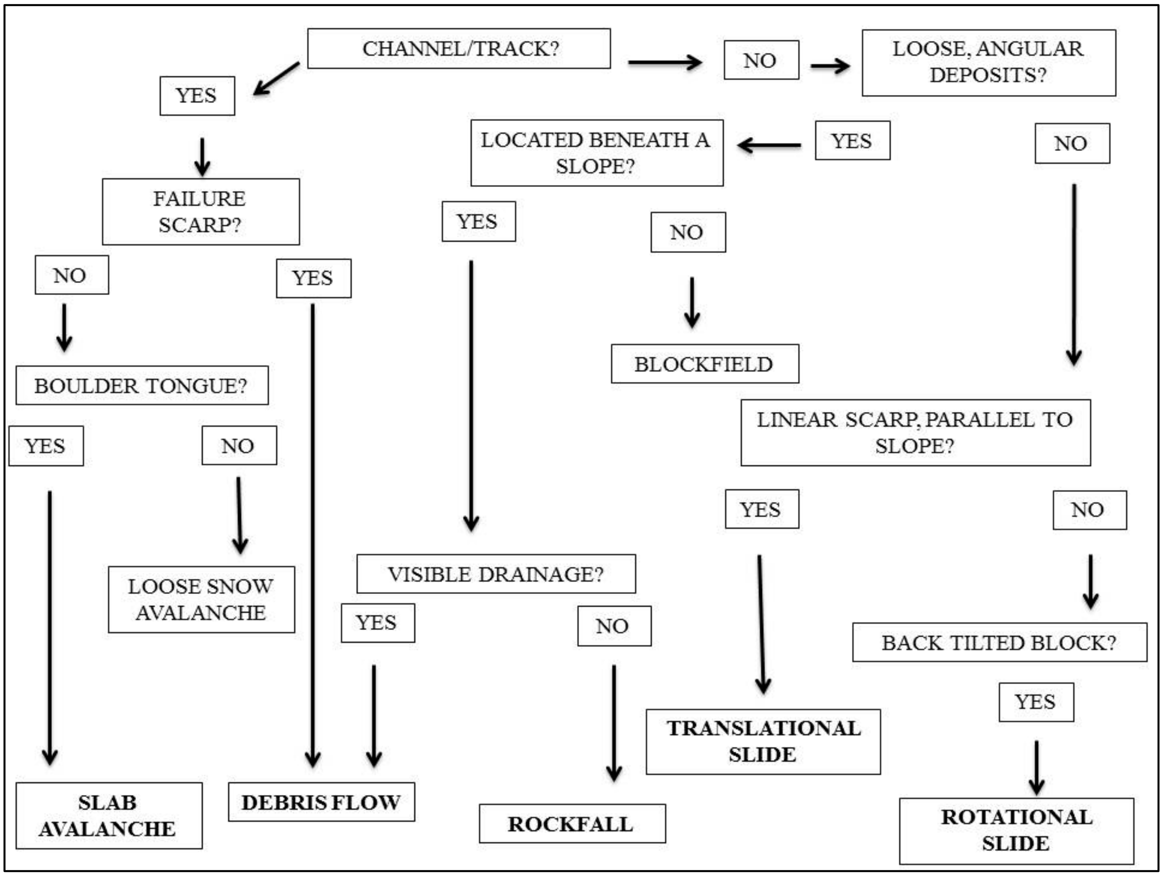

Figure 11. Decision key for classification of mass wasting processes based on observed landforms through airphoto interpretation.

Mass wasting landforms were mapped and digitized as new shapefiles in ArcMap® 10.1, GIS software created by Environmental Systems Research Institute (ESRI) on a 2011 orthophoto. Shapefiles are a vector format and store geometric location and attribute information about a geographic feature. Process types were recorded as an attribute in the GIS shapefile. Processes identified through written historical records were mapped in ArcMap® with a likely zone when sufficient location and details were provided. The trail shapefiles were clipped to the study area to reduce the size of the dataset and include only relevant trails located in the study area. The

Buffer Tool was used to identify any mapped features located within 100 meters of the trails.

Field surveys were done during Summer 2013 to ensure landforms were properly identified based on airphoto identification. Field surveys were used to cross-check airphoto interpretation for accuracy and identify new features in places accessible by trail. Maps of the study area and mapped landforms were brought into the field for reference. Mapped and newly identified landforms were recorded by Iphone application Theodolite 4.0®, a GPS software that overlays geographic information (coordinates and elevation) onto a digital photograph. Cracker Lake, Swiftcurrent Pass, Iceberg Lake, and Ptarmigan Tunnel trails were field checked. Because of the government shutdown in October 2013, Grinnell Glacier and Piegan Pass trails were not checked in the field.

Identifying and Mapping Flooding

Historical flooding was identified through monthly park reports and newspaper articles. Descriptions generally included an area and sometimes noted damage to bridges and trails. A general zone of the likely affected area was mapped in ArcMap® with attribute information including month and year of flood.

Identifying Spatial and Temporal Variables

GIS data layers, combined with the mapped landforms and geomorphic processes, written historical records, and field survey were used to identify spatial and temporal variables controlling mass wasting in the Many Glacier Valley. GIS allowed for qualitative and quantitative analysis of these variables. Attribute information collected included weather, elevation, slope angle, slope aspect, lithology, vegetation coverage, vegetation type, and distance to surface water. The selection of the variables was based on past research by Nemčok, Pašek, and Rybář (1972), Butler (1979, 1986, 1990, 2001) Varnes (1984), Cruden and Varnes (1996), Soeters and van Westen (1996), Hungr et al. (2001), Wilkerson (2004), and Wilkerson and Schmid (2008). The spatial relationships between mass wasting and these variables were determined through a variety of base layers in GIS. Features classified as debris flows, snow avalanches, rotational slides, and translational slides were mapped as polygons, sometimes overlapping multiple elevation, slope angle, slope aspect, lithology, vegetation coverage, and vegetation types. To determine the variables associated with failure, the highest point was recorded as a failure point and tested against these spatial variables for debris flows, avalanches, rotational slides, and translational slides. Rockfall *deposits* were mapped and do not represent accurate locations of rock *failure*. To account for this, probable failure points were recorded above the location of the rockfall deposits in the most likely location of failure to test against spatial variables. The temporal relationship between mass wasting and weather was determined from the successive airphotos, written historical data, and associated weather reports.

Elevation classes were created from a 10 meter DEM raster dataset with the classify tool in the Spatial analyst toolbox in ArcMap®. Elevation in the study area ranges from approximately 900 meters to 3200 meters. Three elevation classes were created and converted to vector format: elevations < 2000 m, elevations between 2000 and 2500 m, and elevations > 2500 m. Features were classified based on elevation and recorded in the attribute table.

Slope angle classes were created from the 10 meter DEM raster dataset with Spatial Analyst in ArcMap®. Four classes were created based on common patterns and converted into vector format. The four classes consisted of slopes < 15 degrees, 16-30 degrees, 31-45 degrees, and > 45 degrees. Slope angle was recorded in the attribute table for each geomorphic feature shapefile and classified based on the four classes above.

Slope aspect was calculated from the 10 meter DEM raster dataset with the Spatial Analyst in ArcMap®. Once the aspect raster dataset was created it was converted to vector format. Aspect was grouped into four classes consisting of slopes facing north 315 - 45º), east (46 - 135º), south (136 - 225º), and west (226 - 315º). Aspect was recorded in the attribute table for each geomorphic feature.

Clipping the geology layer to the study area was done to reduce the size of the dataset to include only relevant geology units. The Analysis Toolbox in ArcMap® was used to join the geology layer to the mapped features and classify all mapped features by geologic formations (Figures 9 and 10).

The vegetation layer was clipped to the shape of the study area to reduce the size of the dataset. The Analysis Toolbox in ArcMap® was used to join the vegetation type to the mapped geomorphic processes and add all attributes of the vegetation layer to the mapped processes, including vegetation coverage and vegetation type based on the United States National Vegetation Classification (USNVC). Vegetation types included non-vegetated, shrubland and grassland, Forest and Woodland, Polar and High Montane, and Non-Vascular and Sparse Vascular. These units were then compared and converted to zones in the study area. Non-Vascular and Sparse Vascular were converted to alpine tundra, Polar and High Montane were converted to supalpine zone, Forest and Woodland were converted to montane forest, and shrubland and grassland were converted to aspen parkland. All conversions were based on elevations given in the descriptions on the life zones published by the National Park Service.

To create the hydrology layer, the 10 meter DEM was used in the Spatial Analyst Toolbox in ArcMap®. The drainage system was delineated by following a series of steps. The Flow Direction Tool was used to determine which direction water would flow out of each cell, with the output becoming a new raster file. Next, the Flow Accumulation Tool was used to input the flow direction raster to calculate the number of upslope cells flowing to a location. The output was a raster file in which the values indicated how many cells flow to it. The higher the value of each cell, the more water present on the landscape. The Raster to Vector Tool was then used to produce a polyline shapefile of the stream network. Finally, the polyline shapefile of the stream network was then compared to the 2011 orthophoto and edited for accuracy. The stream network shapefile allowed for vector analysis of the proximity of streams to mass wasting processes using the Buffer Tool. Two classes were created: areas < 50 m from streams and areas > 50 m from streams.

Chi-square tests were used because the data needed to be sorted into classes and to determine the significance of each control variable to mass wasting (Soeters and van Westen 1996). Chi square tests were performed in Microsoft Excel® and based on mass wasting frequency. Four test groups were assembled: 1) rockfalls, 2) debris flows, 3) avalanches, and 4) translational slides. Expected values for each class were calculated by the percentage of the area of each class of a variable. The expected value assumes there is no significant relationship for a variable class. For example, 200 debris flows were tested in the chi square. To test for a variable such as slope aspect, each slope aspect type would be separated and the area calculated for each type (north, east, south, and west). Once the area is calculated for each slope aspect type, it can be calculated into a percentage. If north facing slopes comprise 25% of the study area, then it should contain 50 debris flows creating an expected value (where 200 * .25 = 50). This was done for each variable class. The chi square test is (Observed value – Expected value)^2/Expected value. This provides a chi square for each class. Each value for each class was then added toghether for the final square statistic for each variable. If the value was significant, then each individual chi square value for each geology class was analyzed to assess which class is the most significant, or the highest individual chi square value. The significance level used for the chi-square test was .05 or 95%. Variables can be significant for two reasons: 1) because the variable has more mass wasting features than the expected value and; 2) because the variable has fewer mass wasting features than the expected value. Rotational slides were not tested for significance because of the low number of mapped features and inconsistencies in control variables. Statistical analysis was not done for flooding because of insufficient information regarding flooding in the study area.

Creating Mass Wasting Hazard Maps

Recording and monitoring places of known hazards can minimize future impacts to surrounding communities. Identification of mass wasting leads to the mapping of those hazards and ultimately, to a better understanding of the geomorphology of the area and subsequent hazards associated with the landscape. The landslide inventory approach is a form of hazard mapping that identifies the spatial distribution of mass wasting and helps identify spatial patterns associated with those processes that can be later used for further landslide zonation techniques (Soeters and van Westen 1996, Sartohadi, Samodra, and Hadmoko 2010). One technique for hazard mapping is the weight of evidence (WOE) approach, assigning different variables corresponding ratings based on their role in the hazard. WOE involves comparing the landslide density of each controlling factor to the landslide density of the entire study area (Sartohadi, Samodra, and Hadmoko 2010). The statistical approach is a technique involving the spatial distribution of mass wasting (landslide inventory) to determine the conditions where landslides are likely to occur based on statistics. Identifying control variables associated with mass wasting, and gaining an understanding of how each variable will influence future processes with similar conditions (Soeters and van Westen 1996). This research used a combination of these known methods for hazard mapping.

Seven mass wasting hazard maps were created. The maps indicate places of likely future geomorphic hazards based on the spatial distribution of past geomorphic hazards. An overall mass wasting hazard map, two rockfall hazard maps, debris flow initiation hazard map, debris flow hazard map, avalanche hazard map, and translational slide hazard map were created. One rockfall hazard map was based solely on slope and the second was based on control variables found significant through the chi-square test.

Six of the mass wasting hazard maps were created using the landslide inventory approach, WOE approach, and the statistical approach (bivariate), the last mass wasting hazard map was based solely on slope angle. ArcGIS® was used to create a geomorphic hazard map, representing each control variable found significant to hazardous mass wasting processes. The statistical approach was used to determine where landslides are likely to occur in the future based on the landslide inventory map and weighting the control variables based on their likely contribution to the hazard (Soeters and van Westen 1996). If the control variable was found significant via the chi-square tests, the control variable was sorted into classes and assigned a value. Values of low = 1, moderate = 2, or high = 3 were assigned based on expected and observed values. A low value was assigned if the observed value was less than the expected value. A moderate value was assigned if the observed value was similar to the expected value. A high value was assigned if the observed value was greater than the expected value. Values were added to each control variable and the Raster Calculator Tool in ArcMap® was used to produce hazard maps for rockfalls, debris flows, avalanches and translational slides. The hazard maps were a result of the sum of control variable maps added together and divided into four equal classes. Four classes were created: very low hazard, low hazard, moderate hazard, and high hazard. A map of rotational slides was not produced because of the low number of rotational slides in the study area.

Because of the complexity of hydrological modeling and lack of sufficient data, no hazard map was created for floods. Areas that have flooded numerous times in the past are more likely to experience floods in the future and are more hazardous than areas that have never experienced a flood. Similarly, with times of the year, months that have experienced floods historically are likely to experience flooding again in the future.

Identifying possible GLOFs is generally done by identifying glacial lakes undergoing frequent change, and the existence of unconsolidated glacial till, colluvium, or snow dams (Bolch et al. 2011). Airphotos and research by Butler (1989) were used to identify any lakes in the study area that meet these two parameters.

Developing Trail Hazard Ratings

No method exists that quantifies and rates trails based on present hazards. This method was developed over the course of this research. Hazard ratings are based on exposure. The more hazards a visitor is exposed to, the more hazardous the trail. For each trail, the total mass wasting landforms, mass wasting-trail crossings, GLOF potential, stream-trail crossings, and trail lengths were recorded and hazards per kilometer were calculated for each trail, quantifying the number of exposures hikers are exposed to overtime. Trails were then evaluated based on types of hazards present and seasons associated with particular hazards. A high number of identified debris flow landforms on a trail make trails more hazardous during mid-summer months while a high number of identified floods and stream crossings make trails more hazardous during spring and early summer months.

Developing Management Recommendations

Educating recreational users of the area about hazards present in an area greatly increases awareness and subsequent safety. This report and associated maps provided to the National Park Service show areas of increased potential for geomorphic hazards based on past processes and variables. The management recommendation is in the form of a written report as well as an opportunity to present findings with park managers. With this information, park managers may educate and increase awareness to users of recreational trails that are modeled as having a potential for geomorphic hazard.

The National Park Service currently provides no literature regarding geomorphic hazards in Glacier National Park and ultimately, visitor safety, one of the agency's primary tasks (Dechano and Butler 2001). The management recommendations involved an analysis of the current management strategy of the National Park Service regarding trails and hazards to better serve the goals and mission put forward by the agency including better signage and literature as park visitors enter Glacier National Park.

CHAPTER V

RESULTS AND DISCUSSION

Mass Wasting Landforms

A total of 394 mass wasting landforms were identified and mapped through airphoto interpretation and field survey (Figure 12). The landforms totaled 13.4 km² and covered ~12.5% of the study area. The largest landform mapped totaled 396,323 m², while the smallest was 121 m² (Table 3). The smallest mapped landforms were identified through field work because they were not visible on airphotos. High densities of geomorphic features were found around cirque head walls, arêtes, and horns with steep, unstable slopes and readily available material. The landforms mapped are historic and prehistoric, with some features likely dating to the Holocene and late Pleistocene.

Rockfall

One hundred and forty-one rockfall taluses were identified and mapped, representing 13% of the total area of mass wasting landforms identified in the study area (Figure 13). Taluses ranged in size from 507 m² to 72,416 m². Landforms associated with rockfall included talus cones, talus aprons, and protalus ramparts. Taluses were typically found at the base of cliffs and were most common along the eastern edge of the Continental Divide. Most rockfall occurred at or below cliffs of the Helena Formation, located along the Continental Divide at high elevations. This coincides with Krautblatter and Dikau’s spatial pattern of rockfall at the foot of rock faces (2007). The Helena Formation is a thick limestone formation that creates many of the steep mountain walls within the Many Glacier Valley, including Mounts Gould, Grinnell, Allen, Wilbur, and

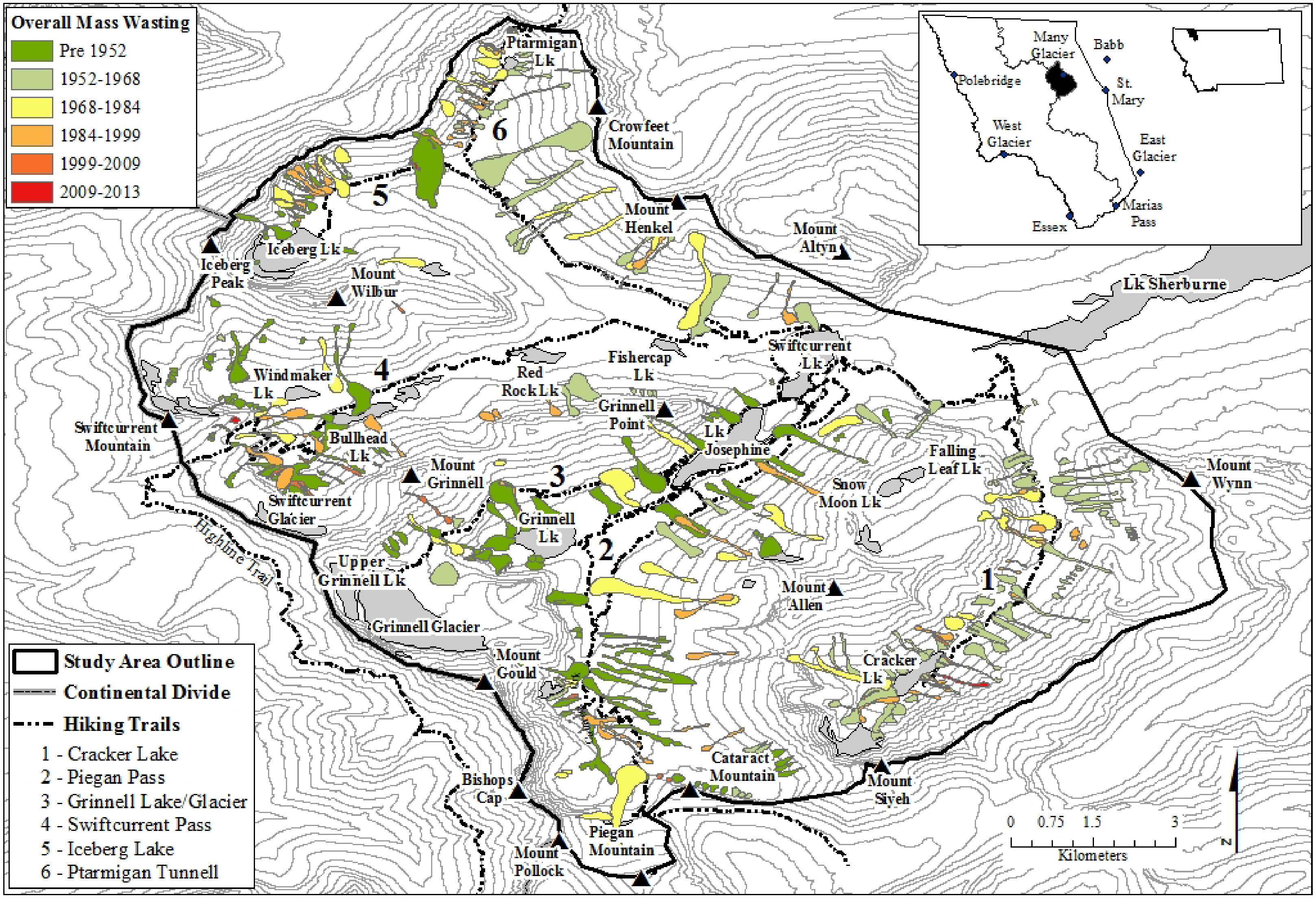

Figure 12. Overall mass wasting in the Many Glacier Valley.

Table 3

Descriptive Statistics for Geomorphic Features in the Many Glacier Valley.

Type	Total number	Total area (m^2)	Mean area (m^2)	Minimum area (m^2)	Maximum area (m^2)	Total mass wasting area (%)	Study Area (%)
Rockfall	141	1,797,762	12,750	507	72,416	13.4	1.8
Debris Flow	200	8,617,913	43,089	239	307,224	64.1	8.0
Slab Avalanche	25	2,538,584	1,01,543	19,591	3,966,323	18.9	2.3
Translational Slide	25	132,993	5319	121	85,281	1.0	0.1
Rotational Slide	3	341,783	113,928	89,150	144,152	2.5	0.3
Total	394	13,429,035	--	--	--	--	12.5

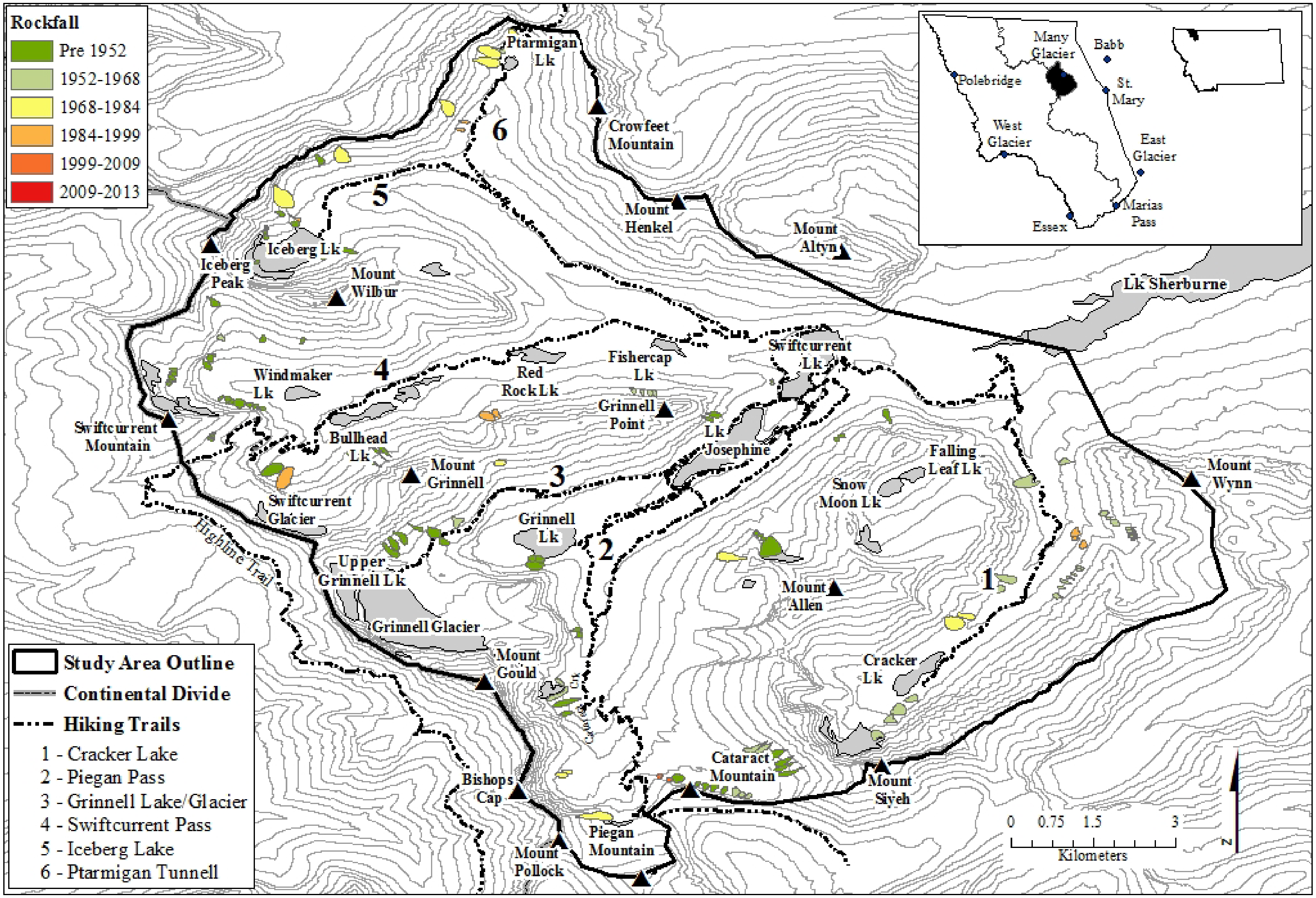

Figure 13. Rockfall distribution in the Many Glacier Valley

Henkel as well as portions of the Garden Wall (Dyson 1952). The trails most impacted by rockfall are Swiftcurrent Pass and Cracker Lake with 36 and 34 mapped taluses, respectively. These trails sit below many of the steep limestone cliffs mentioned above (Figure 14).

Figure 14. Talus apron below the Helena Formation and Swiftcurrent Glacier along the Continental Divide. Photo by author.

Debris Flows

Debris flows are the numerically and areally dominant mass wasting process in the Many Glacier Valley with a total of 200 identified and mapped, representing 64% of the total geomorphic features identified in the study (Figure 15). They totaled 8,617,913 m² or 8% of the study area (Table 3). Landforms associated with debris flows include

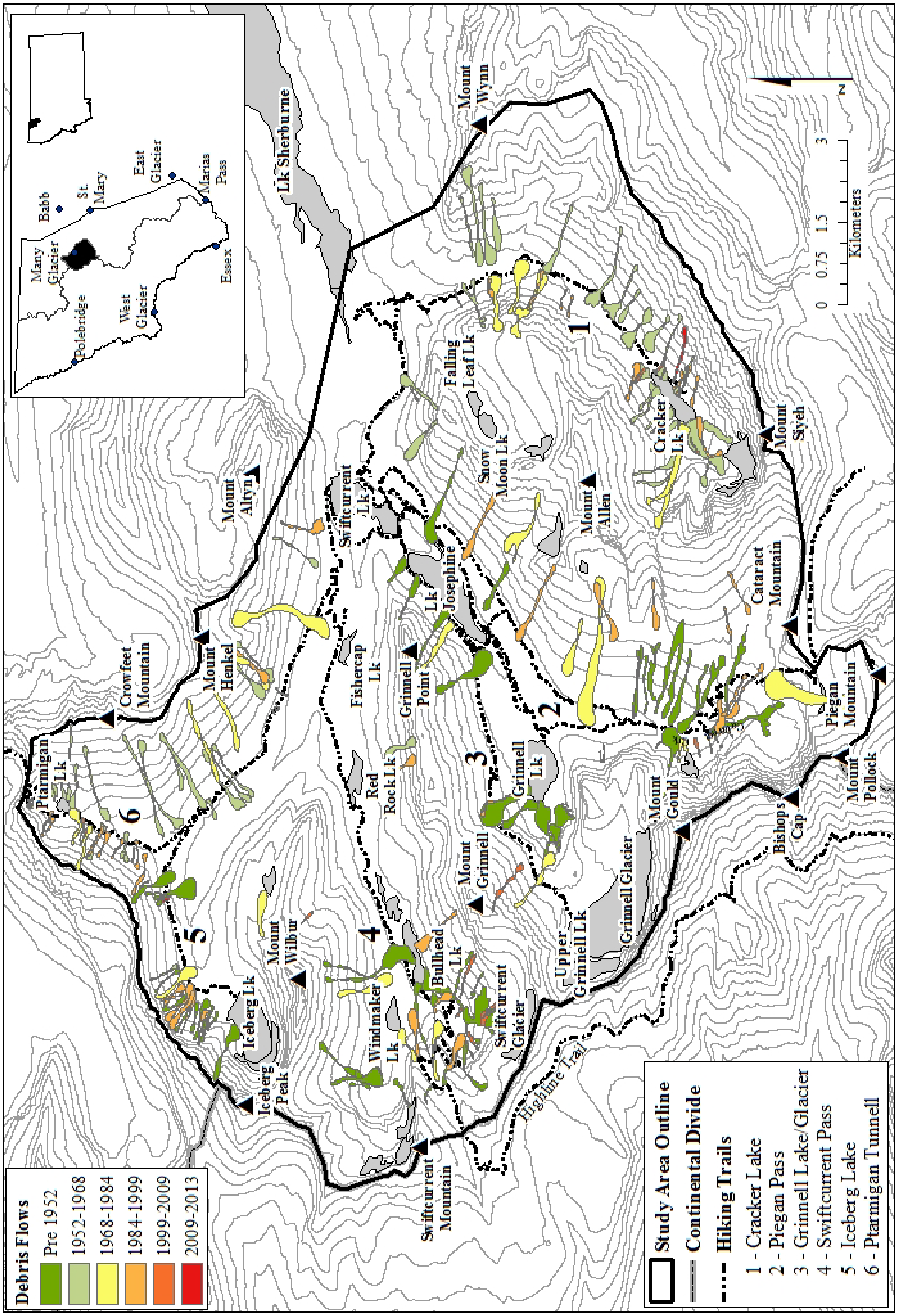

Figure 15. Debris flow distribution in the Many Glacier Valley.

a clear scarp, a channel, and a lobate toe deposit. Debris flows occurred in every basin of the Many Glacier Valley (Figure 15). The size of the debris flows ranged in size from 239 m^2 and 307,224 m^2. The smallest debris flow was identified in the field work and was not visible on airphotos. All flows started along valley walls and contribute to the current shapes of the lakes and streams (Figure 16). Debris flows naturally follow streams leading to lakes and ponds. Once a debris flow occurs in a location, it is likely to occur in the same location at a later date because the previous flow has already removed resistance along the path (Butler and Walsh 1990). As debris flows carry regolith

Figure 16. Debris flow fan contributing to the shoreline of Cracker Lake. Photo by author.

downslope, it is deposited as the slope decreases, often along lake shores, building and changing the shape of the shore (Figure 16). The trail most impacted by debris flows is the Cracker Lake trail, located in a basin surrounded on three sides by steep valley walls of limestone and argillite withreadily available regolith. This coincides with research conducted by Wilkerson (2004) and Wilkerson and Shmid (2008), noting the initiation zone at the break in slope at the base of cliffs where regolith is readily available from rockfall talus.

Slab Avalanches

Twenty-five slab avalanche features were mapped accounting for 18.9% of the total landforms identified in the study (Figure 17). Slab avalanche features ranged in area from 19,591 m^2 to 3,966,323 m^2. Slab avalanches are most common on slopes between 30 and 45º. Debris flows mapped in this research share a path with 56% of the mapped slab avalanche features in the study area (Figure 18). Landforms associated with slab avalanches include traves, levees, debris tails, boulder tongues, pits, and mounds. The trails most affected by slab avalanches are Cracker Lake and Piegan Pass with seven mapped slab avalanche features on each trail with three and seven which intersect the trail, respectively. This coincides with Butler's (1990) and Perla's (1977) research of snow avalanches with most snow avalanches occurring on slopes greater than 25º where snow is able to accumulate but becomes unstable with increased slope and subsequently more shear stress on the slope (Butler and Walsh 1990).

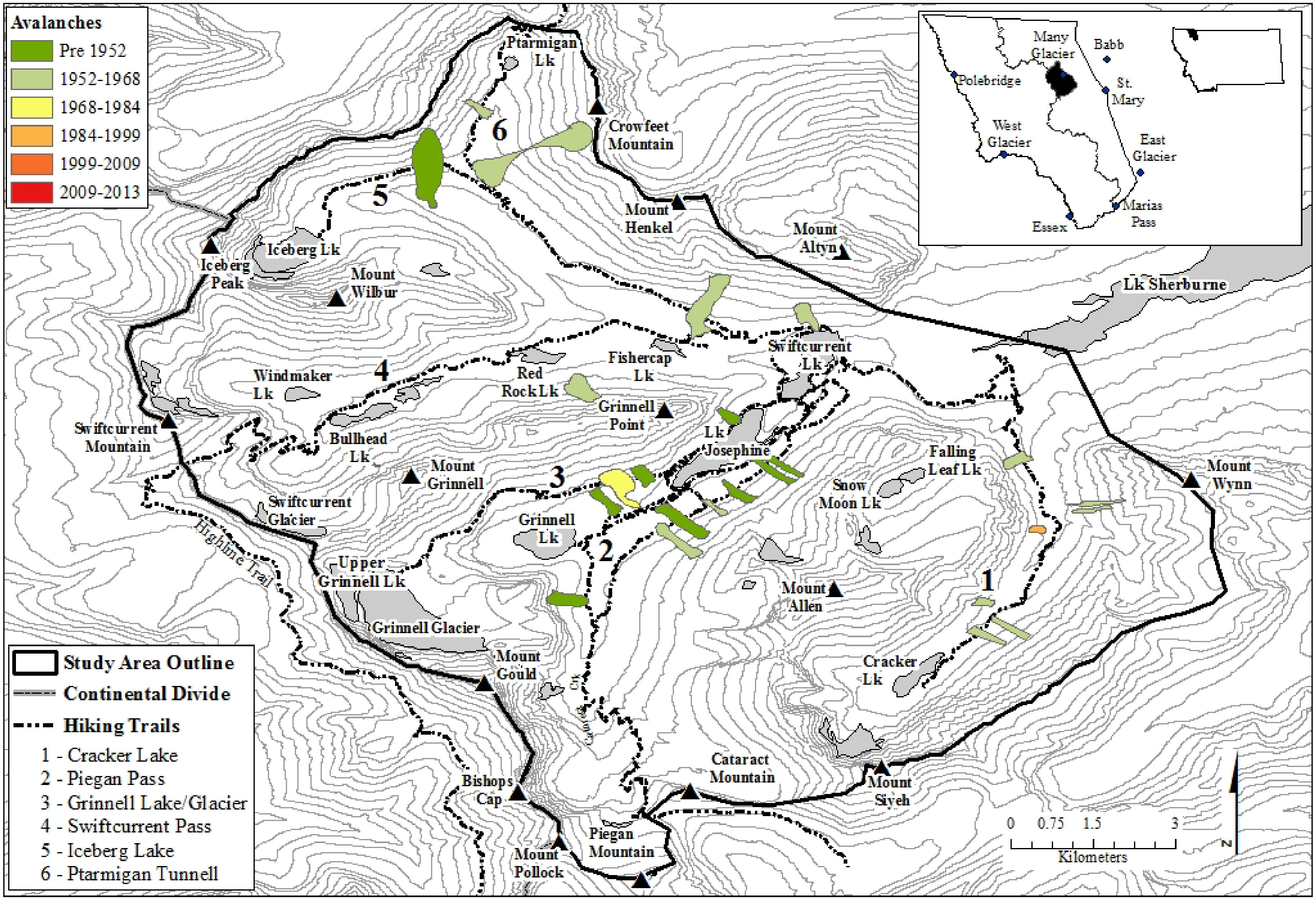

Figure 17. Slab avalanche distribution in the Many Glacier Valley.

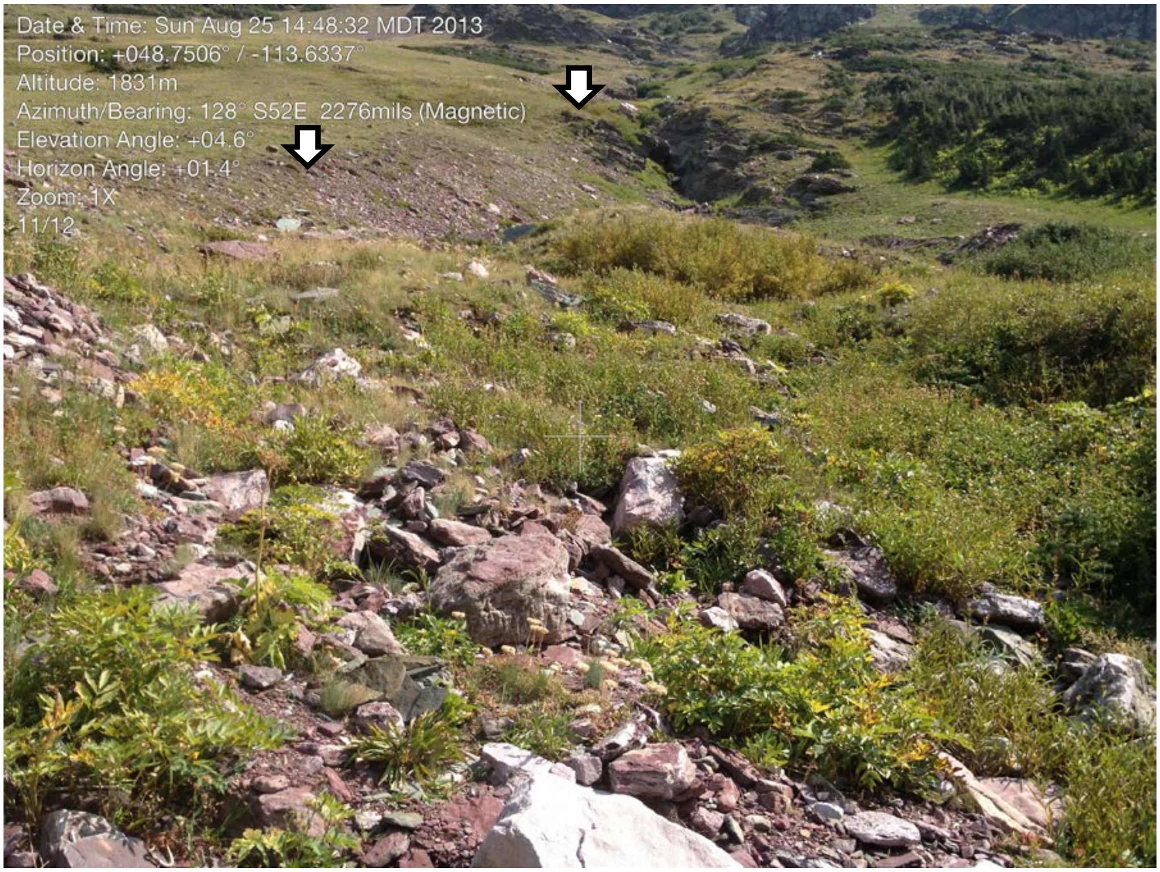

Figure 18. Slab avalanche levees along the Cracker Lake Trail. Photo by author.

Translational Slides

Translational slides accounted for 1% of the total mass wasting with a total of 25 landforms identified in the study (Figure 19). They were small in size ranging in area from 121 m² to 85,281 m², with an average size of 5,319 m². Most translational slides were found in the field along creek banks with linear scarps parallel to the slope (Figure 20). Most were composed of debris and were likely a result of wet weather. Landforms associated with translational slides include linear scarps and hummocky terrain. Translational slides are generally shallow and do not require saturation of regolith. The location of translational slides along creek banks coincides with literature regarding translational slides and wet weather (Ballantyne 1986, Szabó 2003). Wet weather events

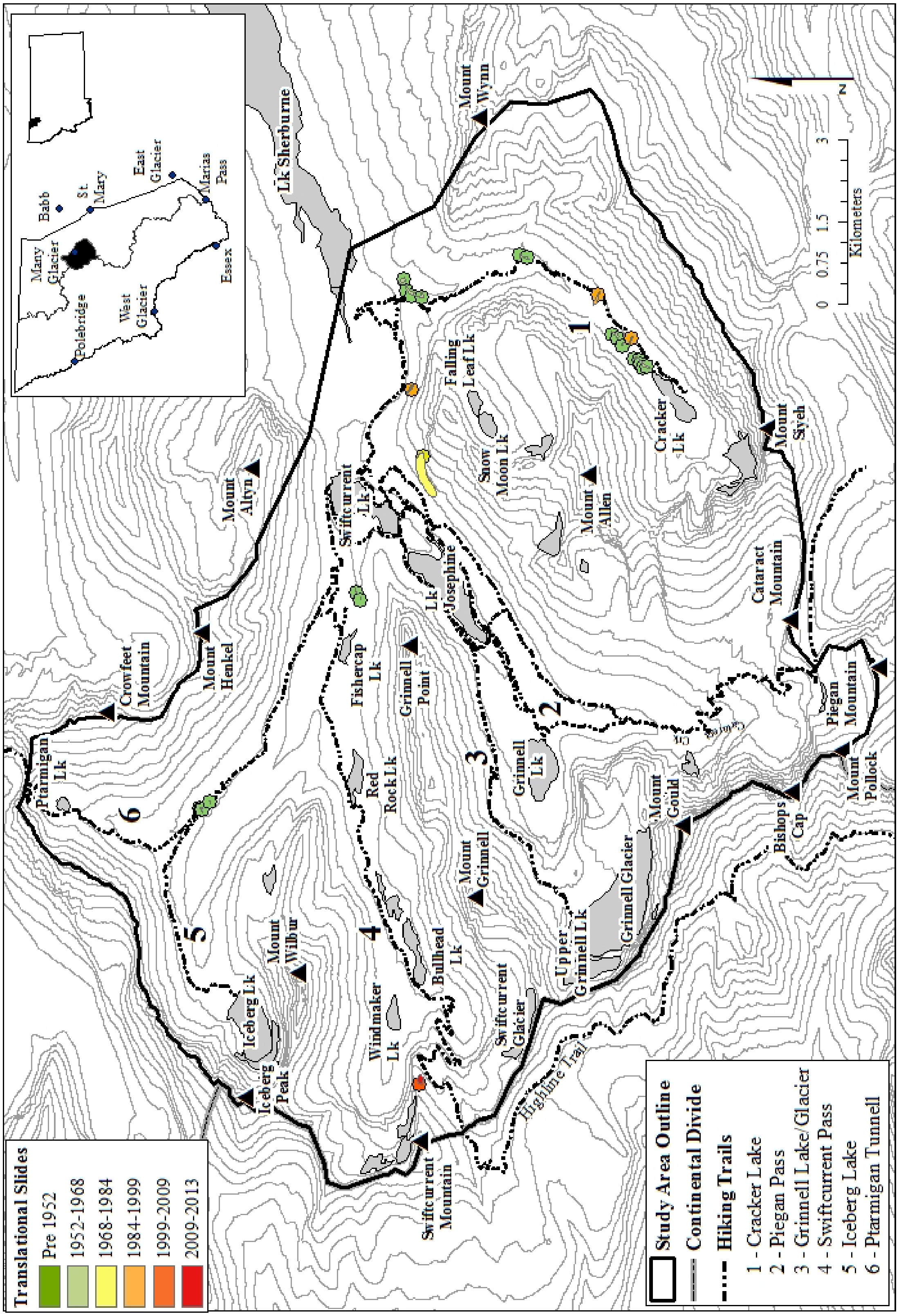

Figure 19. Translational slide distribution in the Many Glacier Valley.

raise the water level, creating peak flow events and increase the undercutting of slopes along stream and river banks, creating unstable slopes prone to sliding. The trail with the most mapped translational slides is Cracker Lake with 17. The trail follows Canyon Creek for almost the entire duration of the hike. Given that most translational slides were too small to be identified on airphotos and mapped in the field, it is likely that they are underrepresented in this study and are located along most major creeks in the Many Glacier Valley.

Figure 20. Linear scarps indicating a translational slide along Canyon Creek on the Cracker Lake Trail. Photo by author.

Rotational Slides

Three rotational slides were mapped accounting for 2.5% of the mass wasting identified in the study area (Figure 21). Rotational slides ranged in size from 89,150 m^2 to 144,152 m^2. The slides mapped in the study were dominantly characterized by hummocky topography, back tilted blocks, and obvious head scarps near the base of cliffs. All occurred near a moisture source such as streams, lakes, and/or perennial snowfields. The trail most affected by rotational slides is the Grinnell Lake/Glacier trail. The slides were not located on north facing slopes as past research in the park suggests but were located in areas known for late lying snow that often keeps the trail closed until well into July every year (Oelfke and Butler 1985).

Historical Geomorphic Processes

Using *Hungry Horse News* weekly newspaper, monthly ranger reports, and past research (Wilkerson 2004), I identified and mapped 34 mass wasting and flooding events that occurred in the Many Glacier Valley between 1940 and 2013 (Figure 22). These events were mapped as bands because of incomplete location data. Bands of likely occurrence were mapped (Figure 22). Some include more than one event (Table 5). Two main issues exist with written historical accounts; poor reporting and under reporting. The newspaper articles, ranger reports, and past research ranged greatly from being extremely detailed (including a map with location, size, and weather, size) to only a brief mention. In most cases, no specific location was given, hindering accurate mapping of events. Most event types needed to be interpreted because of misclassification. Interpretations relied heavily on the descriptions given, often leaving more questions than answers.

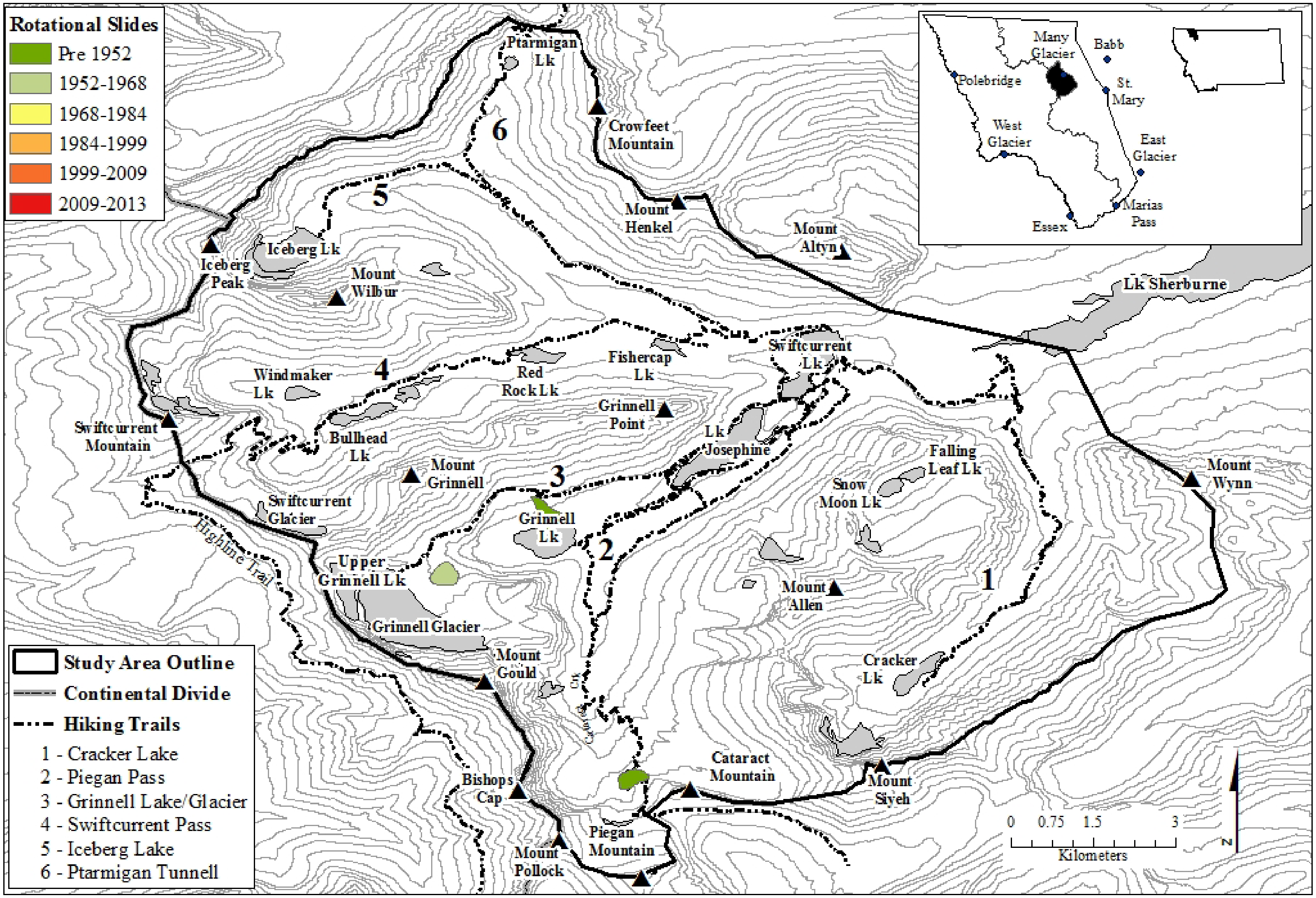

Figure 21. Rotational slide distribution in the Many Glacier Valley.

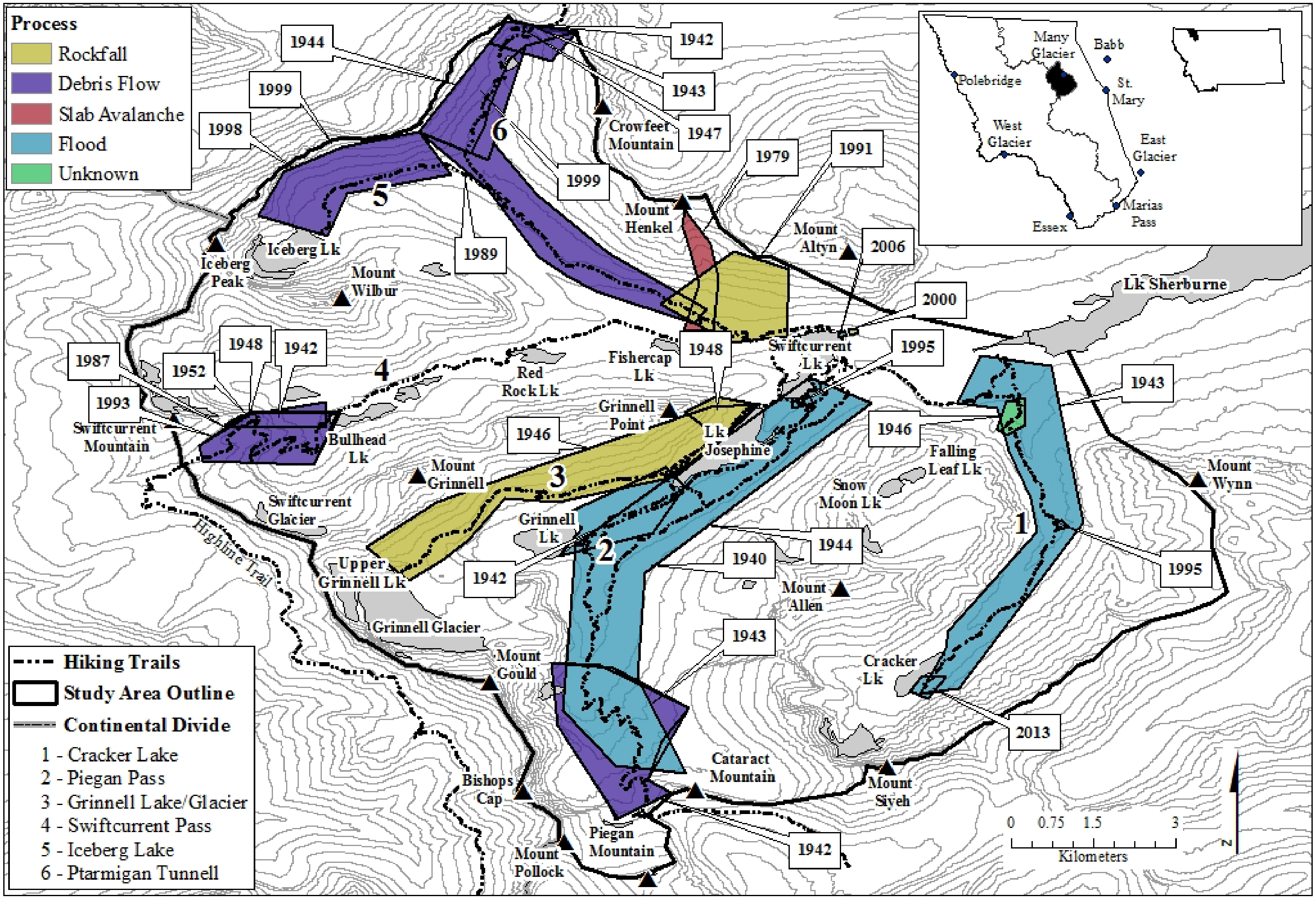

Figure 22. Distribution and geomorphic processes from historical records in the Many Glacier Valley.

The historical record of geomorphic events is undoubtedly incomplete and underestimates small events with no witnesses and/or damage. The Many Glacier Road closes every year around November and stays closed until around April, depending of snow conditions. Since the early 1950's, no park personnel has been stationed in the Many Glacier Valley year round, and no accounts of winter events have been recorded (Deirdre Shaw personal communication 2014). Because the Many Glacier Valley only has one road, events are rarely recorded unless they impact life or infrastructure. NPS trail crew regularly clears small slides and flows from the trails without recording any information (Dan Jacobsen, personal communication 2013). For example, a thunderstorm event occurring on August 6, 1999 initiated nine debris flows on the Iceberg Lake trail and 27 debris flows on the Ptarmigan Tunnel trail. These events were identified in this study through Forrest Wilkerson's past research (2004) as they occurred during his study, but were not mentioned in the local newspaper. There also seems to be gaps in newspaper articles regarding events. Newspaper articles addressing geomorphic hazards are non-existent between 1952 and 1979, but the 1940's have plenty of articles regarding mass wasting events and flooding. The Going-to-the-Sun-Road is closed almost yearly for rockfall, avalanches, and debris flows. Using the Going-to-the-Sun-Road as a proxy, it is evident these events happen regularly, but are not reported or witnessed.

Mass Wasting

Historical records identified 24 mass wasting processes in the Many Glacier Valley (Table 4). Five rockfall, 16 debris flows, one avalanche, one translational slide and one unknown process were identified and mapped (Figure 22).

Four out of five of the rockfalls identified occurred during late July and August with only one associated with a recorded heavy rain event. It is likely that rain occurred with all four as it is known that intense heavy rain is conducive to rockfall activity (Butler 1990, Krautblatter and Moser 2009). Butler (1990) identified three rockfall events, during the spring and summer of 1989, along roads in Glacier National Park that coincided with over three inches of rain in a three day period. The other recorded rockfall occurred during October when temperatures commonly fluctuate between freezing and non-freezing. These conditions are also conducive to rockfall activity (Luckman 1976, Butler 1990, Matsuoka and Sakai 1999). The most common trail for rockfall was Grinnell Glacier with two recorded occurrences.

All debris flows identified occurred during the months of July, August, and September. Four recorded heavy rain/thunderstorm events in 1942, 1948, 1952, and 1993 coincided with debris flow occurrence in the record. The weather for these events was included in the newspaper accounts. It is likely other debris flows coincided with rain events given the time of year recorded and large input of water required to trigger a debris flow (Nemčok Pašek, and Rybář 1972, Butler and Walsh 1994, Hungr et al. 2001, Wilkerson 2004). Four events classified as debris flows occurred in the same place along the switchbacks on the Swiftcurrent Pass Trail in 1942, 1948, 1952, and 1993. This indicates the likelihood of debris flows occurring in the same locations. All four events used plural language when describing the processes indicating more than one debris flow occurred on each noted date.

Table 4

Historical Mass Wasting in the Many Glacier Valley as Identified Through Newspaper Accounts, Park Reports, and Past Research.

Date of Event	Location/Trail	Event/Damage/Notes	Inferred Process	Source
5/1942	Swiftcurrent Pass	Slides damage 2 mile stretch	Debris Flow	NPS Ranger Reports
7/1942	Ptarmigan Tunnel	Slides, trail in need of repair	Debris Flow	NPS Ranger Reports
7/1942	Piegan Pass b/w Morning Eagle Falls and pass	Slides, trail in need of repair	Debris Flow	NPS Ranger Reports
7/1943	Ptarmigan Tunnel	Slide at the south end (occurred previous year also)	Debris Flow	NPS Ranger Reports
7/1943	Piegan Pass	Slides, trail in need of repair	Debris Flow	NPS Ranger Reports
10/1944	Ptarmigan Tunnel	Rockfall, large boulders removed from trail	Rockfall	NPS Ranger Reports
8/1946	Cracker Lake	Slide, trail washed out at switchbacks	Unknown	NPS Ranger Reports
8/1946	Grinnell Glacier Trail	Rockfall, rocks removed from trail, heavy rainfall	Rockfall	NPS Ranger Reports
8/1947	Throughout Many Glacier *	Earthslides, several occur during heavy rainfall, no specific location given	Debris Flow	NPS Ranger Reports

Table 4
(continued)

Date	Location/Trail	Event/Damage/Notes/ Etc.	Inferred Process	Source
9/1947	Ptarmigan Tunnel	Slides, near tunnel	Debris Flow	NPS Ranger Reports
6/1948	Throughout Many Glacier *	Earthslides, sinks, and washouts reported, no specific location given	Translational Slides	NPS Ranger Reports
7/1948	Swiftcurrent Pass	Slides, trail closed 2 days, 3 slides	Debris Flow	NPS Ranger Reports
7/30/1948	Grinnell Glacier, NE end of Josephine Lake	Rockfall, hiker injured	Rockfall	NPS Ranger Reports
8/1948	Swiftcurrent Pass at Devil's Elbow	Earthslide	Debris Flow	NPS Ranger Reports
8/7/1952	Swiftcurrent Pass	Mudslides	Debris Flow	NPS Ranger Reports
2/12/1979	Ptarmigan Tunnel	Avalanche on Mt Henkel near trailhead	Avalanche	NPS Ranger Reports
9/?/1984	Ptarmigan Tunnel	Rockslide buried 3 m of trail	Debris Flow	*Hungry Horse News*, Butler
8/2/1987	Swiftcurrent Pass	Rockfall, hiker seriously injured	Rockfall	*Hungry Horse News*, Butler
8/27/1989	Ptarmigan Tunnel	Slide, 5 meter section of trail buried, closed to horse travel	Debris Flow	*Hungry Horse News*, Butler

Table 4
(continued)

Date	Location/Trail	Event/Damage/Notes	Inferred Process	Source
8/?/1998	Iceberg Lake	Debris flows, thunderstorm initiates debris flows on Iceberg Lake trail	Debris Flow	Wilkerson
8/6/1999	Iceberg Lake/ Ptarmigan Tunnel	Debris flows, thunderstorm initiates 9 debris flows on Iceberg Lake trail and 27 on Ptarmigan Tunnel trail	Debris Flow	Wilkerson
8/10/2000	Swiftcurrent Falls	Rockfall, man killed by falling rock	Rockfall	*Hungry Horse News*

Note. *indicates event was not mapped because of lack of location information.

The avalanche identified and mapped was recorded with great detail. It occurred on February 12, 1979 on Mount Henkel at the trailhead of the Ptarmigan Tunnel Trail. The report outlined an exact location and noted a rain-on-snow event that coincided with the avalanche. Avalanches are common during rain-on-snow events when the snow becomes heavy and saturated with water (Thorn 1978, Butler 1986).

The translational slides had much less information and no location given. This was classified as translational size based on the small size, association near streams, and wet weather. One event could not be classified because of general lack of information.

Flooding

Ten floods were identified in the Many Glacier Valley through historical records (Table 5). Eight of the ten floods occurred in late spring/early summer when the area is experiencing annual snow melt, increased temperatures and steady precipitation (Figure 23). This is supported by Merz and Blöschl (2003), who differentiated flood type by control variables. These events fall into two categories, rain-on-snow events and snowmelt but are interrelated. The trails most impacted by flooding are Cracker Lake and Piegan Pass with three recorded floods each that caused damage. The remaining two flooding events occurred in the fall and early winter coinciding with seasonal cyclonic storm events.

Spatial and Temporal Variables

Temporal Variables

The timing of mass wasting and flooding is usually associated with weather events. The identification of mass wasting landforms through successive airphotos and written historical records can help link climate and weather to geomorphic events.

Most mass wasting landforms mapped were from the 1950-52 set of photos, but does not indicate increased activity because it was the first series of photos used in the study. Carrara and McGimsey (1981) and Carrara (1989) note a warm dry period between 1918 and 1943, leading to a rapid retreat in glaciers but not necessarily a spike in mass wasting. Following the warm, dry period glacial recession slowed (Carrara and McGimsey 1981). The climate shows a slightly wetter, cooler period after 1940 which should have been more conducive to mass wasting (Figure 23). Most mass wasting occurred between the 1950-52 and 1968 (Table 6). The climate associated with this time

Table 5

Historical Flooding in the Many Glacier Valley as Identified Through Newspaper Accounts, Park Reports, and Past Research.

Date	Location/Trail	Event/Damage/Notes/Etc.	Source
12/1940	Piegan Pass	Flooding, trail in bad shape from flooding	NPS Ranger Reports
5/1942	Swiftcurrent Pass	Flash floods damage 2 mile stretch	NPS Ranger Reports
5/1942	Grinnell Glacier	Flash Floods damage footbridge below Grinnell Lake	NPS Ranger Reports
7/1943	Cracker Lake	Flooding, trail in need of repair	NPS Ranger Reports
7/1944	Piegan Pass	Flooding	NPS Ranger Reports
6/1953	Throughout Many Glacier *	Flooding, damage to trails, no specific location given	NPS Ranger Reports
6/1964	Throughout Glacier National Park*	Flooding, damage to Hotel, trails, bridges	NPS Ranger Reports
5/15/1995	Piegan Pass Cracker Lake	Flooding, bridges washed out over Grinnell Creek on Piegan Pass and Canyon Creek on Cracker Lake	*Hungry Horse News*
11/8/2006	Throughout Many Glacier	Flooding, rain-on-snow event, major flooding, Swiftcurrent bridge under 4 feet of water, trail damage	*Hungry Horse News*
6/2013	Throughout Many Glacier	Flooding, Cracker Lake Campground Closed	*Hungry Horse News*

Note. *indicates flood was not mapped because of lack of location information.

Table 6

Mass Wasting Landforms Identified per Airphoto Set

Event Type	≤1950-52	1950-52 –1968	1968–1984	1984–1999	1999 –2011
Rockfall	70	44	13	9	3
Debris Flow	46	49	24	41	30
Slab Avalanche	10	13	1	1	0
Translational Slide *	0	0	1	3	0
Rotational Slides	2	1	0	0	0
Total	128	107	39	54	33

* Additionally, 22 small translational slides were mapped from field survey, with their age unknown

period was slightly wetter and cooler than normal. Glaciers actually increased in size during this time period (Figure 23) (Carrara and McGimsey 1981l, Pederson et al. 2004).

The glacially conditioned valley of Many Glacier has gone through rapid geomorphic change since the end of the last glacial maximum and more recently, the LIA in the 1850s. This research suggests that the landscape initially changed very rapidly with many mass wasting processes occurring before 1950. The cool and wet climate associated with the time period through the 1950s and 1960s was conducive to mass wasting and occurred higher rate through 1968. The rate of change has since slightly

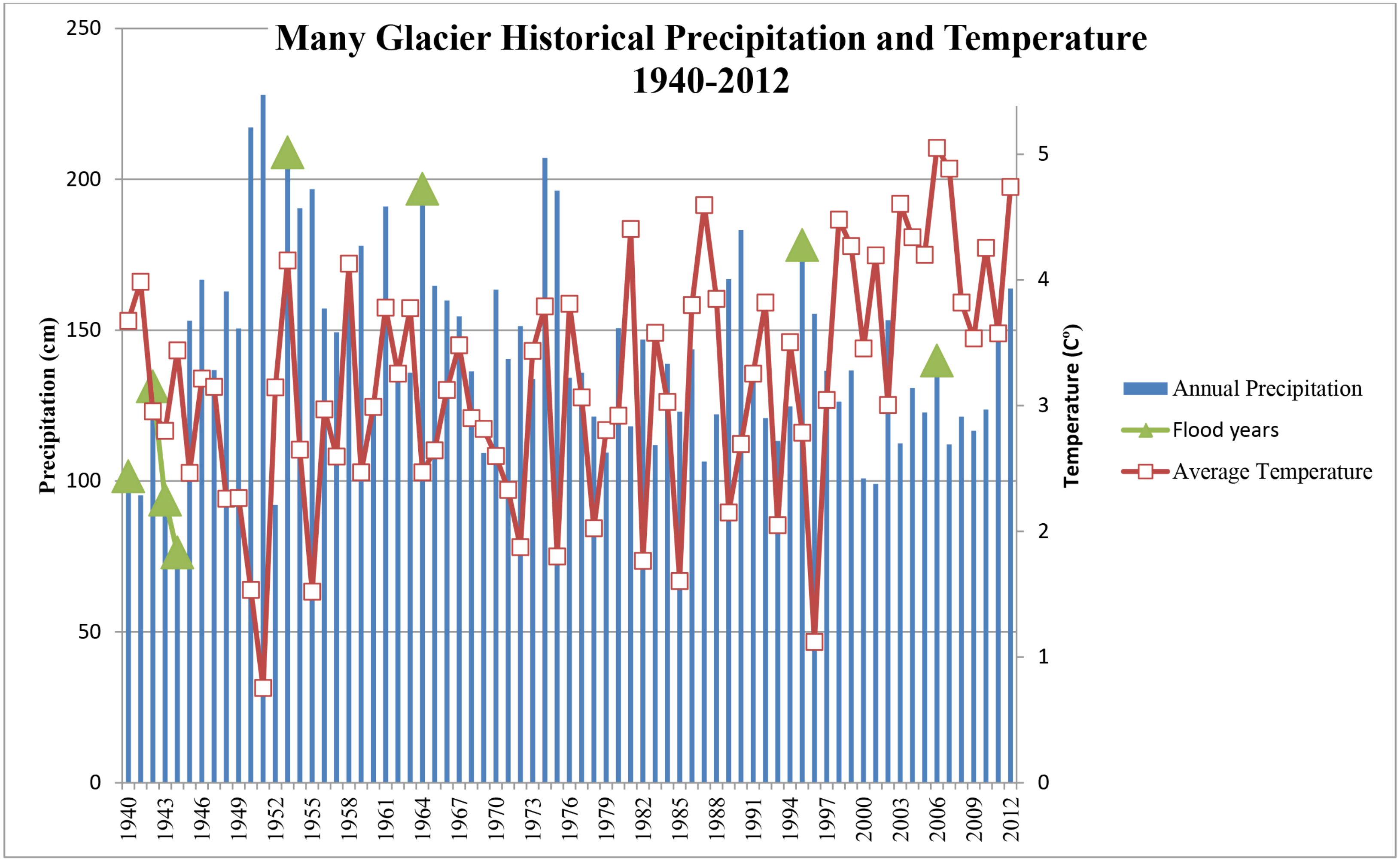

Figure 23. Historical precipitation and annual average temperature based on PRISM data for the Many Glacier Valley.

slowed for some proccesses, and corresponds with the warmer, drier period we are experiencing now. This suggests mass wasting is closely tied to precipitation and less to warmer temperatures associated with melting glaciers. Although the landscape is being exposed, the drier climate limits the amount of mass wasting occurring. Development of some landforms, such as taluses associated with rockfall have slowed and are relatively stable while debris flow landforms are still being produced at a relatively constant rate (Table 6). This may indicate some processes are more closely linked to climate and others are more closely linked to weather events.

It is possible that these processes are still occurring in the same places as first identified and therefore are underreported. For example, four debris flows were recorded in written historical record, having all occurred on the same section of the Swiftcurrent Pass Trail. The 1950-52 photos showed 128 landforms from geomorphic events but their age is unknown. It is very likely these landforms are late Pleistocene or early Holocene features and may be locations of current events using the same tracks, as they are the paths of least resistance.

The month with the most reported mass wasting in the Many Glacier Valley is August. In the written historical records, these are described as slides and flows and are often noted as experiencing heavy rainfall and/or thunderstorms. Eight mass wasting processes, occurring in July, August, or September were likely a result of heavy precipitation. Thunderstorms are common in August in late afternoon to early evening and increase over rugged terrain at high elevations (Finklin 1986). These are likely debris flows based on initiation and shape. The occurrence of debris flows remains relatively constant throughout the decades. The debris flows occurring on a regular basis in new locations as well as defined gullies and streams.

Written historical records (Park naturalist caught in freak hailstorm on Swiftcurrent trail 1993, Wilkerson 2004) show debris flows are mainly controlled by precipitation events. Short, intense summer thunderstorms are able to produce enough surface runoff to trigger debris flows. A *Hungry Horse Newspaper* article described an intense thunderstorm producing 2 inches of hail/rain within 2 hours, initiating 11 ‘slides’ on the Swiftcurrent Pass trail (12 August 1993). Although, the *Hungry Horse Newspaper* identified the events as slides, descriptions of the landforms (long gullies with levies and fans) and preceding weather indicated that these were debris flows. During a storm in August of 1999, a heavy rainstorm began around 2 pm, initiating several debris flows along the Iceberg Lake, Ptarmigan Tunnel trail in the Many Glacier Valley (Wilkerson 2004). A few hikers and one park ranger became stranded between two active debris flows on the Iceberg Lake trail during the 6 August 1999 thunderstorm. Overall, archival research was able to link seven likely debris flow events to heavy rainfall and/or thunderstorms.

Slab avalanches are most common in the winter during heavy snowfall, warming periods, and rain-on-snow events, and spring during snowmelt when the snow becomes saturated and heavy with water (Thorn 1978). Weather that produces wet snow “ripens” the snowpack, ultimately saturating the snow to the point of failure. Wet, heavy snow results in more shear stress as well as water at the base of the snowpack, decreasing shear strength. An account of a slab avalanche was recorded by a ranger in February 1979 along the cliffs of Mt. Henkel during a rain-on-snow event at the beginning of the Ptarmigan Tunnel trail, allowing the snow to ripen and saturate (NPS 1979).

Flood years recorded in park reports and archival newspaper articles note 1940, 1942, 1943, 1944, 1953, 1964, 1995, 2006, and 2013 as flood years in the Many Glacier Valley. Daily precipitation and temperature data is not available for flooding events recorded in 1940, 1942, 1943, or 1944, but inferences can be made about the annual precipitation those years. The years between 1940 and 1944 weren't particularly wet but the flooding recorded during those years could be a result of heavy precipitation events or the ranger writing the reports being extremely thorough in damage done annually by spring melt. El Niño years correspond with 1940, 1942, and 1964 flood years.

Daily precipitation and temperature data is available for flooding events in 1953, 1964, 1995, 2006, and 2013. On the 3rd and 4th of June 1953, the area received 7.5 cm of precipitation in 48 hours leading to flooding and damage to trails. On the 7th and 8th June 1964, the area received significant rainfall across this portion of the state June with over 10cm of rain within a 48 hour period. Flooding was prevalent throughout northwestern Montana leading to significant damage across the state (Figure 5). In May of 1995, the area received 11 cm of rain in a 72 hour period on the 6th, 7th, and 8th. Bridges and trails were washed out. In June of 2013, 6.8 cm of rain fell on the 19th and 20th leading to flooding and subsequent damage. These four floods likely all had antecedent high streamflow, were experiencing snowmelt, and abundant soil moisture and were combined with intense high volume rains that lead to widespread flooding (Boner and Stermitz 1967). This was likely a rain-on-snow event at higher elevations, leading to rapid snowmelt and subsequent flooding. The written historical records note most flooding happened during the months of May and June coinciding with the wet season and annual snowmelt (Table 6). Flooding occurs annually in almost every basin during the spring, especially May and June, when snow is melting and precipitation is heavy but can be disastrous when combined with other factors (National Park Service 1942a, 1942b, 1943, 1944, 1953, 1964, Rain washes away park bridges 1995). Flooding has also been recorded in the fall during cyclonic storm events (National Park Service 1940, Road heavily damaged on west side, completely gone near east side tunnel 2006). In November of 2006, 18.5 cm of rain fell on the 6th and 7th, leading to widespread flooding and damage to bridges and trails (NRCS 2014).

Spatial Variables

Overall Mass Wasting Spatial Variables

Overall, spatial control variables differed among all forms of geomorphic events. For all events combined, the spatial control variables found to be significant included elevation, slope angle, slope aspect, lithology, vegetation coverage, vegetation type, and distance to surface water (Table 7).

Elevations between 2000 and 2500 m accounted for 59% of all events. Elevation is considered an indirect factor because of slope angles present at these elevations. Slope angles greater than 31° accounted for 83% of all events mapped in the inventory.

Slope aspect played a significant role in the spatial occurrence of geomorphic hazards with 57% occurring on northern and eastern slopes. This is likely attributed to the combination of the steep walls of the continental divide (east facing) and the location of cirque walls (north and east facing) in the Many Glacier Valley.

Table 7

Controlling Variables Analyzed for Overall Mass Wasting in the Many Glacier Valley

Control Variable	Class %	Hazard Rating	χ^2
Elevation			57.85*
<2000 meters	37	1	
2000-2500 meters	59	3	
>2500 meters	3	1	
Slope Angle			265.18*
0-15 degrees	5	1	
16-30 degrees	12	1	
31-45 degrees	43	3	
>45 degrees	40	3	
Slope Aspect			42.86*
North	24	2	
East	34	3	
South	20	1	
West	22	1	
Lithology			67.87*
Alluvium	.2	1	
Colluvium	.2	1	
Till	1.2	1	
Landslide Deposit	1	2	
Altyn Formation (Limestone)	1.2	1	
Appekunny Formation (Shale and Argillite)	22.3	3	
Grinnell Formation (Argillite)	26.4	2	
Empire Formation (Argillite)	13.5	2	
Helena Formation (Limestone)	30.7	3	
Snowslip Formation (Argillite)	2.7	2	

Table 7 (continued)

Control Variable	Class %	Hazard Rating	$\chi 2$
Vegetation Coverage			50.4*
60-100%	9	1	
25-60%	40.6	2	
10-25%	15.7	3	
0-10%	34.2	3	
Vegetation Type			66.27*
Alpine Tundra	28.6	3	
Subalpine Zone	36.5	3	
Montane Forests	22.5	1	
Aspen Parklands	6.8	1	
Non-vegetated	4.3	1	
Distance to Surface Water			402.77*
<50 meters	48	3	
>50 meters	52	1	

Note. *indicates significant results. χ^2 = Chi Square Value. 1 = Low Hazard, 2 = Moderate Hazard, 3 = High Hazard. N = 394. P = .05

The Appekunny and Helena Formations were found to be most prone to hazard, accounting for 53% of mapped events. The limestones of the Helena Formation creates large amounts of talus, providing material for mass wasting events. Both are found along the steep rocky cliffs of the study area.

Approximately 50% of the mapped events occurred on areas with 25% or less vegetation cover. Roots from vegetation provide stability to slopes, and with less root strength, slopes are subsequently less stable and prone to mass wasting. The vegetation types associated with high hazard ratings are alpine tundra and subalpine zone, with 65%

of events occurring on the combination of these vegetation types. Alpine tundra vegetation generally has shallow roots, and occurs on rocky talus, scree fields, and bedrock above the upper treeline. They are associated with sparse vegetation coverage of no more than 25% (Faber-Langendoen et al. 2011). The subalpine zone refers to low to moderate cover forbs and grasses occurring above the upper treeline. They are generally exposed areas controlled by late lying snow, wind, permafrost, and a short growing season.

Rockfall Spatial Control Variables

The control variables found to be significant to rockfall included elevation, slope angle, slope aspect, lithology, and vegetation type (Table 8). Elevations above 2000 m accounted for 74% of all rockfall events. Elevation is considered an indirect factor because of slope angles present at these elevations. Slope angles greater than 31° accounted for 97% of all rockfall. The most important variable associated with rockfall is slope angle. Open, steep cliff faces are essential for rocks to fall freely through the air, ultimately accumulating at the base in the form of talus cones and aprons (Hungr et al. 2001). Without a steep slope angle other control variables would not contribute to rockfall events. The glacially eroded, U-shaped valleys in the study area provide nearly vertical slopes prone to rockfall activity.

Slope aspect played a significant role in the spatial occurrence of geomorphic hazards with 63% occurring on northern and eastern slopes. This is unexpected, south facing slopes are expected to have higher instances of rockfall associated with larger daily temperature fluctuations (Luckman 1976). This is likely attributed to the

Table 8

Controlling Variables Analyzed for Rockfall in the Many Glacier Valley

Control Variable	Class %	Hazard Rating	χ^2
Elevation			51.95*
<2000 meters	26	1	
2000-2500 meters	71	3	
>2500 meters	3	2	
Slope Angle			283.08*
0-15 degrees	.7	1	
16-30 degrees	2	1	
31-45 degrees	33	2	
>45 degrees	64	3	
Slope Aspect			25.17*
North	28	2	
East	35	3	
South	13	1	
West	23	2	
Lithology			69.42*
Alluvium	0	1	
Colluvium	0	1	
Till	0	1	
Landslide Deposit	0	1	
Altyn Formation (Limestone)	.7	1	
Appekunny Formation (Shale and Argillite)	24	3	
Grinnell Formation (Argillite)	14	1	
Empire Formation (Argillite)	13	2	
Helena Formation (Limestone)	41	3	
Snowslip Formation (Argillite)	6	3	

Table 8 (continued)

Control Variable	Class %	Hazard Rating	χ^2
Vegetation Coverage			49.34*
60-100%	2	1	
25-60%	40	2	
10-25%	23	3	
0-10%	35	3	
Vegetation			50.62*
Alpine Tundra	34	3	
Subalpine Zone	39	3	
Montane Forest	24	1	
Aspen Parkland	1	1	
Non vegetated	2	1	

Note. *indicates significant results. χ^2 = Chi Square Value. 1 = Low Hazard, 2 = Moderate Hazard, 3 = High Hazard. N = 141. P = .05

combination of the steep walls of the Continental Divide (east facing) and the location of cirque walls (north and east facing) in the Many Glacier Valley.

The shale and argillite of the Appekunny Formation and the Helena limestone were found most prone to hazard, accounting for 65% of rockfall. Both formations form the steep, nearly vertical rocky cliffs of the study area.

Approximately 57% of rockfalls occurred on areas with 25% or less vegetation cover. Roots from vegetation provide stability to slopes, and with less root strength, slopes are subsequently less stable and prone to mass wasting (Roering et al. 2003). The vegetation types associated with high hazard ratings are alpine tundra and subalpine zones, with 73% of events occurring on one of these vegetation types. They are generally exposed areas controlled by late lying snow, wind, permafrost, and a short growing season. Alpine tundra vegetation is associated with sparse vegetation coverage of no more than 25% (Faber-Langendoen et al. 2011).

Historical records of rockfall events are limited, with only five occurring in the historical record. The remoteness of the study area creates a situation where it is only reported if it harms property or injures a person. For this reason, rockfall in the Many Glacier Valley is highly underestimated and occurs in every basin in the study area. The trail with the most reported rockfall is the Grinnell Glacier Trail with two reported events. This trail sits below the glacially conditioned, steep cliffs of the Grinnell Formation, composed of red argillite.

Debris Flow Spatial Control Variables

Elevation, slope angle, slope aspect, vegetation coverage, vegetation type, and distance to surface water significantly contributed to the spatial pattern of debris flows in the study area. Elevations between 2000 m and 2500 m were significant to debris flows, with 64% initiating on these slopes (Table 9). Given the U-shape of the valleys, elevations above 2000 meters generally have higher slope angles, that are more prone to mass wasting. Slope angles above 31 degrees were significant to debris flows, with 79% initiating on these slopes.

East facing slopes were found to be significant to debris flow occurrence with 32% of debris flows occurring on these slopes. This is likely attributed to the combination of the steep walls of the Continental Divide (east facing) and the location of cirque walls (north and east facing) in the Many Glacier Valley that often have late lying snow, where water is able to mobilize regolith during rain-on-snow events.

Table 9

Controlling Variables Analyzed for Debris Flows in the Many Glacier Valley

Control Variable	Class %	Hazard Rating	$\chi2$
Elevation			43.89*
<2000 meters	33	1	
2000-2500 meters	64	3	
>2500 meters	3	1	
Slope Angle			90.75*
0-15 degrees	5	1	
16-30 degrees	16	1	
31-45 degrees	50	3	
>45 degrees	29	3	
Slope Aspect			20.00*
North	20	1	
East	32	3	
South	27	2	
West	21	1	
Vegetation Coverage			21.27*
60-100%	9.5	1	
25-60%	40.5	2	
10-25%	14	3	
0-10%	36	3	
Vegetation Type			34.06*
Alpine Tundra	29.5	3	
Subalpine Zone	36	3	
Montane Forest	19.5	1	
Aspen Parkland	8.5	1	
Non vegetated	6	2	

Table 9 (continued)

Control Variable	Class %	Hazard Rating	χ^2
Distance to Surface Water			
<50 meters	58	3	334.97*
>50 meters	42	1	

Note. *indicates significant results. χ^2 = Chi Square Value. 1 = Low Hazard, 2 = Moderate Hazard, 3 = High Hazard. N = 200. P = .05

Slopes with 25% or less vegetation coverage were found to be significant to debris flows, with 50% of debris flows occurring in these low coverage areas. Vegetation type is significant to debris flows, with 65% occurring on alpine tundra and subalpine areas lacking root strength on steep slopes and decreasing slope shear strength (Roering et al. 2003).

Distance to surface water was extremely significant with 58% of debris flows occurring within 50 meters of surface water. Surface water, especially streams, are in concave basins that are capable of concentrating runoff and provide confined paths for debris to flow (Nemčok et al. 1972, Baeza and Corominas 2001, Hungr et al. 2001).

Lithology was tested and found not significant to the spatial pattern of debris flows. Most debris flows occurred below large cliffs of argillite and limestone, and appeared to be more of a function of debris supply (taluses) and not debris type (Wilkerson 2004).

Avalanche Spatial Control Variables

Slope angle, lithology, and distance to surface water were found to be significant for the spatial distribution of avalanches (Table 10). Slope angles between 31 and 45º account for 68% of avalanches in the inventory. Slopes steeper than 45ºcannot maintain sufficient snowcover for avalanche development and slopes under 31º are generally stable. This is slightly different from Butler and Walsh (1990) findings of avalanche tracks on slopes between 25 and 35º in Glacier National Park, but correspond with Perla and Martinelli (1978) who found a pattern of avalanches on slopes between 30 and 45º. Avalanche tracks are evenly distributed across slope aspect, meaning observed and expected values were similar and therefore insignificant. There are slightly more on the south facing slopes versus north facing slopes. This is normal and attributed to the amount of sun south facing slopes receive versus north facing slopes.

The Appekunny and Grinnell formations account for 88% of avalanches in the study area. The Appekunny and Grinnell formations include many couloirs along the lateral margins of dikes, forming natural conduits for avalanches (Butler and Walsh, 1990). The Appekunny and Grinnell formations lie just below steep cliffs that are unable to maintain snowcover.

Surface water, especially streams, create natural conduits for avalanches. The distance to surface water plays a significant role in avalanche path location, with 68% of avalanche tracks within 50 meters of surface water location.

Table 10

Controlling Variables Analyzed for Slab Avalanches in the Many Glacier Valley

Control Variable	Class %	Hazard Rating	χ^2
Slope Angle			22.72*
0-15 degrees	0	1	
16-30 degrees	8	1	
31-45 degrees	68	3	
>45 degrees	24	2	
Lithology			44.148*
Alluvium	0	1	
Colluvium	0	1	
Till	0	1	
Landslide Deposit	0	1	
Altyn Formation (Limestone)	0	1	
Appekunny Formation (Shale and Argillite)	64	3	
Grinnell Formation (Argillite)	24	2	
Empire Formation (Argillite)	0	1	
Helena Formation (Limestone)	12	2	
Snowslip Formation (Argillite)	0	1	
Distance to Surface Water			62.34*
<50 meters	68	3	
>50 meters	32	1	

Note. *indicates significant results. χ^2 = Chi Square Value. 1 = Low Hazard, 2 = Moderate Hazard, 3 = High Hazard. N = 25. P = .05

Translational Slide Spatial Control Variables

Slope aspect, lithology, and distance to surface water were found to be significant to translational slide occurrence (Table 11). East facing slopes accounted for 48% of translational slides in the study area. The Appekunny formation accounted for 44% of translational slides in the study area. Eighty-eight percent of all translational slides were within 50 m of surface water.

Most mapped translational sides occur along the banks of streams. These streams cut through stream banks, creating oversteepened slopes prone to landsliding. Literature regarding translational slides points to wet weather events as a key factor to translational slide occurrence (Cruden and Varnes 1996). Wet weather raises the water level, creating peak flow events and increasing the undercutting of slopes along stream and river banks.

Spatial Patterns of Geomorphic Hazards

Seven hazard maps were created for the Many Glacier Valley. Six hazard maps were created using the bivariate statistical approach. These include overall mass wasting hazard, debris flow initiation hazard, debris flow hazard, avalanche hazard, rockfall hazard, and translational slide hazard. The last hazard map was a rockfall hazard map based on slope only (Figures 24 – 30). For the bivariate statistical approach, a combination of landslide inventory, WOE, and statistical approach is employed (Table 12).

Table 11

Controlling Variables Analyzed for Translational Slides in the Many Glacier Valley

Control Variable	Class %	Hazard Rating	χ^2
Slope Angle			5.03
0-15 degrees	40	2	
16-30 degrees	36	2	
31-45 degrees	16	1	
>45 degrees	8	2	
Slope Aspect			14.26*
North	24	2	
East	48	3	
South	4	1	
West	24	2	
Lithology			54.81*
Alluvium	0	1	
Colluvium	0	1	
Till	8	2	
Landslide Deposit	16	2	
Altyn Formation (Limestone)	12	2	
Appekunny Formation (Shale and Argillite)	44	3	
Grinnell Formation (Argillite)	16	1	
Empire Formation (Argillite)	10	1	
Helena Formation (Limestone)	4	1	
Snowslip Formation (Argillite)	0	1	
Distance to Surface Water			153.2*
<50 meters	88	3	
>50 meters	12	1	

Note. *indicates significant results. χ^2 = Chi Square Value. 1 = Low Hazard, 2 = Moderate Hazard, 3 = High Hazard. N = 25. P = .05

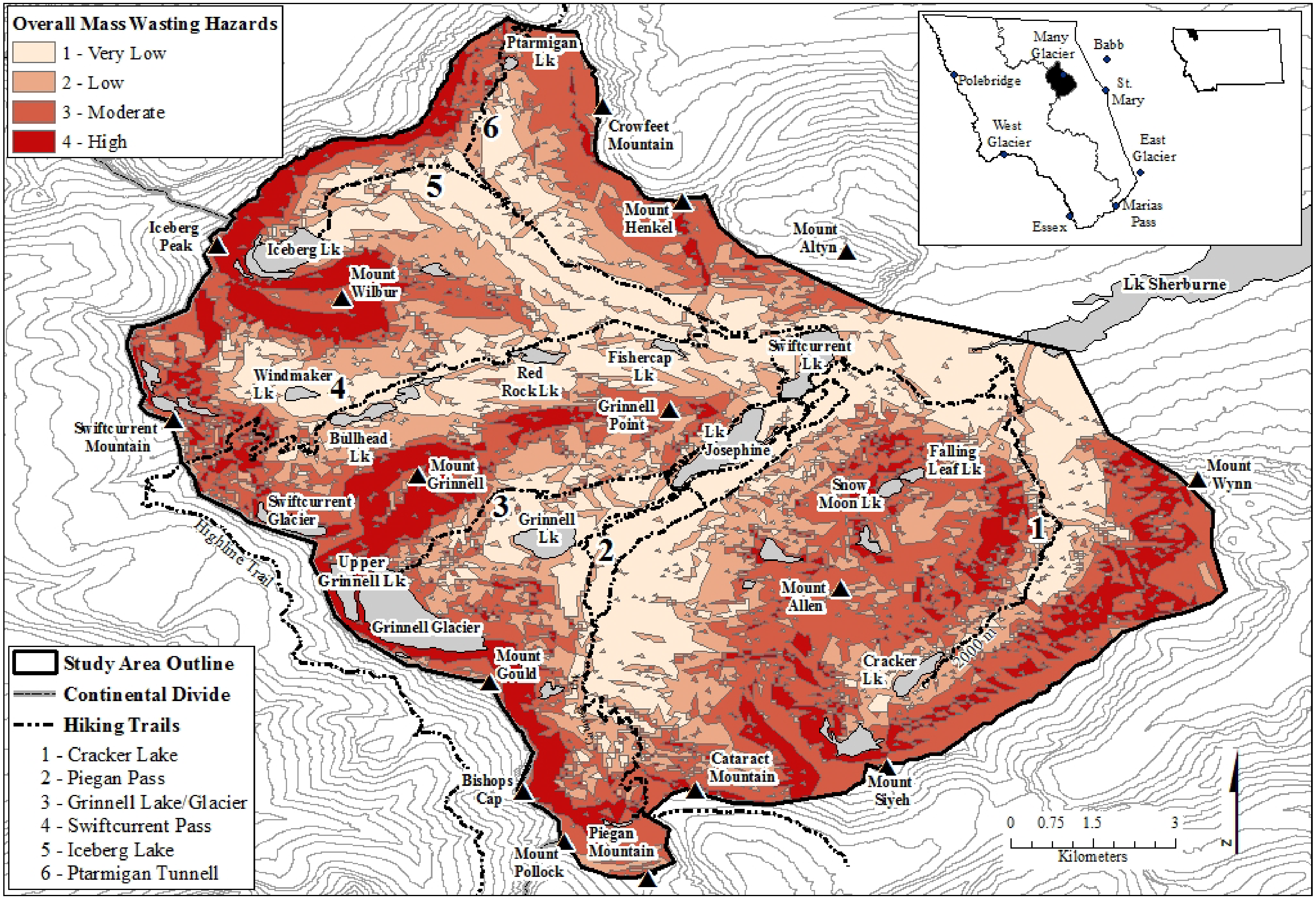

Figure 24. Overall mass wasting hazard map for the Many Glacier Valley.

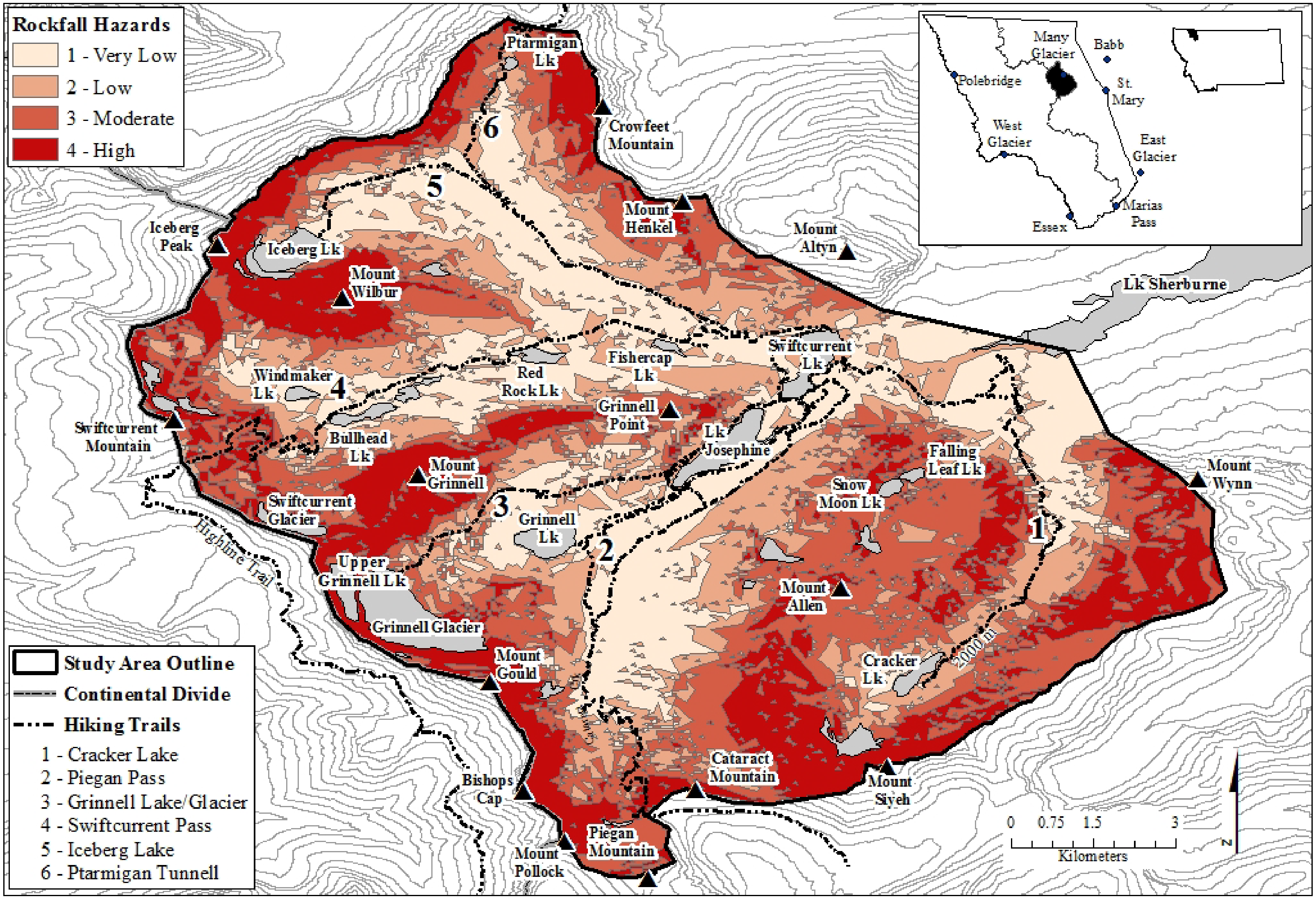

Figure 25. Rockfall hazard map for the Many Glacier Valley

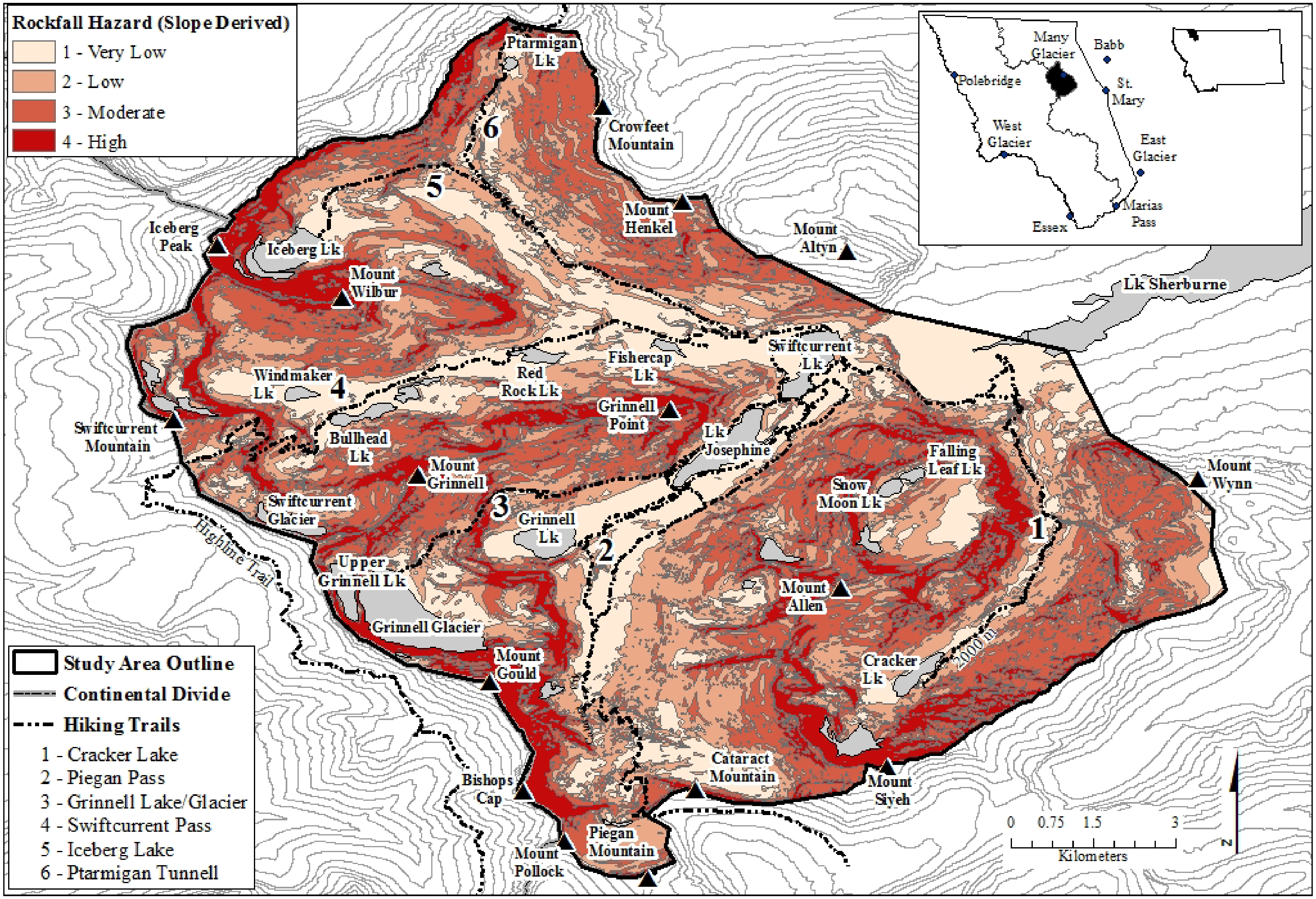

Figure 26. Rockfall hazard map based on slope angle for the Many Glacier Valley

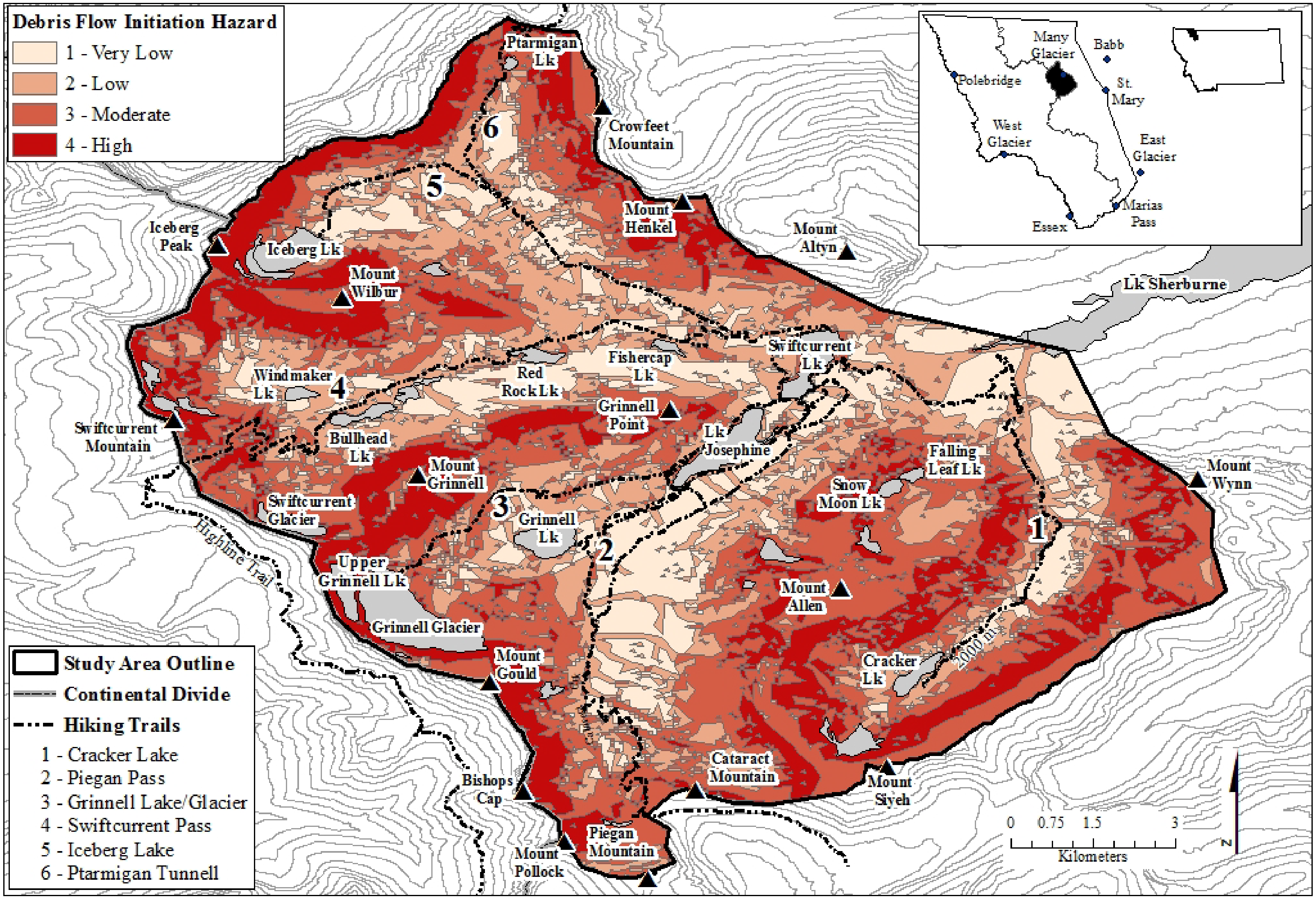

Figure 27. Debris flow initiation hazard map for the Many Glacier Valley.

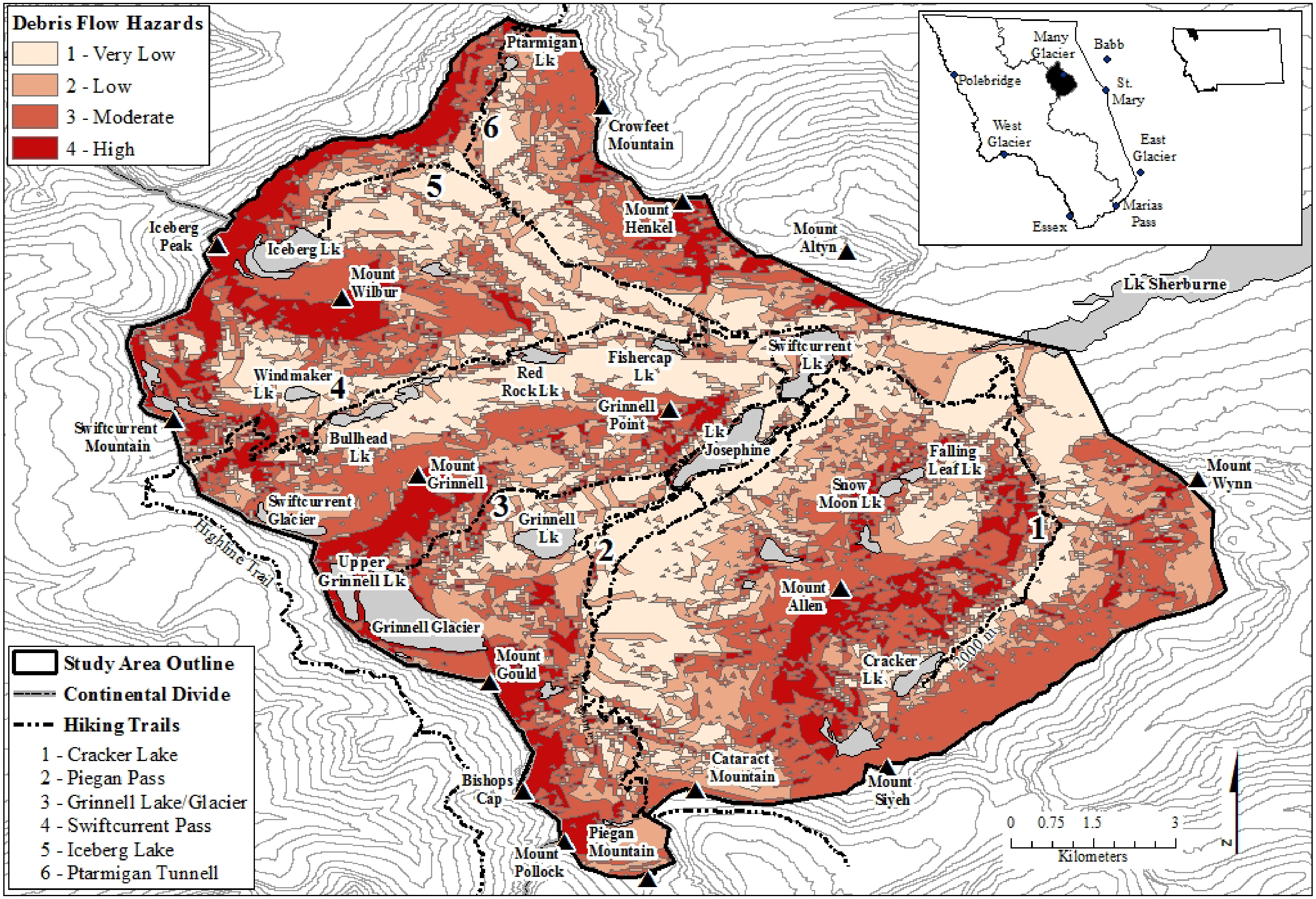

Figure 28. Debris flow hazard map for the Many Glacier Valley.

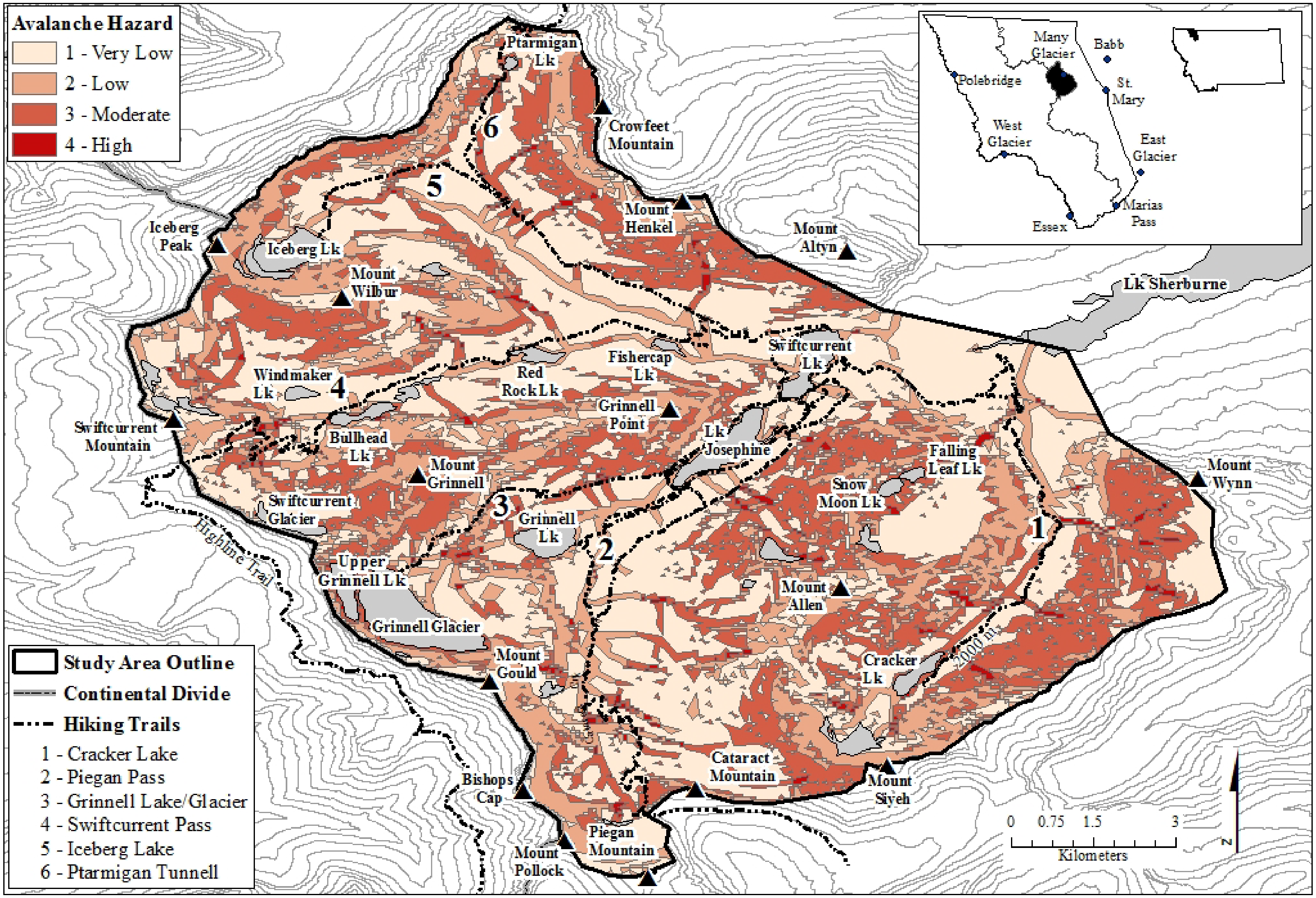

Figure 29. Slab avalanche hazard map for the Many Glacier Valley.

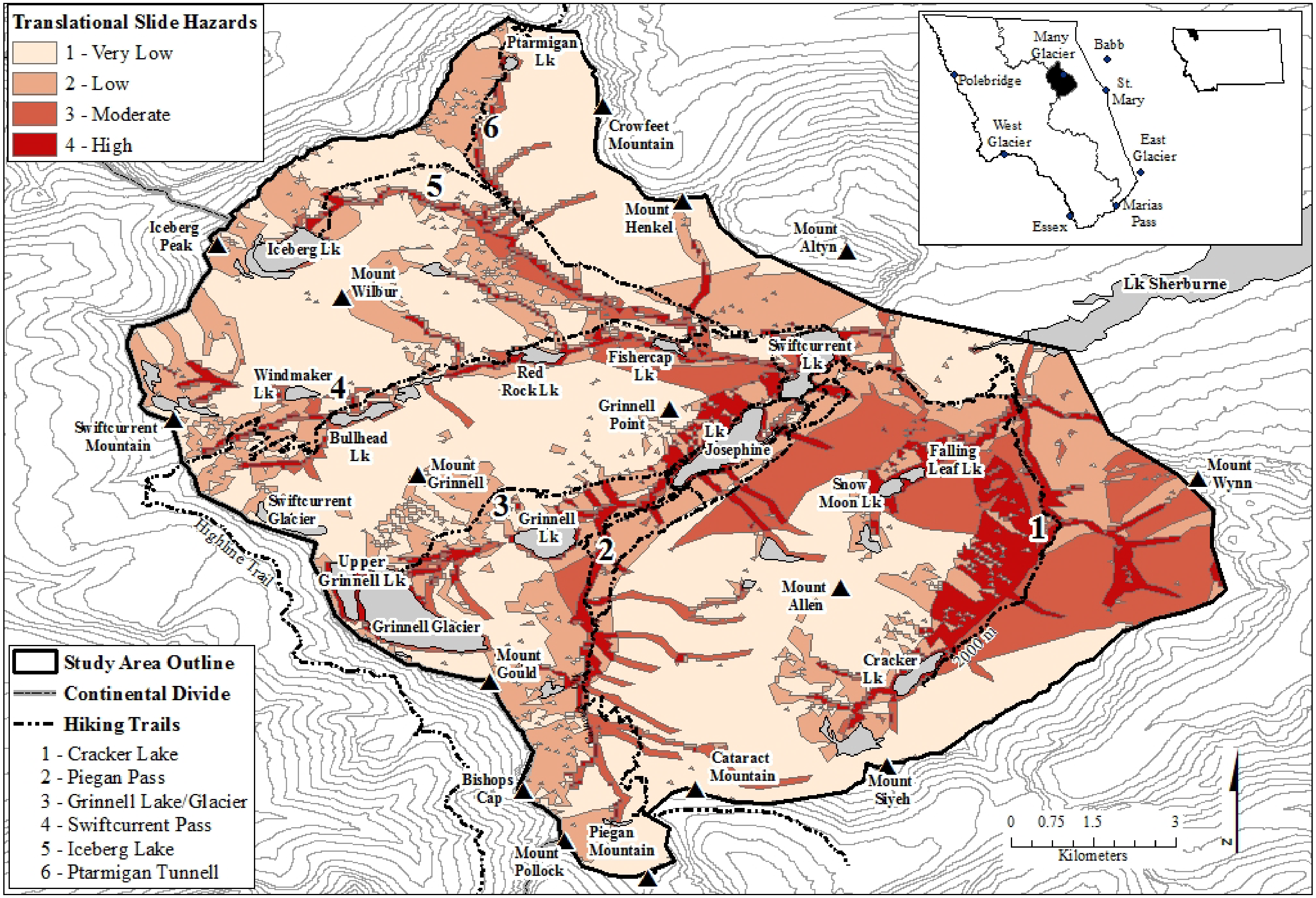

Figure 30. Translational slide hazard map for the Many Glacier Valley.

Table 12

Weights Assigned to Control Variables for the Creation of Hazard Maps

Control Variable	Overall	Debris Flow Initiation	Debris Flow	Avalanche	Rockfall	Translational Slide
Elevation	1	1	--	--	1	--
Slope Angle	2	2	2	2	3	--
Slope Aspect	1	1	1	--	1	2
Lithology	1	--	--	1	2	1
Vegetation Coverage	1	1	1	--	1	--
Vegetation Type	1	1	1	--	1	--
Distance to Surface Water	2	2	2	2	--	2

Note. Control variable weight based on significance value. 1 = Significant, 2 = Very Significant, 3 = Extremely Significant.

Overall Mass Wasting Hazard Map

The overall geomorphic hazard map indicates that 15% of the study area is classified as high hazard (Table 13). The areas of highest hazards were steep slopes located along cirque walls, arêtes, and horns (Figure 24). The areas classified as very low and low hazard are located in areas of low topographic relief in valleys, accounting for 60% of the study area.

Table 13

Percentages of Each Hazard Class by Mass Wasting Type in the Many Glacier Valley

Hazard Map	High %	Moderate %	Low %	Very Low %
Overall	15	25	32	28
Debris Flow Initiation	21.5	28	30.5	22
Debris Flow	15	33	27	25
Avalanche	1.5	27.5	25.5	45.5
Rockfall (slope)	15	31	30	24
Rockfall	19.5	25	23	32
Translational Slide	6	10	30	54

Rockfall Hazards

Two hazard maps were created for rockfall hazards in the Many Glacier Valley. One map was based solely on slope angle (Figure 25) while the other used the bivariate statistical approach, giving slope angle a higher weight than other control variables (Figure 26). Rockfall deposits were found in all areas containing steep cliffs. In many cases, the talus slopes resulting from rockfall resulted in debris readily available for debris flows, namely in the Iceberg Creek and Ptarmigan Creek basins. The hazard map created solely from slope displayed 15% of the study area as high hazard, while the hazard map using the statistical approach showed 19.5% as exhibiting a high hazard for rockfall.

Debris Flow Hazards

Debris flows are the most prevalent geomorphic hazard in the Many Glacier Valley, accounting for approximately 50% of all events mapped in the study. Two separate debris flow hazard maps were created for the study area: 1) initiation hazards created from all significant variables (Figure 27); and 2) overall debris flow hazards using all significant variables except elevation (Figure 28). The first map indicates hazards for debris flow initiation, where elevation was significant, showing that higher elevations are more hazardous than lower elevations. However, debris flows create a hazard not only where they begin, but also where they flow and terminate. By excluding elevation in the second map, a more accurate map is created to show potential hazards for debris flows at lower elevations. The debris flow hazard initiation map indicates 21.5% of the study area as high hazard. The overall debris flow hazard map indicates that 15% of the study area is high hazard.

Slab Avalanche Hazards

The study area is classed as 9% high hazard, with most existing mainly in gullies with high slope angle (Figure 29). Distance to surface water is extremely significant to avalanche events, even if the stream is ephemeral. Avalanche hazard exists in winter and spring months during warming periods when snow is “ripe” and during rain-on-snow events. Although this analysis has only one instance where weather could be associated with an event, the literature supports this (Thorn 1978, Butler 1986).

Translational Slide Hazards

Six percent of the study area is displayed as high hazard to translational slides (Figure 30). Moderate hazard areas account for 10% of the study area, low hazards account for 30%, and very low hazards account for 54% of the total study area. Although this number is low, it is important to note the location of the hazard along streams and creeks in the study area. Trails in the study area often follow these creeks, potentially indicating a strong link between the location of the high hazard areas, and areas of visitor use. The link between translational slides and gullies is strong, indicating the link between translational slides and water. East facing slopes, in combination with gullies where water is readily available, produce the most likely locations for translational slides in the Many Glacier Valley.

Flooding

The hazard for flooding exists in every basin in the Many Glacier Valley. Flooding can cause major damage to the trails costing the National Park Service hundreds of thousands of dollars. The *Hungry Horse News* reported that the National Park Service spends $675,000 to 1,000,000 dollars annually on trail maintenance and repair (2012). There is no indication of how much is spent on flooding damages, but often bridges are washed out during floods and are expensive to repair. The hazard analysis identified places of likely flooding every spring as well as the potentially unstable moraine at the base of Upper Grinnell Lake, a proglacial lake at the foot of Grinnell Glacier. The most hazardous trail in terms of potential flooding is the Grinnell Lake/Glacier trail because of the potential impacts a GLOF could have on people versus the minor and mostly financial impacts of spring flooding. Piegan Pass and Cracker Lake have numerous stream crossings and historical flooding, making it hazardous during spring months when snow is melting and temperatures are increasing.

Trail Hazard Ratings

The trails with the most mapped, mass wasting features and most stream crossings are classified as potentially more hazardous than those trails with fewer. Trails with potential GLOFs are exponentially more hazardous. The written archival record indicates August is the most geomorphically active month and also the highest for visitor use (Table 14). Each type of mass wasting process was totaled for each trail (Table 15). Mass wasting trail crossings, stream trail crossings, GLOF potential, and hazards per kilometer were calculated for each trail (Table 16).

Table 14

Geomorphic Events and Visitor Use by Month in the Many Glacier Valley

Month	Geomorphic Events Recorded from Written Archival Sources	Average Automobile Count for the Many Glacier Entrance Station 1998 – 2013
February	1	72
May	4	2,029
June	4	12,071
July	8	17,459
August	10	17,842
September	2	11,757
October	1	1,866
November	1	85
December	1	1

Table 15

Mass Wasting Type by Trail

Trail	Rockfall	Debris Flow	Slab Avalanche	Translational Slide	Rotational Slide	Totals
Cracker Lake	34	46	7	17	0	104
Piegan Pass	33	36	7	1	1	78
Grinnell Lake/ Glacier	15	16	4	0	2	37
Swiftcurrent Pass	36	33	2	3	0	74
Iceberg Lake	16	25	1	0	0	42
Ptarmigan Tunnel	7	44	4	4	0	59

Table 16

Hazard Categories by Trail

Trail	Trail Length (km)	Total Mass Wasting Landforms	Mass Wasting-Trail Crossings	GLOF Potential	Stream-Trail Crossings	Hazards per Kilometer
Cracker Lake	9.8	104	20	No	7	11.3
Iceberg Lake	7*	63*	25*	No	9*	10.3
Ptarmigan Tunnel	8	59	30	No	7	8.25
Swiftcurrent Pass	10.5	74	13	No	9	7.9
Grinnell Lake/Glacier	3.9/9	37	12	Yes	9	5.5
Piegan Pass	20.5	78	20	No	27	5.1

Note. * Iceberg Lake Trail follows the Ptarmigan Tunnel trail for the first 4km and consequently contains overlap with Ptarmigan Tunnel.

There is no data available regarding the amount of visitor use for each individual trail. For this reason, the number of users was not taken into account for each trail. However, the most popular and likely most used trails in the Many Glacier Valley are Grinnell Lake/Glacier and Iceberg Lake Trails.

Cracker Lake Trail

The Cracker Lake Trail has the highest relief in the park and subsequently the hazards are associated with high slope angles (i.e. rockfall and debris flows). With 104 mapped mass wasting landforms and seven stream crossings, the Cracker Lake trail is extremely geomorphically active with an average of 11.3 hazards per km. Twenty mapped mass wasting landforms cross the trail. The biggest hazard on the Cracker Lake trail is debris flows with 46 mapped features (Table 15). Most features occur around the head of the lake, along the cirque wall, as well as along the banks of the Canyon Creek.

Iceberg Lake Trail

The Iceberg Lake Trail has 63 mass wasting landforms and nine stream crossings. Twenty-five mass wasting landforms cross the trail to Iceberg Lake (Table 15). The first 4 km of the trail are shared with the Ptarmigan Tunnel trail and any hiker headed to Iceberg Lake is exposed to the potential hazards on the first 4 km of the Ptarmigan Tunnel Trail as well. This trail has a high number of landforms crossing the trail and potentially hikers with 10.3 hazards per km. The biggest hazard on the Iceberg Lake trail is debris flows with 25 mapped features, occurring along steep arête walls. Most hazards occur along the north wall as the trail is approaching the lake. These cliffs are composed of steep cliffs with plenty of available material from rockfall.

Ptarmigan Tunnel Trail

The Ptarmigan Tunnel Trail has 59 mass wasting landforms and 7 stream crossings. Thirty mass wasting landforms cross the trail to Ptarmigan Tunnel (Table 14). This trail is rated as having a moderate geomorphic hazard. As with the Iceberg Lake trail, this has a high number of landforms crossing the trail and potentially hikers, with 8.25 hazards per km. The biggest hazard on the Ptarmigan Tunnel trail is debris flows with 44 mapped features. Most hazards occur on the valley wall as the trail approach the cirque headwall leading up to the tunnel.

Swiftcurrent Pass Trail

The Swiftcurrent Pass Trail has 74 mass wasting landforms and nine stream crossings. Thirteen mapped mass wasting landforms cross the trail (Table 15). Most of the mass wasting landforms are on the latter part of the trail towards the pass. The first part of the hike is located on the floor of the Swiftcurrent Valley. The Swiftcurrent Pass Trail has 7.9 hazards per km. Rockfall is the most mapped hazard (Figure 14). Most hazards occur on the switchbacks as the trail climbs the valley wall approaching the pass.

Grinnell Lake/Glacier

The Grinnell Lake/Glacier Trail has a relatively lower number of mass wasting landforms (37) as well as stream crossings (12) (Table 14). The Grinnell Glacier Trail has 5.5 hazards per km. Twelve mapped mass wasting landforms cross the trail. The moraine at the foot of Upper Grinnell Lake is relatively new and potentially unstable. As Grinnell Glacier shrinks and Upper Grinnell Lake grows, the pressure on the moraine will increase and potentially fail causing a GLOF. Debris flows are the most mapped feature, occurring along the side of Mount Grinnell, with 16 mapped.

Piegan Pass Trail

The Piegan Pass Trail has a lower amount of mapped mass wasting landforms (78) but a higher number of stream crossings (27) than the Cracker Lake trail, with a total of 5.1 hazards per km (Table 15). The high number of stream crossings has the potential for flooding as well as the potential for debris flows based on the occurrence of debris flows in stream beds. Twenty mapped mass wasting features cross the trail. The biggest hazard on the Piegan Pass trail is debris flows, along the cirque wall, with 36 mapped features.

Management Recommendations

The Many Glacier Valley is a top destination for mountain access in northwest Montana and Glacier National Park. The mass wasting and flood inventory and subsequent hazard maps produced as part of this research can be used by the National Park Service to educate visitors of the hazards present in the Many Glacier Valley environment. A geomorphic hazard management plan is essential to the Many Glacier Valley given the results of this study and the National Park Service's mission and interest in visitor safety.

Pre-event measures including land use planning and zoning laws typically used for mitigation for geomorphic hazards are not feasible in the Many Glacier Valley because of the National Park Service commitment to allow natural process to continue unimpeded and the element of nature and beauty visitors seek in the Many Glacier Valley. In the unlikely event that the National Park Service develops more land in the Many Glacier Valley, planning and zoning laws are needed. Although the National Park Service has a commitment to the natural environment, it also has a commitment to the visitors who come to enjoy Glacier National Park. This dual commitment "to understand, maintain, restore, and protect the inherent integrity of the natural resources, processes, systems, and associated values of the parks, as well as the opportunity to enjoy them" limits the National Park Services choices of mitigation measures (NPS 2006).

Hazard prevention associated with recreational experiences relies on park personnel as well as the individual visitor. The shared responsibility relies on park personnel to make a reasonable effort to assess risk, mitigate and/or eliminate those risks, and communicate present hazards within the limits of their resources. Individual park visitors should be prepared and seek information and warnings provided by park personnel in relation to the environment in which they are recreating (NPS 2006).

Currently, the National Park Service closes trails for heavy bear traffic. Trail closures and trail relocation should be thought of as last resorts. Trail closures are undesirable and difficult in the Many Glacier Valley because of the lack of ability to predict exactly where the hazard will occur, especially during a storm event. Visitors should be able to make decisions to take part in recreational activities involving risk. Trails should only be closed in extreme events that threatening human life. Trail relocation is undesirable because of the lack of places available to relocate to that would actually decrease the hazard while keeping the aesthetic values visitors seek in the Many Glacier Valley. Trails, if needed should be relocated above or below their current location to avoid a repeat hazard. Potential active pre-event mitigation measures include closing, relocating, and modifying the trails including building up the trails with bridges and the installation of large culverts could reduce the damage while allowing natural processes to proceed uninhibited.

Bulletin boards with current hazards (mostly wildlife) and trail closures are located at most trailheads in the Many Glacier Valley. With little effort, the National Park Service could post information regarding geomorphic hazards at these locations, fulfilling their duty to communicate present hazards to visitors. Further, interpretive programs, funded by NPS, could be aimed at geomorphic hazards present in Glacier National Park, increasing awareness. Articles in the park newspaper could be aimed at geomorphic hazard awareness, including likely weather associated with hazards. Collecting data regarding trail use could be valuable to the National Park Service in many ways. Knowing which trails visitors are using would allow park service to adjust hazard education to better fit the needs of visitors.

In addition to these mitigation measures, geomorphic events affecting trails should be recorded by trail crews. Simple GPS points and a few notes when events are noticed could add to the current database and overtime, increase the accuracy of future hazard maps and hazard understanding. The Citizen Science Program, currently active in Glacier National Park, could have citizens learn about geomorphic hazards and identify/report events occurring throughout the park.

Looking into the future, park officials can use this research and others to anticipate hazards such as mass wasting events after a fire. Fires lead to vegetation removal, essentially decreasing shear strength. Major fires occurred in 2003 and 2006, and lead to a spike in mass wasting events in these areas. Mass wasting increases for an average of seven years after a major fire in Glacier National Park (Dan Jacobsen personal communication 2013). The Many Glacier Valley has not experienced a large fire in the recent past and is overdue. Once a fire sweeps through the valley, park officials should anticipate a spike in mass wasting events, potentially limiting access to some trails in areas, highly prone to mass wasting.

Climate change is another area park officials can anticipate to affect geomorphic hazards in the Many Glacier Valley. If average annual precipitation increases, geomorphic hazards likely would increase as well. As temperature increases, research has indicated a likely increase in extreme weather events such as heavy precipitation and/or rain-on-snow events and likely debris flows (IPCC 2007, 2014). Glacially conditioned landscapes have readily available material, combined with steep slopes, providing potential for mass wasting. Water provides the triggering mechanism. Increased education of visitors is one way to mitigate the hazards associated with a changing climate. If visitors know severe weather events are triggers for mass wasting, they will likely be more aware, following these events, decreasing the potential for injury.

CHAPTER VI

CONCLUSIONS AND FURTHER RESEARCH

Geomorphic Features and Events

A total of 394 mass wasting landforms were identified, mapped, and classified in the Many Glacier Valley. An additional 34 mass wasting and flooding events from written historical sources were identified and classified, and most were mapped in likely zones. Some processes identified via written historical documents were not mapped because of insufficient information. Overall, the mapped mass wasting landforms totaled 12.5% of the study area, with 27% of landforms crossing hiking trails. High densities of mass wasting landforms were found around cirque walls, arêtes, and horns with steep, unstable slopes associated with glacially conditioned landscapes. Some landforms are historic, while others likely date to earlier. The most common mass wasting landforms were associated with debris flows, followed by rockfalls, snow avalanches, translational slides, and rotational slides.

Spatial and Temporal Control Variables

Spatial and temporal control variables differ with each type of mass wasting. Rockfalls are mainly influenced by slope angle, with slopes over 31º accounting for 97% of rockfall events. Other significant factors included elevation, slope aspect, lithology, vegetation coverage, and vegetation type. Debris flows are mainly influenced by distance to surface water and slope angle. The temporal aspect of debris flows is controlled by weather events, namely summer thunderstorms. Slab avalanches are heavily influenced by distance to surface water, lithology, and slope angle. Distance to surface water is likely attributed to existing gullies and couloirs, acting as natural conduits for avalanche tracks. Translational slides are mainly controlled by distance to watercourses where creeks have formed cliffs and over-steepened slopes.

Flooding occurs annually and the extent mainly depends on winter snowpack and spring weather. Five flooding events were linked to heavy precipitation events combined with already high streams from annual snow melt.

Hazards and Trails

Hazard maps were created for each type of mass wasting hazard including rockfall, debris flows, slab avalanches, and translational slides. In addition an overall mass wasting hazard map including rotational slides was created. The overall mass wasting, rockfall, debris flow, slab avalanche, and translational slide maps were statistically-based, created from the results of significant spatial variables through chi-square tests. An additional hazard map for rockfall, based solely on slope was created. The result of the hazard mapping indicates the Many Glacier Valley is a geomorphically hazardous place, experiencing different hazards at different times of the year.

The Cracker Lake Trail had the most mapped landforms (104) including 46 debris flows and 34 rockfall taluses. The location beneath nearly vertical glacially conditioned cliffs of the Helena Formation provides an environment favorable for rockfall and the readily available supply of talus along glacially eroded valley walls provide an environment favorable for debris flows. The trails with successively lower mapped geomorphic hazards are Piegan Pass, Swiftcurrent Pass, Ptarmigan Tunnel, Iceberg Lake, and Grinnell Lake/Glacier.

Management Recommendations

Management recommendations were based on the hazard maps as well as the historical record analysis. These maps could be used as educational tools for visitors seeking information regarding hazards in the Many Glacier Valley. In the unlikely event that the National Park Service develops more land in the Many Glacier Valley, planning and zoning laws are needed and can be based off the hazard maps provided in this report.

As a recreation area, the National Park Service should provide literature to visitors entering geomorphically hazardous areas as they do regarding bears. Bulletin boards are located at most trailheads in the Many Glacier Valley. With little effort, the National Park Service could post information regarding geomorphic hazards at these locations, fulfilling their duty to communicate present hazards to visitors. Signs warning visitors of present hazards could include pictures associated landforms and specific areas likely to be of issue. For example, at the trailhead of Swiftcurrent Pass, a map indicating the switchbacks are historically dangerous, with a picture of a debris flow fan, and potential triggers would educate the visitor as to what areas and landforms to stay away from during an intense thunderstorm.

Interpretive programs, already implemented by NPS at most park campgrounds, could be aimed at geomorphic hazards, further increasing awareness. In addition to increasing visitor awareness, geomorphic events affecting trails should be recorded by trail crew and/or citizen science volunteers. Simple GPS points and a few notes when mass wasting landforms and evidence of flooding are noticed could add to the current database and overtime, increase the accuracy of hazard maps.

Knowing which trails visitors are using would allow park service to adjust hazard education to better fit the needs of visitors. A program collecting visitor use data in the form of surveys or counting visitors or trails would benefit the National Park Service and the visitor in regards to what trails visitors are using and ultimately what hazards they are exposed to.

The Citizen Science program is an active program in the park where citizens are able to collect useful data for the National Park Service. A program could be designed to have citizens learn about geomorphic hazards and identify/report events occurring throughout the park, record events with a GPS unit, and/or record visitor use by asking visitors to complete surveys or simply counting visitors on trails.

Future Research

Future potential research regarding geomorphic hazards in Glacier National Park's transitional, glacially conditioned landscape is abundant. Further research on mass wasting and flooding can help provide a more in depth understanding of where and when geomorphic processes occur in transitional landscapes. An in-depth look at each mass wasting process would add attribute information about each landform, adding to the greater understanding of how these processes work. Lichonometry and dendrochoronology could be used to find relative ages of landforms and potentially gauge return intervals and frequency. LIDAR data, as it becomes available could be used to identify mass wasting landforms not visible from airphotos, especially landforms located in forests. The study identified a relationship between debris flows and snow avalanches.

A more in-depth look at how these two processes interact would be beneficial to other alpine areas.

The DEM used in this study is only accurate to 10 m. When a 1 m DEM becomes available, an accurate flood hazard map could be created. Ten meters is significant when dealing with small streams that often do not measure 10 m in width. LIDAR data could greatly add to the accuracy of a flood hazard map.

A similar study, located on the west side of the Continental Divide would be useful to differentiate how climate and vegetation affect mass wasting. Adding a baseline study of the west side of Glacier National Park could help create a proxy for mass wasting the west side of the Continental Divide. In addition, a mass wasting inventory of recent fire areas on both sides of the Continental Divide would increase clarity on how fire affects mass wasting. In 2003, Robert’s fire swept through the area on the west side of Lake McDonald (west of the divide) and in 2006, Red Eagle Fire swept through the area on the southeastern side of St. Mary Lake (east of the divide). An analysis of these two areas could provide better understanding to both the effects of fire and climate, and how these affect mass wasting in Glacier National Park.

Keeping a better record of geomorphic events and trail interaction could provide valuable data for future research regarding magnitude-frequency relationships (Hungr et al. 1999). A log recording GPS points, digital photos, and weather conditions could greatly add to the understanding of how geomorphic hazards impact trails in the Many Glacier Valley.

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