SIGNATURE HYDROLOGICAL AND METEOROLOGICAL CONDITIONS LEADING TO ICE JAM FORMATION AND BREAKUP ON THE FLATHEAD RIVER, GLACIER NATIONAL PARK, MONTANA

THESIS

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Dedication: To my parents. Thank you for your endless love and support. And for my Mom, by the time you read this you will be healed.

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Above all, I give thanks to God.

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CHAPTER I

INTRODUCTION

Ice jams and ice jam floods can occur on virtually any river flowing in a temperate or cooler climatic zone given the suitable coincidence of ice, discharge, and meteorological conditions (Carey et al., 1973). This includes "anywhere in the continental United States and Canada north of the 0°C isotherm, an area which includes more than two-thirds of North America" (Doyle 1987, 1).

Ice jams are hazards specific to cold regions. During the winter season, air temperatures drop, causing streams and rivers to freeze. Precipitation form and temperature deviations can trigger the breakup of the ice, which acts as a dam to the water behind it. Ice jam breakups can send surges of water and large slabs of ice downstream at rapid rates.

Despite its significance to the environment and economy, river ice science is still in its infancy, achieving relatively slow progress beginning this century (Morse and Hicks, 2005). As a result, fairly little is known about ice-induced flooding. Consequently, a potentially dangerous situation arises, in which this lack of understanding affects lives, property, infrastructure, and the environment. Flooding associated with ice jam events leaves little time for engineers and state officials to prepare and evacuate communities or structures affected by the rapidly rising waters (White and Eames, 1999). More attention needs to be given to ice-induced flooding in order to create and implement possible mitigation strategies.

Little is known about the signature air temperature and river discharge characteristics needed to produce ice jam events. Hydrological and meteorological geographic variability leads to smaller scale studies since findings cannot be expanded to fit all communities or circumstances. This study relies on local, historic data to provide insight into the hydrological and meteorological conditions needed to produce ice-jamming events. These data need to date back far enough and be fairly complete. Since this is often not the case, newspapers, local records, and first-hand observations can supplement the field research and historic data of ice jams.

This study focuses on three ice jams known to have occurred on the Flathead River, which spans the Canada-Montana border. By analyzing the hydrographs and meteorological conditions surrounding each event, it is hypothesized that there are signature river discharge, air temperature, and precipitation characteristics that lead to the formation of ice jams and ice-jam break-up events. It is expected that during freezing temperatures, the lower the river discharge, the higher the probability that freeze-up ice jams will develop, and vice versa. It is also projected that periods of intense cold followed by drastic warming can trigger the break-up of ice cover that leads to breakup ice jam events. Such temperature deviations are often experienced alongside precipitation changes from snow to rain, which may significantly amplify the event. If signature characteristics can be identified, this can potentially aid in the planning and mitigation surrounding these events.

Types of Ice Jams

Ice jams are generally classified three ways: by the season during ice-jam formation; by the governing formation processes; and, by conditions at the toe of the jam (Healy and Hicks, 2006). The most commonly used differentiation of ice jams refers to the time of formation, either freeze-up or breakup. Freeze-up jams generally form during late fall or early winter due to the accumulation of loose ice. Due to periodic freezing between the melts that produce ice floes, cohesion in sub-zero temperatures often adds strength to freeze-up jams. Breakup ice jams most commonly occur in spring when ice is broken up by the hydraulic and buoyant forces of rising waters from spring runoff. Breakup ice jams are more commonly studied due to their more destructive nature, especially their impacts on biologic communities (Beltaos, 2000; Prowse and Culp, 2003; Healy and Hicks, 2006).

Background of Study

In defining ice jam events, the International Association for Hydraulic Research (IAHR) definition is most commonly used. According to this definition, an ice jam is "a stationary accumulation of fragmented ice or frazil that restricts flow" (Healy 2006, 3).

Ice jams are complex events that are not fully understood. While we can only speculate as to why some winters produce ice jams, and others with similar meteorological conditions do not, "the most likely explanation is probably related to the discharge levels of the rivers during the course of intensely cold winters" (Butler and Wilkerson 2001, 62). These discharge levels are in turn dependent on pre-existing flow conditions and precipitation events prior to the onset of the bitter cold. If discharge is low, the likelihood of a complete or partial freeze of the river increases. Frozen rivers should have a lower discharge as some of the water is locked into a stationary frozen state. Higher discharge levels may promote continual flow of water and the likelihood that ice jams will not develop. Higher discharge levels should require substantially more intense freezing conditions in order to freeze the river.

Local meteorological conditions "play a role, but a role for which no documentation currently exists" (Butler and Wilkerson 2001, 62). Extremely cold air temperatures experienced for several weeks can cause rivers to freeze. Sudden temperature increases can trigger the breakup of river ice and the water held behind it. If temperatures abruptly rise, not only does the snowpack melt and runoff into the stream raising the discharge, but increased discharge levels can attribute to buoyancy which further aids in the process of ice breakup. Rapid increases in air temperature are often experienced alongside a change in precipitation from snow to rain. Rain and snowmelt runoff both contribute to rising water levels, but rainfall on the existing snowpack has an additive effect. Warm temperatures and rain onto frozen river and tributary surfaces can initiate widespread break-up conditions (Butler and Wilkerson, 2001).

The purpose of this study is to analyze the discharge records of the Flathead River to determine if a relationship exists between river discharge and the likelihood or unlikelihood of ice jam development, within the context of local meteorological conditions. If signature characteristics of ice-jam formation can be identified, local land-use managers and emergency planners will be better aided in their ability to forecast the ice jam event, and mitigate or adapt appropriately. If signature characteristics of ice-jam formation cannot be identified, mitigation and adaptation employers will continue to haphazardly and impulsively respond to ice-jam events after they have already occurred.

CHAPTER II

LITERATURE REVIEW

As the number of studies has increased, river-ice breakup has become increasingly recognized as a major control in cold-regions hydrology "capable of producing hydrologic extremes that regularly exceed the frequency and magnitude of those under open-water conditions" (Prowse and Culp 2003, 139). Ice jams as hazards specific to cold regions have resulted in an array of publications spanning the globe. Although many European and Asian countries are significantly affected by ice jams that result in many studies and publications, these were not considered due to language barriers. The literature regarding ice jams in the United States and Canada will be the focus of this study because the study site, the Flathead River watershed, spans the United States-Canada border.

Publications focusing on ice jams in the United States, combined with Canadian research, directed and focused this study. This study will contribute to the existing literature by providing signature air temperature and river discharge characteristics leading to the formation of ice jams, which have not been specifically addressed within the literature. These characteristics will be determined through a case study heavily guided by existing literature, especially the Butler and Wilkerson (2001) publication.

Ice Jams in the United States

The United States suffers annual damages of approximately $120 million due to ice jams and other ice accumulations. These damages include the potential for loss of life, property, and infrastructure, bed and bank erosion and scour, increased flood prevention and assistance costs, and environmental damages. These events often go undocumented, and their rising costs prompted the United States Army Corps of Engineers' (USACE) Cold Regions Research and Engineering Laboratory (CRREL) to collect ice data, ultimately resulting in the formation of the Ice Jam Database (IJDB) in the early 1990s (White et al., 2007).

In light of the above, surprisingly few studies have been conducted on ice-jamming in the United States despite the rising costs and frequency of reported ice-jam events. White et al. (2007) conducted the most comprehensive study by analyzing ice jam occurrence and severity in the United States using the nearly 15,000 entries in the CRREL IJDB (Figure 1). The IJDB contains data for ice events in 43 states dating back to 1785. Montana and New York most frequently reported ice jams, each with more than 1,400 events, followed by Pennsylvania and Minnesota, each with more than 1,000 reported events. As many as 24 other states have reported more than a combined total of 100 ice-jam events (White et al., 2007). As of March 2010, there were 18,074 ice jam events recorded in the IJDB.

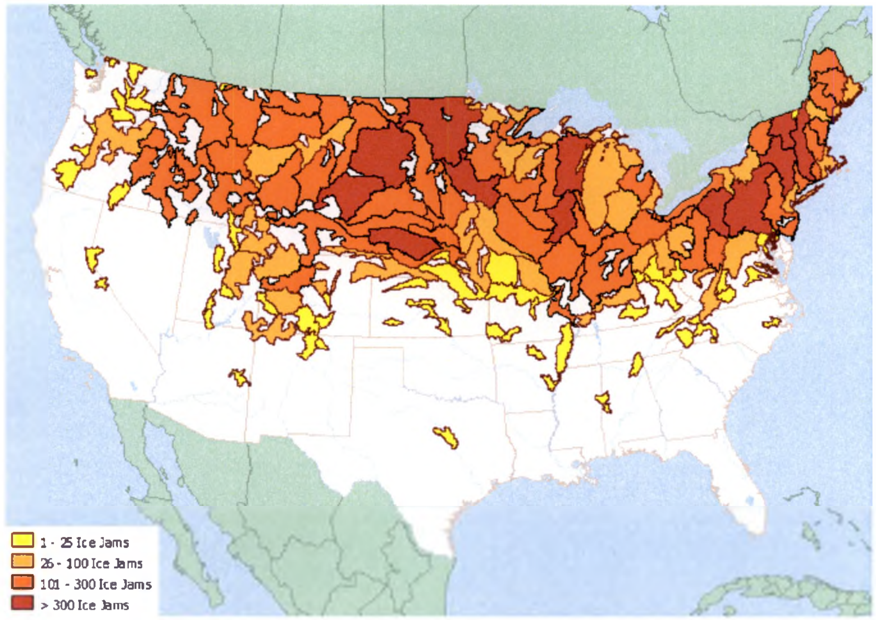


Figure 1. Ice Jams in the United States (White et al., 2007).

In order to meet the needs of affected communities, engineering and design studies must rely on a large number of observations primarily because the complexity of ice jam physical processes has prevented the development of complete analytical models (Jasek, 2003; White et al., 2007). In the late 1980s, the USACE and CRREL recognized that this lack of systematically compiled data on ice events was not only hampering research and development in the areas of ice processes, but was an obvious detriment to effective ice jam response (White et al., 2007). In order to provide data for use in research and engineering design and to assist in emergency management, the CRREL IJDB project was initiated in the early 1990s. This clearly indicates that ice jam research in the United States has only barely begun and therefore relies heavily upon studies originating in other countries, particularly Canada.

Ice Jams in Montana

Ice jams have a frequent and destructive history in the state of Montana. While the number of ice jams reported each year varies greatly depending on the jam location and the availability of jam records, Montana is currently ranked first in total number of events by state, with 1,595 documented ice jams occurring on 163 different rivers, in 449 different locations. Approximately 59% of Montana ice jams occurred in March and April, indicating that these ice jams are largely breakup ice events. The approximately 32% of jams that occur in January and February could be either freeze-up or breakup types (USACE, 1998). All of Montana's rivers carry floating ice during the late winter or early spring. The greatest volume of flow on Montana's rivers occurs during the spring and early summer months during the melting of the winter snowpack. Heavy rains falling during the spring thaw constitute a serious flood threat as ice jams, usually occurring in March, cause backwater flooding (WRCC, 2010). The earliest recorded jam occurred January 1st, 1895, and the most recent occurred January 11th, 2010. The highest number of recorded ice jam events occurred in 1996 (one of the study years), with more than 65 ice jams reported (USACE, 1998). Approximately 80% of the IJDB's information on ice jams in Montana was derived from the United States Geological Survey (USGS) Water Supply Paper 1679 (Patterson, 1966).

Many of the sources relied upon for information on ice jams in Montana lack quantitative data on damages. Approximately 11% of the reported ice jams in Montana have known damages, a higher percentage than the database as a whole, which is approximately 2%. The most common damages include bridge and residential damage, road flooding, evacuations, dike and levee damage, and agricultural damage. Compared to other states, Montana has experienced significantly more mortality from ice jam flooding. As of 2004, there have been at least 17 deaths from ice jam flooding in Montana, the majority of which were due to flash floods released during ice jam breakup (USACE, 1998).

Due to the highly localized, yet serious damages that Montana experiences during ice jam events, the state of Montana addresses ice jams, specifically, in their state management plan. The Montana Department of Military Affairs' Disaster and Emergency Services Division executed *The State of Montana Multi-Hazard Mitigation Plan and Statewide Hazard Assessment*. The document is a collaborative effort and is the State's primary hazard mitigation document. It is the product of extensive input from governmental and tribal agencies, non-governmental organizations, research, and hazard analysis (DES, 2004).

Flooding is consistently a highly ranked concern and priority in this plan. Ice jam events and associated flooding are extensively discussed in Section 3, the Hazard Assessment. Here the history of occurrence, probability of occurrence, severity resulting from-, and the vulnerability to- ice jams are discussed. The term "ice jam" appears approximately 60 times within this section and receives its own subheading entitled "Ice Jam Floods." The document cites sudden seasonal changes in temperature and precipitation as the greatest factor increasing the risk of ice jam flooding and suggests that the best means to determine vulnerability is to evaluate patterns and frequency of previous ice jam flooding. The plan also plotted ice jam events recorded by USACE to show the spatial occurrence (Figure 2). The map serves as a visual reminder that areas that experienced ice jam events in the past are the most likely to experience future flooding related to ice jams, even though ice jams can occur statewide; no one is exempt (DES, 2004).

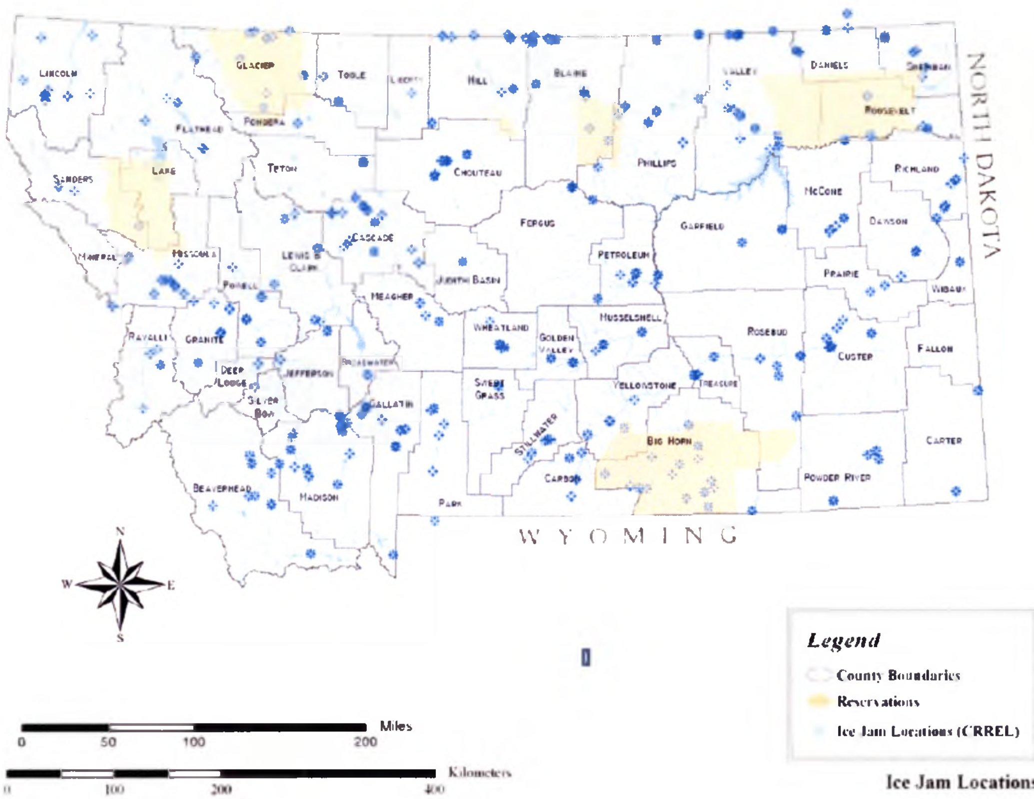


Figure 2. Ice Jams in Montana (DES, 2004).

Ice Jams in Canada

River ice is present in nearly all Canadian rivers, for periods ranging from days to many months. Annually, ice-jam related costs are estimated to be $60 million in Canadian 1990 dollars. This figure does not reflect other serious impacts such as loss of life, resident dislocation, or loss of potential gains that cannot be realized. River ice poses a major flood threat to riverside communities and can have multiple impacts on the economy and ecosystem because it interacts with river flow in various ways (Beltaos, 2000).

Canadian river ice science is still in its infancy, achieving relatively slow progress beginning this century. The hindrance slowing the progress of Canadian river ice science is partially caused by the complexity surrounding river ice phenomena, which encompasses many diverse areas of science. Concurrently, only a limited amount of resources has been dedicated to concerted research on river ice processes. Nonetheless, since the 1970s, Canada has played a key role in river ice research (Morse and Hicks, 2005).

Canadian research and development efforts have been directed at a variety of problems between 1996 and 2000. This period represents one of consolidation instead of innovation. The focus was on the development of existing theories and numerical models. An improved understanding of the salient geomorphological and hydroclimatic factors, enhanced modeling and prediction capabilities, and development of techniques for *in situ* measurement of ice jam properties are the result of a focus on ice breakup and ice jam processes (Beltaos, 2000; Prowse and Culp, 2003). Major contributions in the study of ecological impacts on river ice and ice jams have led to solid advances in knowledge as well as an appreciation of the vast scope of this subject and its many links to environmental science (Beltaos, 2000). For the first time, the flux of suspended sediment in ice-laden rivers was studied in order to delineate the effects of the ice on sediment and associated contaminant loads (Beltaos and Burrell, 1998). Several studies have addressed the growing concern regarding climate change and variability and the resulting implications to ice regime, and in turn, to economy and ecology (Beltaos, 2000; Beltaos, 2002; Prowse and Beltaos, 2002; Beltaos and Burrell, 2003).

Recent concerted efforts spanning 1999-2003 have contributed substantially to the advancement of river-ice hydrology. At the level of science, Beltaos (1995), Prowse and Culp (2003), and Morse and Hicks (2005) brought the hydrological, ecological, and climatological issues associated with river ice processes to the scientific community. The recent integration of sciences marked a new phase in river-ice hydrological studies characterized by an increased awareness of: the dearth of winter data, the importance of ecology to ensure sustainable living and development, the importance of extreme events in the health of ecosystems, the potential impact of climate change and variability, and the importance of developing strategies to prepare our responses to changes in the environment (Morse and Hicks, 2005).

Ice Jam Forecasting and Prediction Methods

A significant need exists to advance forecasts of ice jams and their associated flood levels (Ashton, 1978; White, 2003; Morse and Hicks, 2005). One factor significantly limiting the ability to forecast ice-jam formation and release events is the lack of scientifically documented events (Ashton, 1978; Prowse and Culp, 2003; White, 2003) because of safety and logistical reasons (Morse and Hicks, 2005). The improvement of knowledge regarding river ice jams and their evolution is further hindered by a lack of quantitative data (Ashton, 1978; Beltaos, 1997; Healy and Hicks, 2006), and the inability to predict their occurrence which makes it difficult to be in the right place at the right time to undertake scientific monitoring (Beltaos and Burrell, 2005; Morse and Hicks, 2005). Consequently, researchers have turned to experimental studies in order to investigate the dynamic aspects of ice jam formation and breakup (White, 1996; Blackburn and Hicks, 2003; Mahabir et al., 2006; Beltaos, 2007).

Climate Change and Variability

Beltaos (1997) noted no studies had examined possible changes to ice-jamming processes during the period of hydrometric records. Using projected climatic change scenarios, he discussed the anticipated changes to the ice-jam regime of Canadian rivers, along with probable ecological impacts. Although the predictions were general and qualitative, they provided insight into ice jam frequency and severity, and the ecological impacts that might result (Beltaos, 1997). Review of the limited evidence available indicated a shorter ice season in northern regions of the globe, including Canada, and an increase in mid-winter jams (Beltaos, 2002) that may become more severe in a changing climate (Prowse and Beltaos, 2002; Beltaos and Burrell, 2003). The ice season in this area is experiencing both later freeze-up and earlier breakup dates (Beltaos, 2000; Prowse and Beltaos, 2002; Prowse and Culp, 2003). Modifications to the regime of ice jams, via changing climatic conditions, in turn affect stream ecology and infrastructure (Beltaos, 2000; Prowse and Beltaos, 2002).

If global warming proceeds as predicted by General Circulation Models, winter temperatures in Canada will increase by several degrees within the next century (Beltaos, 2002). If global warming proceeds as predicted by models developed by researchers at NASA, Glacier National Park and the surrounding areas will see a 30% increase in precipitation and a 0.5°C increase in annual temperature within fifty years (Fagre, 2000). There is a predicted trend in temperature from 1850-1979 that shows a .45°C degree change toward warmer weather (Hall and Fagre, 2003). Temperatures in the area affect the snow water equivalent which has decreased due to earlier melting times and a decline in snow cover (Fagre et al., 1997). As a result of these climatic changes, the number and size of alpine glaciers in Glacier National Park are deteriorating at alarming rates. Of the 150 active glaciers within Glacier National Park in 1850, only 37 remain today, all of which are a fraction of the size they were in 1900. If these trends continue, it is expected that all of the glaciers of Glacier National Park will be gone by 2030 (Hall and Fagre, 2003). As glaciers shrink and disappear, scientists expect stream flows, park-wide, to drop. While it is impossible to predict all the consequences, it is understood that unglaciated basins contribute much less water to streams than glaciated basins because the glaciers buffer the timing and extent of runoff (CSKT and MFWP, 2003).

Several studies into the links between climate and river-ice processes, as well as the possible impacts of global warming, were motivated by the emergence of climate change and variability as a major environmental issue (Beltaos, 2000; Prowse and Beltaos, 2002). The potential impacts of climate change and variability appear to be numerous and significant, because of the high sensitivity of river-ice processes to climatic factors (Beltaos, 2000; Prowse and Beltaos, 2002). Beltaos argues that the flow hydrograph, the thickness of winter-ice cover, and stream morphology are the main factors governing the occurrence and severity of river ice jams (Beltaos, 2002; Beltaos and Burrell, 2003). These factors are all directly or indirectly influenced by climate, in particular air temperature and precipitation (Doyle, 1987; Beltaos and Burrell, 2003; Robichaud, 2003). Links between climate and river ice "remain largely unexplored and most evaluations to date have focused on simple measures, thought to be directly related to, and principally determined by, changes in temperature" (Beltaos and Prowse 2001, 159). Prowse and Beltaos (2002) summarized potential links between river ice and climate change stating:

> A brief review of the hydrologic aspects of river ice shows strong climatic links and illustrates the sensitivity of the entire ice regime to changes in climatic conditions… It is only in the past few years that attention has been paid to the more complex, and practically more important, question of what climatic change may do to the frequency and severity of extreme ice jams, floods and low flows…
>
> Overall, changes in almost any of the major meteorological fluxes are capable of producing significant change in ice conditions, including the nature and timing of freeze-up, ice thickness, and break-up severity. In addition to having important hydrologic implications, such changes can produce important geomorphologic, ecological and socio-economic impacts (819).

In order to bridge the gaps in current knowledge, it is necessary to eliminate much of the empiricism used (Beltaos and Burrell, 2003). Empirical methods cannot rely on detailed historical records at specific locations and cannot be used to extrapolate future conditions with confidence because many climatic parameters are assumed to be constant yet will vary from site to site (Beltaos, 2000; Beltaos and Burrell, 2003). In order to reduce our reliance on empiricism, future efforts will require sound understanding of the physical processes involved (Jasek, 2003).

Related Impacts

Geomorphology

River-ice only recently became recognized as a key agent of geomorphological change (Prowse and Beltaos, 2002). Most scientific literature analyzes the impacts of ice-jam floods on channels and riparian vegetation (Smith and Pearce, 2000; Beltaos and

Prowse, 2001; Smith and Pearce, 2002), including the ability of river ice to limit woodland development (Smith and Pearce, 2000). Geomorphologic effects are most pronounced at breakup when ice is capable of producing unique erosional and depositional features (Beltaos and Prowse, 2001; Prowse and Culp, 2003). Since most geomorphological activity takes place during freeze-up and breakup, changes to the timing of these events should not have any considerable effect. Alternatively, if the severity and frequency of ice jams are altered by climatic conditions, certain geomorphologic processes are likely to be affected (Beltaos and Prowse, 2001; Prowse and Beltaos, 2002; Beltaos and Burrell, 2003).

Smith and Pearce (2000, 2002) were among the first to focus on the role of river ice in connection with geomorphology. Their first study focused on the role of river ice in limiting woodland development on a sandy braid-plain on Montana's Milk River (2000). Later they focused on the morphology or origin of gullies and scours and the possible linkages between ice jams and the formation of gullies and scours on Montana's Milk River floodplain (2002). These studies presented the first reports of fluvial gullies and scour holes on floodplain meander lobes of sand bed rivers that were caused indirectly by river ice jams (Smith and Pearce, 2002). Geomorphic effects are expected to be rather common, but research is needed to quantify the extent of this theory.

Few geomorphological studies have analyzed ice-jamming in the Rocky Mountains of the interior American West where "ice jams and associated flooding are fairly common phenomena during the spring season in mid- and high-latitude environments" (Butler and Wilkerson 2001, 57). An ice jam in the winter of February 1996 prompted a study describing both the episode as well as the resulting impacts.

Butler and Wilkerson (2001) assessed the hazards of ice jams within the area, analyzed past ice-jamming, and addressed meteorological conditions typical of ice jams in the local environment. The study was undertaken in hopes that local land-use planners would be able to prepare and mitigate when conditions were favorable for ice-jam development.

Socio-Economic Impacts

Most ice jam damages primarily occur during extreme flood events (Prowse and Beltaos, 2002; Beltaos and Burrell, 2003). Damage estimates do not reflect other serious impacts such as loss of life, resident dislocation, or loss of potential gains that cannot be realized, especially in the transportation and hydropower generation sectors (Beltaos, 2000; Prowse and Beltaos, 2002). River ice poses a major flood threat to riverside communities and can have multiple impacts on the economy and ecosystem because it interacts with river flow in various ways (Beltaos, 2000).

At present, it is not possible to predict the effects of climatic change on ice-jam frequency and severity at specific sites without the advantage of local hydroclimatic records and climate-change modeling (Prowse and Beltaos, 2002; Beltaos and Burrell, 2003). It is probable that damages may increase in some places, decrease or disappear in others, or start to occur for the first time at other sites (Beltaos and Prowse, 2001; Prowse and Beltaos, 2002). If the latter occurs, it will perhaps be the most serious impact because the affected communities will likely be unprepared for extreme ice-jam events, and thus at risk to maximum damages and risk to human life (Prowse and Beltaos, 2002).

CHAPTER III

STUDY AREA

The Flathead River, spanning the Canada-Montana border (Figure 3), was chosen because the area is prone to ice-jamming events, previously documented ice jams have occurred, and air temperature, precipitation, and river discharge data exist.

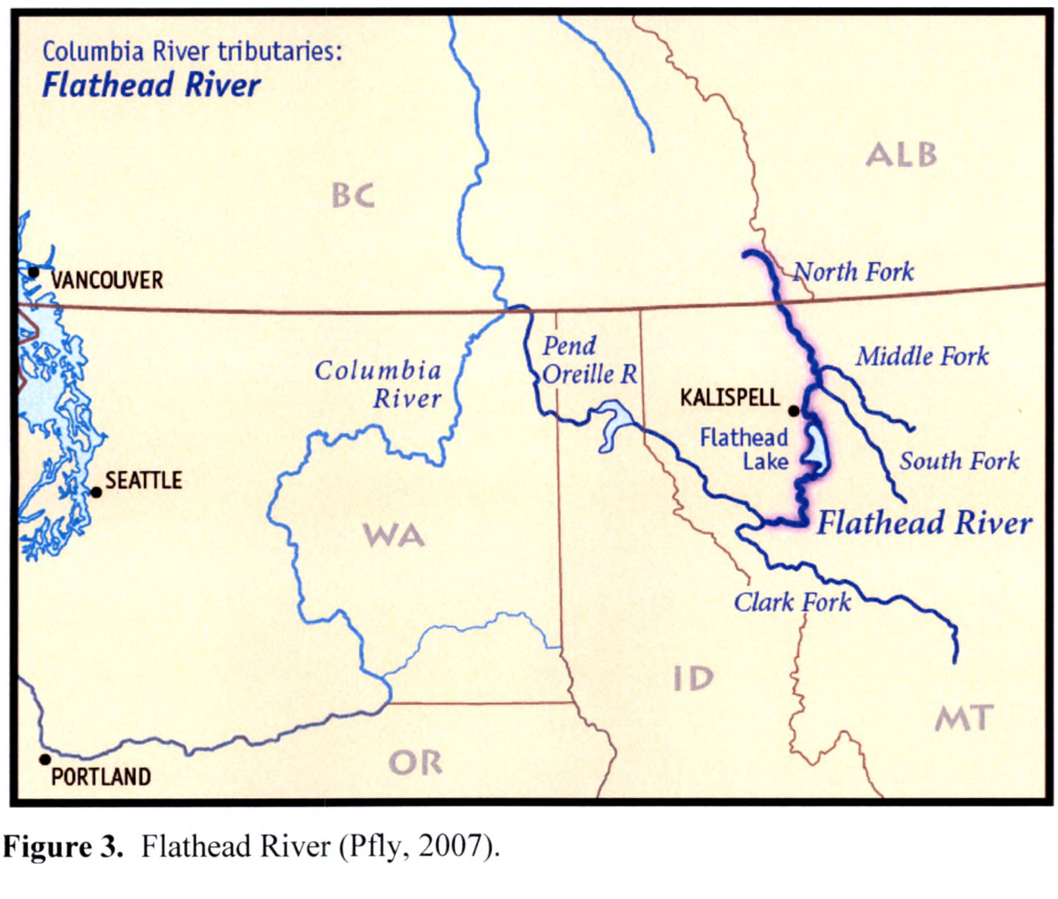


Figure 3. Flathead River (Pfly, 2007).

The Flathead River drainage comprises an area of 23,509.32 square kilometers (9,077 square miles), 1165.49 (450 square miles) of which lie within Canada (Stermitz et al., 1963).The Flathead River has three forks – the North, Middle, and South Forks. Together the three forks supply 80% of the water carried within the watershed (CSKT and MFWP, 2003). This study focused on three ice jam events that occurred along the North and Middle Forks of the Flathead River and its Glacier National Park tributaries (Figures 4 and 5).

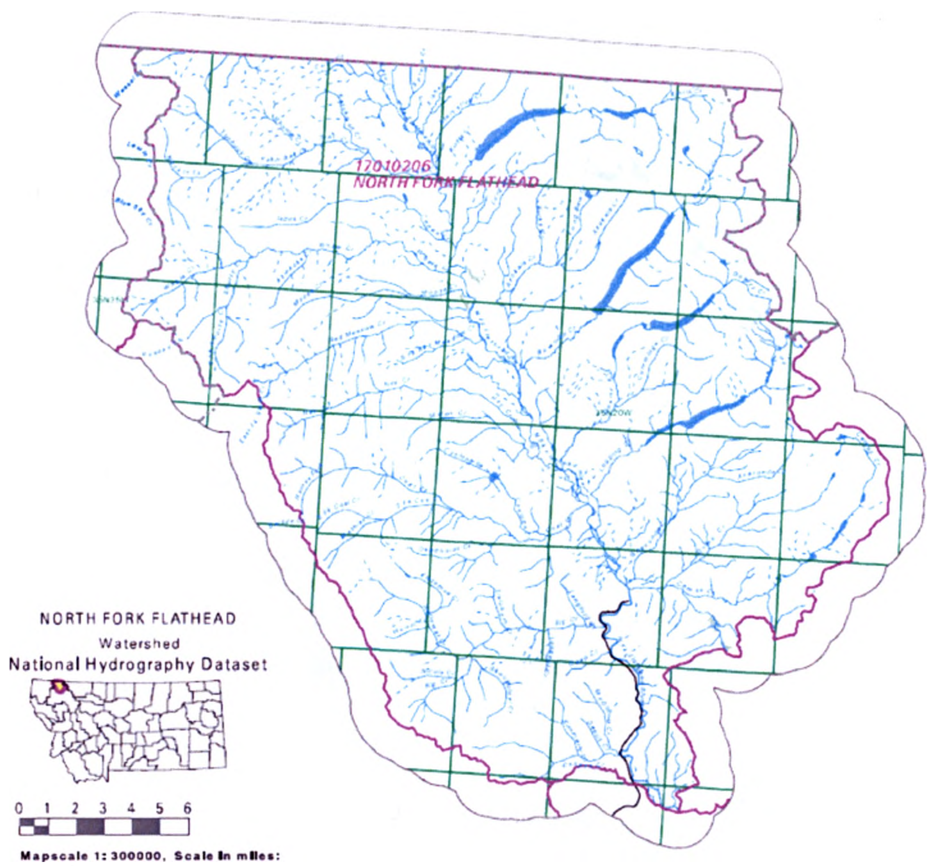


Figure 4. North Fork Watershed of the Flathead River, Montana (Adapted from Montana Natural Resource Information System, 2003).

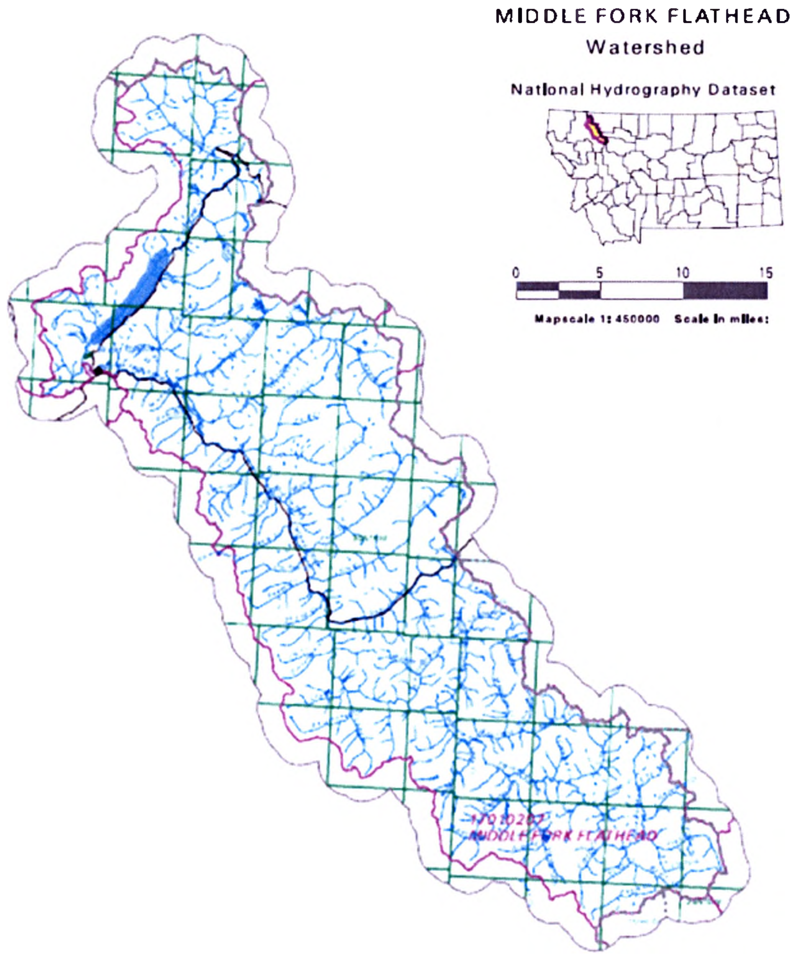


Figure 5. Middle Fork Watershed of the Flathead River, Montana (Adapted from Montana Natural Resource Information System, 2003).

The climate of the Flathead River watershed is classified as modified maritime because it is strongly influenced by moist, Pacific air masses. The mountain ranges to the east of the Flathead River act as a barrier to the frigid Arctic air that flows south along the east side of the Rockies out of Alberta during the winter. This results in moist Pacific air dominating in winter, covering the area in low-lying clouds and bringing mild temperatures (CSKT and MFWP, 2003). Periodically, continental Arctic or polar air masses will spill over the Continental Divide, bringing clear skies and frigid temperatures

(CSKT and MFWP, 2003). Winters, while usually cold, have few extended cold spells (WRCC, 2010). Local topography also plays a large role in the watershed's weather. The North Fork receives 58.4 centimeters (23inches) of precipitation a year at Polebridge, Montana near the Canadian border while West Glacier, Montana, 32.19 kilometers (20 miles) southeast and 121.92 meters (400 feet) lower, receives 76.2 centimeters (30 inches). The pattern reflects geography: the northern part of the drainage falls in the rain shadow of the Whitefish/Macdonald Range. Mountains in the watershed receive approximately 80% of their precipitation as snow (CSKT and MFWP, 2003).

The Flathead River watershed is situated along the west limb of the Rocky Mountains. Prominent intermontane valleys, formed by block faulting occupy the main stream (Stermitz et al., 1963). The terrain often promotes ice accumulation in areas where ice cannot flow past narrow gorges and other constrictions (Butler and Wilkerson, 2001; Woessner et al., 2004). In British Columbia, headwater streams originate from the Clark and Macdonald Ranges and flow into the North Fork. Here the river is bordered by a series of benches and rolling hills that extend to the higher ranges (Flathead Transboundary Network, 1999). In the Montana portion of the North Fork, the Clark Range gives way to the Livingston Range on the east side of the Flathead Valley, while on the west side, the Macdonald Range becomes the Whitefish Range. The valleys of the North and Middle Forks trend northwest to southeast with valley elevations ranging from 975.36 meters (3,200 feet) to 1280.16 meters (4,200 feet). Both valleys have been downdropped on the east and are underlain by sedimentary rocks of the Kishenehn Formation consisting of lacustrine and fluvial sediments. On the east side of the North and Middle Fork valleys, and trending northwest to southeast, are two rugged mountain ranges that define Glacier National Park. The Livingston Range, on the west, extends 40.23 kilometers (25 miles) from the Canadian border south to the Lake McDonald region. To the east is the Lewis Range, which extends 85.3 kilometers (53 miles) from the border south through the park to Marias Pass. Extensive parts of both ranges are above timberline (approximately 1981.2 meters or 6,500 feet) and many of the peaks exceed 2804.16 meters (9,200 feet). The relief of this area is rugged, with valley floors as much as 1493.52 meters (4,900 feet) below the surrounding peaks. The North and Middle forks experience an average elevation drop of 4.57 meters (15feet) and 7.92 meters (26 feet) per 1.61 kilometers (1 mile), respectively. The Continental Divide follows the crest of the Livingston Range in Canada and shifts to the crest of the Lewis Range in the United States. The Flathead Range, also treading northwest to southeast, bounds the west side of the Middle Fork Valley (Carrara, 1990).

The geology of the watershed is predominantly Precambrian metasedimentary rocks of the Belt Supergroup, with glacial deposits and valley fill. Belt sediments are highly stable and tend to have low erosion potential, therefore contributing little dissolved ions, nutrients, and suspended particulates to streams (CSKT and MFWP, 2003). Water tends to be more uniform in chemical character and mineralization and is generally classified as a calcium bicarbonate type with relatively low concentrations of dissolved solids (Stermitz et al., 1963).

The Flathead River is Montana's fourth largest river in terms of volume. It has a mean annual discharge of 8.8 million acre-feet with flow rate averaging just under 339.8 cubic meters per second (12,000 cubic feet per second) (USGS, 2002). Since 80% of the precipitation in this area is received as snow, streams are classic examples of spring snowmelt systems. Flood flow varies depending upon winter snowpack, spring warming patterns, and spring rainfall (Fagre et al., 2007). The main stream and its tributaries form an unusual drainage pattern typical of those basins with heavy winter precipitation and relatively light summer precipitation. The Flathead River joins the Columbia River which ultimately drains into the Pacific Ocean (WRCC, 2010). The North Fork is one of the few remaining, fully functional alluvial floodplain systems in the Columbia River Basin (Jamieson, 2002). The principal use of water is for the generation of hydroelectric power which occurs along the South Fork of the Flathead River at Hungry Horse Reservoir (Stermitz et al., 1963).

Soils in the North and Middle forks tend to be thin and incompletely developed because the landscape has relatively recently been disturbed by glaciers. Alluvial soils are an exception and are relatively productive deposits on the river floodplains and adjacent benches and terraces. These alluvial soils range from shallow, well-drained, relatively deep, coarse-textured sands, loams, and gravels, to boulder-size rocks. These porous soils support grasses or deciduous plant communities, depending upon their proximity to streams (CSKT and MFWP, 2003).

Vegetation is typical of the Northern Rocky Mountain Forest-Steppe-Coniferous Forest-Alpine Meadow Province (Bailey et al., 1994). River floodplains are able to support ponderosa pine, Rocky Mountain juniper, Douglas-fir, black cottonwood, aspen, paper birch, willow, chokecherry, serviceberry, alder, dogwood, rose, and snowberry. The drainage basin is mostly timbered but grasslands are common in the semiarid southwestern portion (Stermitz et al., 1963).

CHAPTER IV

DATA AND METHODS

This study relied on local, historic data to provide insight into hydrological and meteorological conditions needed to produce ice-jamming events. These data needed to date back far enough and be fairly complete. Since this is often not the case, qualitative data from newspapers, local records, and first-hand observations supplemented the field research and historic data of ice jams. The use of qualitative data to reconstruct weather conditions in the western United States has proven to be satisfactory when compared with modern meteorological data (Mock, 1991).

Data

This study focused on three ice jams known to have occurred on the Flathead River in February 1963, 1979, and 1996. While this was a limited data set, it was chosen because river discharge, air temperature, and precipitation data existed and was supplemented by written and photographic evidence found in the Hungry Horse News, a local weekly newspaper published in nearby Columbia Falls, Montana. The data of a previous publication by Butler and Wilkerson (2001) was of upmost importance in guiding this study.

Hydrologic data were obtained from two United States Geological Survey (USGS) gauging stations along the Flathead River: 12355500 – North Fork of the Flathead River near Columbia Falls (Table 1) and 12358500 – Middle Fork of the Flathead River near West Glacier (Table 2). Gauge 1235500 was used for the 1979 ice jam and gauge 12358500 was used for the 1963 and 1996 ice jams. These gauges were chosen for their proximity to the documented ice jam events in the given study years. Each gauge provided historic and site description information that was accessed online. The gauging stations each provided records spanning discharge, temperature, and gauge height characteristics. All discharge values were denoted with a superscript "A," meaning they were approved for publication because processing and review were completed. Eight of the 1996 discharge values were denoted with a superscript "e" and "A" meaning the values were estimated but still approved for publication.

Table 1. USGS Gauge 12355500 - North Fork Flathead River near Columbia Falls, MT (USGS, 2010).

Description:
Latitude 48°29'44", Longitude 114°07'36" NAD 27
Flathead Country, Montana, Hydrologic Unit Code 17010206
Drainage Area: 1,548 square miles
Datum of gage: 3,145.59 feet above sea level NGVD29

Data Type	**Begin Date**	**End Date**	**Count**
Daily Data / Statistics			
Temperature, water, degrees Celsius	01-12-1996	Present	13,510
Discharge, cubic feet per second	10-01-1910	Present	31,113
Gage height, feet	01-29-1987	Present	2,981

Table 2. USGS Gauge 12358500 – Middle Fork Flathead River near West Glacier, MT (USGS, 2010).

Description:
Latitude 48°29'43", Longitude 114°00'33" NAD 27
Flathead Country, Montana, Hydrologic Unit Code 17010207
Drainage Area: 1,128 square miles
Datum of gage: 3,128.72 feet above sea level NGVD29

Data Type	Begin Date	End Date	Count
Daily Data / Statistics			
Discharge, cubic feet per second	10-01-1939	Present	25,724
Gage height, feet	10-22-1985	Present	3,390

Meteorological data were obtained from the National Climatic Data Center (NCDC) operating under the National Oceanic and Atmospheric Administration (NOAA). Essex (used for the 1963 ice jam along the Middle Fork), Polebridge (used for the 1979 ice jam along the North Fork), and West Glacier (used for the 1996 ice jam along the Middle Fork), Montana, weather stations were utilized (Table 3). These stations were chosen for their proximity to the documented ice jam events in the given study years. The record of weather observations gave daily minimum, maximum, and mean air temperatures. It also provided precipitation data that were classified as either rain/melted snow or as snow/ice pellets. The NCDC data all completed processing and quality control and should therefore not contain errors. There were two precipitation values in 1996 that were not received or missing from the data set. These two missing values were assigned a value of zero as reported by the Hungry Horse News. The Hungry Horse News was used for local temperature and precipitation data where necessary. Some NCDC precipitation values were reported "T" for trace. For the purpose of this study "T" values were assigned a value of zero because they were less than 0.03 centimeters (0.01 inches). The Historical Weather Data Archives, operating under the National Severe Storms Laboratory and the US Storm Events Database, operating under NOAA, provided supplemental data.

Table 3: NCDC Weather Station Periods of Record (NCDC, 2010).

Station Name	Station Number	Period of Record
Polebridge, MT	246615	07-01-1948 to 07-31-2000
Essex, MT	242812	08-16-1951 to 09-30-1970
West Glacier, MT	248809	10-01-1949 to 12-31-2005

Historic data on ice jam occurrence and frequency were obtained from the United States Army Corps of Engineers' (USACE) Cold Regions Research and Engineering Laboratory (CRREL) Ice Jam Database (IJDB) and NOAA's United States Storm Events Database. The IJDB provided location, date, CRREL contact, hydrologic unit codes, publications, and descriptions of each ice jam within the database. The Storm Events Database provided location, date, time, magnitude, deaths, injuries, property damage, and crop damage data specific to each ice jam. The Hungry Horse News provided local accounts and photographs of ice-jamming events. Every issue, from inception in 1946 to present, is housed in the Texas State University Geography Department's Geomorphology and Biogeography Lab.

Ice-jam data can be difficult to acquire and is often incomplete. It was essential to explore multiple data sources in order to ensure that the results were comprehensive and complete.

Methods

Ice jam events can be quantified and analyzed in many different ways. A variety of approaches are needed in order to fully understand the complexity of these events. When trying to understand processes conducive to ice jam formation, data analysis is often done at smaller scales using local, historic hydrological and meteorological data acquired from a range of sources. While there are meteorological and hydrological features common to all breakups or ice jams,

> one must consider not only the local geographic and climatic conditions, but also that an intrinsic variation from site to site is likely to alter the nature of the interaction between the common factors and local features, and thus change the specific characteristics of any derived relationships, if not their basic form (Doyle 1987, 3).

River discharge, air temperature, and precipitation data were obtained for the fifteen day period before and after each ice jam breakup occurred. The fifteen day period was deemed a sufficient timeframe for this study to show the hydrological and meteorological conditions surrounding the event without clouding the results. The literature has not established a widely accepted timeframe for studies of this nature.

Hydrological data from the USGS gauges were given in cubic feet per second (cfs) and were converted to cubic meters per second (m^3 / s). Discharge data were plotted in Microsoft Excel as a hydrograph and then analyzed to determine if shared discharge characteristics existed between the known ice-jamming events. Special attention was paid to "spikes" in the hydrograph relative to mean conditions. The mean discharge values used in the hydrographs were calculated over the fifteen day period surrounding the event. Because discharge is the dominant ice jam formation factor, it was plotted against air temperature and precipitation to determine if a relationship indeed existed.

Meteorological data acquired from the NCDC illustrated the local air temperature and precipitation characteristics surrounding the known ice-jamming events. These data were reported in degrees Fahrenheit and inches, and were converted to degrees Celsius and centimeters (cm), respectively. Special attention was given to periods of rapid warming and changes in precipitation from snow to rain, often experienced simultaneously.

In order to obtain accurate and comprehensive results on historic ice jam occurrence and frequency, it was essential to cross-reference multiple data sources. In obtaining data on ice jam events within the study area, it was necessary to check both the IJDB and the United States Storm Events Database. These results were then cross-referenced with the USGS hydrologic data and the NCDC air temperature and precipitation data. Lastly, these results were compared to local accounts of ice jam events within the Hungry Horse News which provided both written and photographic documentation.

CHAPTER V

ANALYSIS

This study focused on three ice jams known to have occurred on the Flathead River. Hydrological and meteorological data, in addition to qualitative reports from the Hungry Horse News, provided a framework for understanding the local conditions that produce ice-jamming events.

1963 Ice Jam

In early February 1963, a period of prolonged bitterly cold weather was followed by an early spring thaw (Butler and Wilkerson, 2001). This produced a two kilometer long ice jam on the Middle Fork on February 8th (Figure 6). The river deposited large ice slabs along the edge of the channel as it shifted into an area of braiding where the river is not constricted between narrow canyon walls. In some cases, mid-channel bars were completely submerged by ice slabs (Butler and Wilkerson, 2001).

SPRING THAW in February brought 1½ mile ice jam to Flathead's Middle Fork. River changed channel at Nyack flats, and left accumulations of ice along its shore. Here's the jammed Middle Fork near Nyack with an island submerged. No reports of serious damage.

Figure 6. Spring Thaw (Anonymous, 1963a).

The average discharge for the period examined (January 24th – February 23rd) was 36.66 m^3 / s (1294.77 cfs). Discharge remained below this average, at approximately 18.5 m^3 / s (653.32 cfs) between January 24th and February 3rd, and began rising on February 4th. Discharge peaked at 65.13 m^3 / s (2300 cfs) on February 8th; the day the ice jam was reported. The Hungry Horse News reported that the Middle Fork "freed itself of ice as the jam came through" indicating that this was a breakup event (Figure 7). The discharge was below average because the river was frozen over and the breakup of the ice released the water that was being stored behind it.

FLATHEAD'S MIDDLE FORK freed itself of ice as the jam came through West Glacier Friday. River left blocks of ice on the shores.

Figure 7. Flathead's Middle Fork (Anonymous, 1963b).

Meteorological conditions also contributed to the rapid rise in discharge. Air temperatures remained below freezing January 24th to February 2nd, reaching freezing on February 3rd. Air temperature peaked at 5.56°C (42°F) on February 4th and stayed above freezing through February 7th. Warming air temperatures during this timeframe contributed to melting, and consequently, the rise in discharge which peaked the day after, Feb. 8th. The NCDC data support the early spring thaw reported by the Hungry Horse News, later summarized by Butler and Wilkerson (2001). Figure 8 shows a substantial direct relationship between river discharge and air temperature. Rising discharge levels can be largely attributed to warming air.

Another meteorological variable analyzed was precipitation, as snow/ice pellets or as rain/melted snow. Snow fell during the cold temperatures experienced from January 24th to February 2nd and maximum daily values reached 36.58 cm (14.4 in) on February 1st. Rain January 31st through February 3rd melted the preexisting snow accumulations. Rain and snowmelt runoff contributed to the rise in discharge; however the effect on the hydrograph was not immediate. It takes a period of time for runoff to appear on the hydrograph because runoff from the farthest reaches of the drainage basin takes a while to reach the main stem of the river. This lag time is demonstrated in Figure 9, where the rain and snow peaks were a few days before the rising limb on the hydrograph.

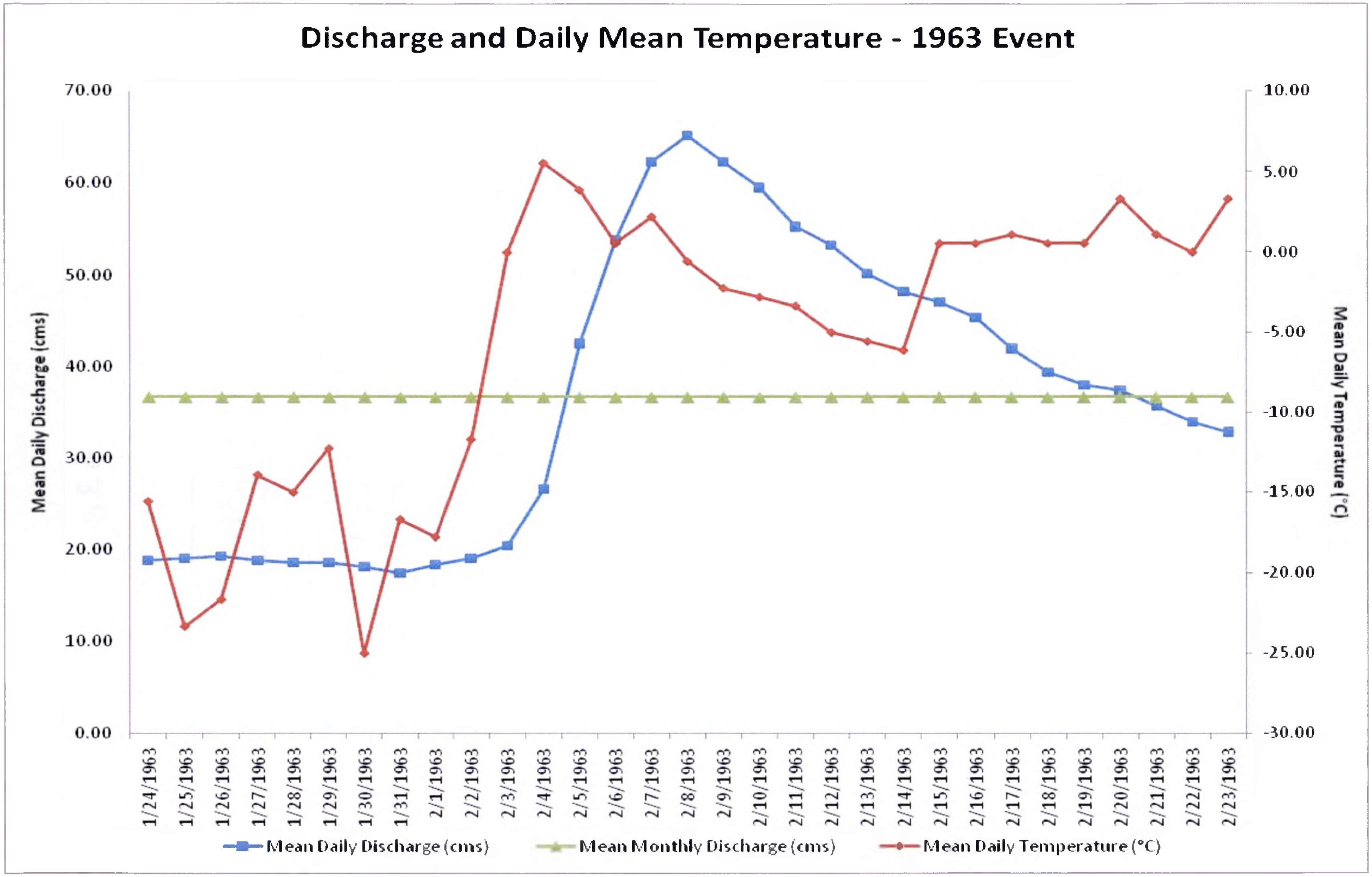


Figure 8. Discharge and Daily Mean Temperature – 1963 E ent.

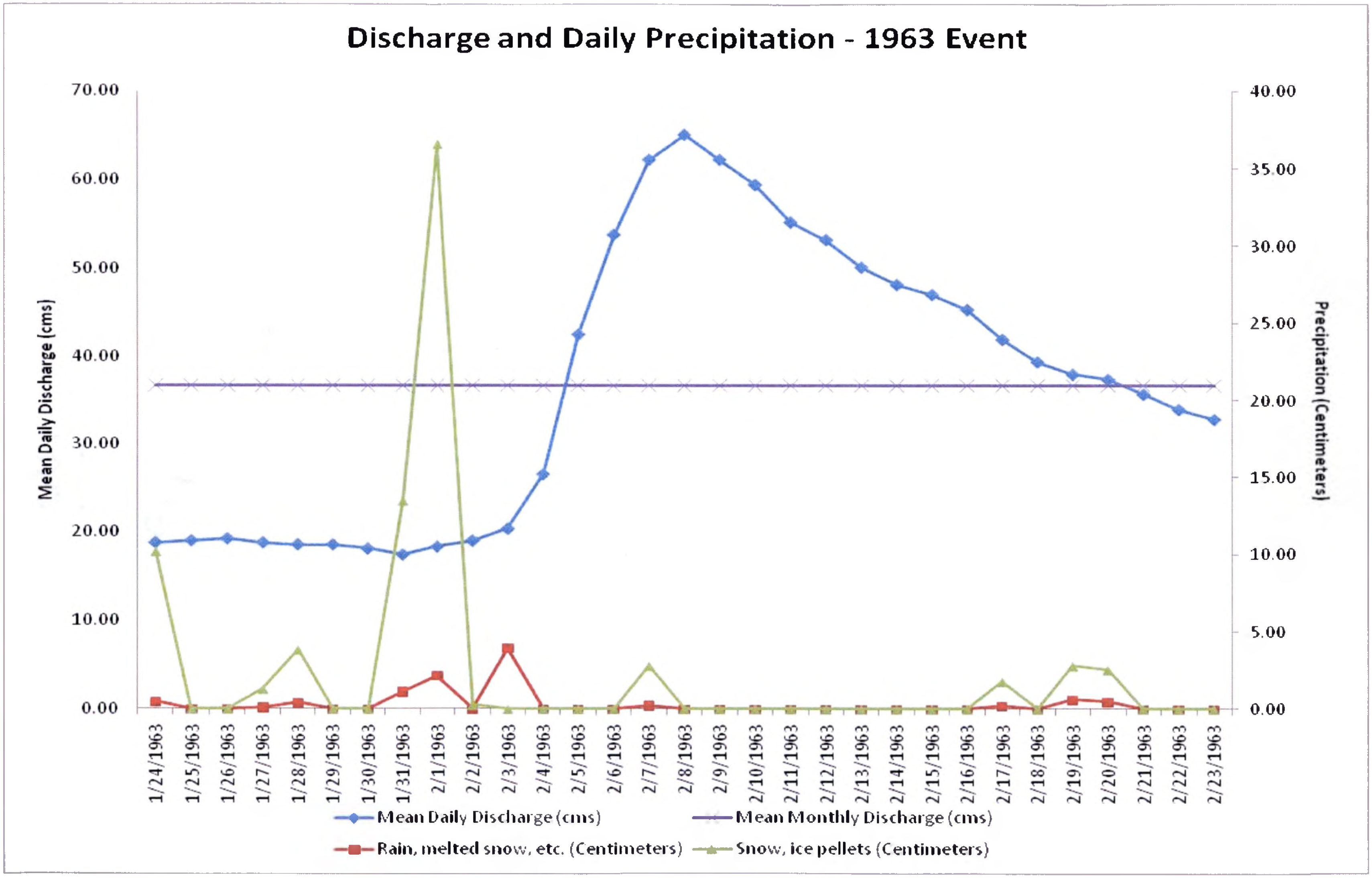


Figure 9. Discharge and Daily Precipitation – 1963 E ent.

1979 Ice Jams

In January and early February, 1979, similar conditions of bitterly cold weather were followed by an early thaw prevalent in the area. The Hungry Horse News reported that January 1979 was the coldest month on record since the start of weather records in 1897 (Crandell 1979; Ruder 1979b). The average monthly temperature was -17.66°C (0.2°F); normal was -7.17°C (19.1°F). The National Weather Service said the cold snap was due to a high pressure ridge that trapped cold air in the valley and predicted that the break up of this ridge would bring warmer temperatures and snow (Crandell, 1979). The Hungry Horse News also reported a minor ice jam developed along the North Fork of the Flathead River, approximately thirty kilometers north of the Middle Fork location (Butler and Wilkerson, 2001). Interestingly, however, there were no reports of ice jamming along the Middle Fork (Ruder, 1979a).

The average discharge for the period examined (January 17th – February 16th) was 12.62 m^3 / s (445.81 cfs). Discharge peaked at 20.67 m^3 / s (730 cfs) on February 16th, a few weeks after the minor ice jams were reported. The Hungry Horse News reported chunks of ice floating down the North Fork on January 25th (Figure 10). The river was flowing but was carrying with it blocks of ice that posed the threat of jamming between narrow constrictions downstream. The USGS data supported this in reporting discharge at 11.89 m^3 / s (420 cfs), just below average.

CHUNKS OF ICE float down the North Fork of the Flathead River. The sun shone briefly Monday morning but soon retreated behind more clouds.
Mel Ruder photo

Figure 10. Chunks of Ice (Ruder, 1979a).

The Hungry Horse News later indicated a possible freeze-up jam on February 1st, when they reported that the "coldest January in Flathead's recorded history sees Flathead's North Fork frozen over" (Figure 11). Discharge was expected to be low because the river was frozen over. Again the USGS data confirm that this was a freeze-up jam as proposed by the Hungry Horse News; the lowest discharge values occurred on January 31st and February 1st at 9.34 m^3 / s (330 cfs) and 9.63 m^3 / s (340 cfs), respectively.

COLDEST JANUARY in Flathead's recorded history sees Flathead's North Fork frozen over at Canyon Creek Point. Snow depths up the North Fork are below normal. Mel Ruder photo

Figure 11. Coldest January (Ruder, 1979b).

All NCDC January air temperatures were below freezing, with the lowest mean temperatures occurring February 1st through 3rd at -20°C (-4°F). During this time discharge values were also at their lowest, supporting the theory that this was a freeze-up event (Figure 12).

Snow and rain were experienced in the days leading up to the minor ice jam reported on January 25th. Rainfall on frozen surfaces likely contributed to the breakup of ice more so than rising discharge levels due to runoff, as the discharge value remained below normal and did not increase (Figure 13). No precipitation was reported for the days leading up to the February 1st freeze-up jam. Below freezing, calm, dry conditions likely added strength to the cohesion of ice.

Two factors may help explain the less pronounced relationships between discharge and meteorological conditions surrounding the 1979 ice jams. First, these jams were reported as “minor events” and therefore do not exude the clarity and definition associated with stronger examples. Second, 1979 is considered by some definitions and models to have been an El Niño year. This may account for some of the meteorological variability experienced in the area, especially in terms of air temperature (Dixon et al., 1999) (Figure 12).

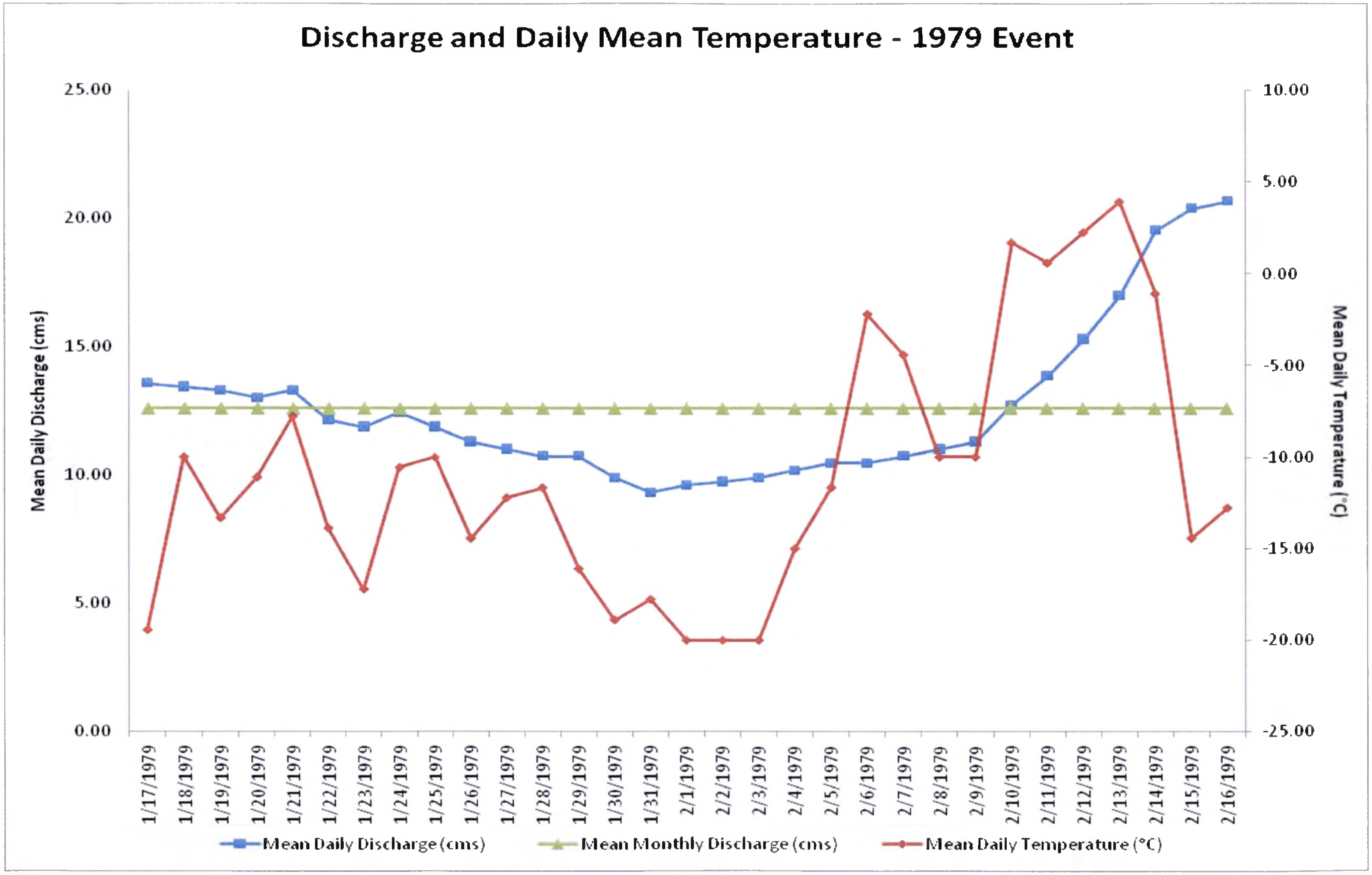


Figure 12. Discharge and Daily Mean Temperature – 1979 Event.

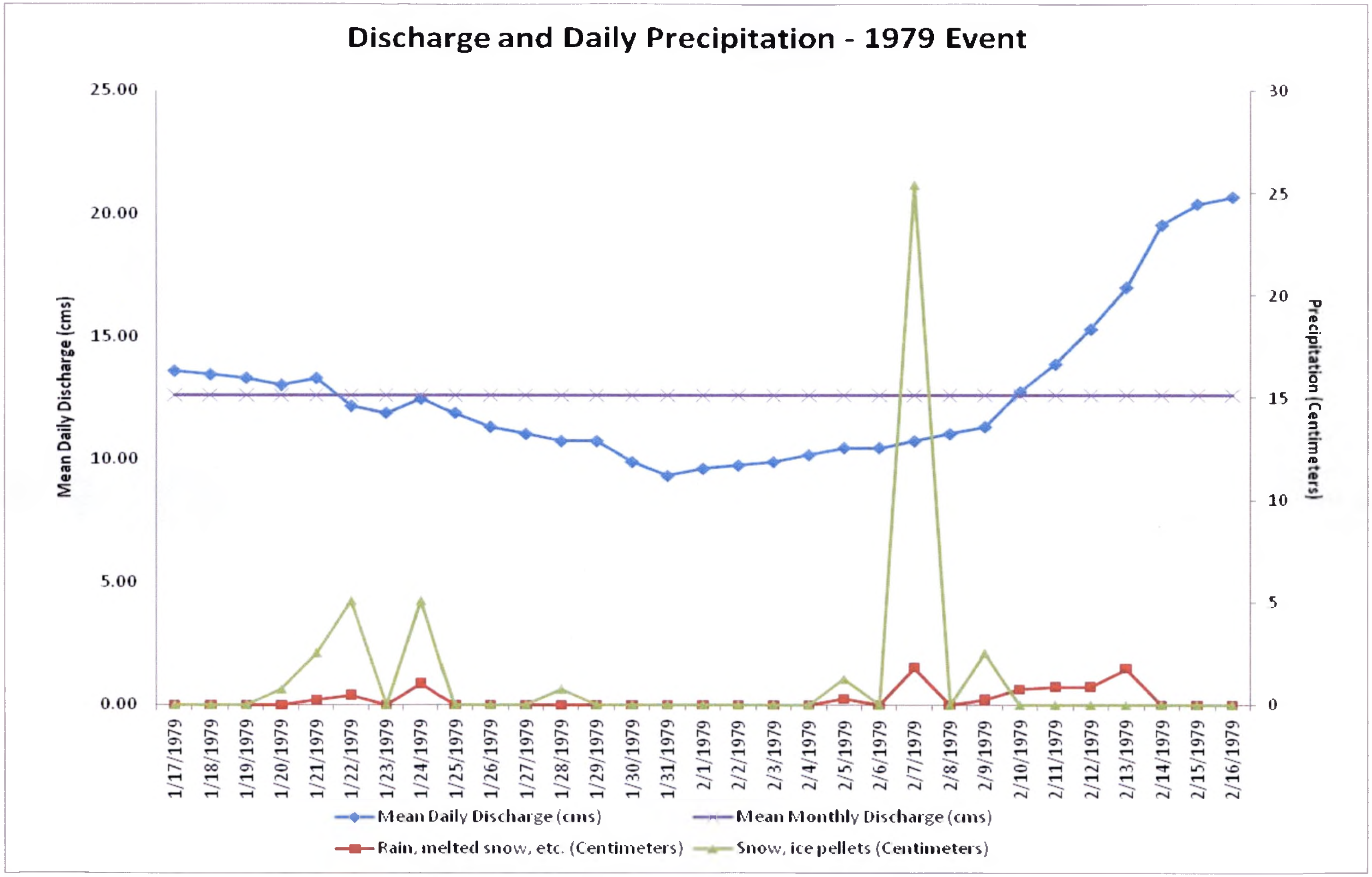
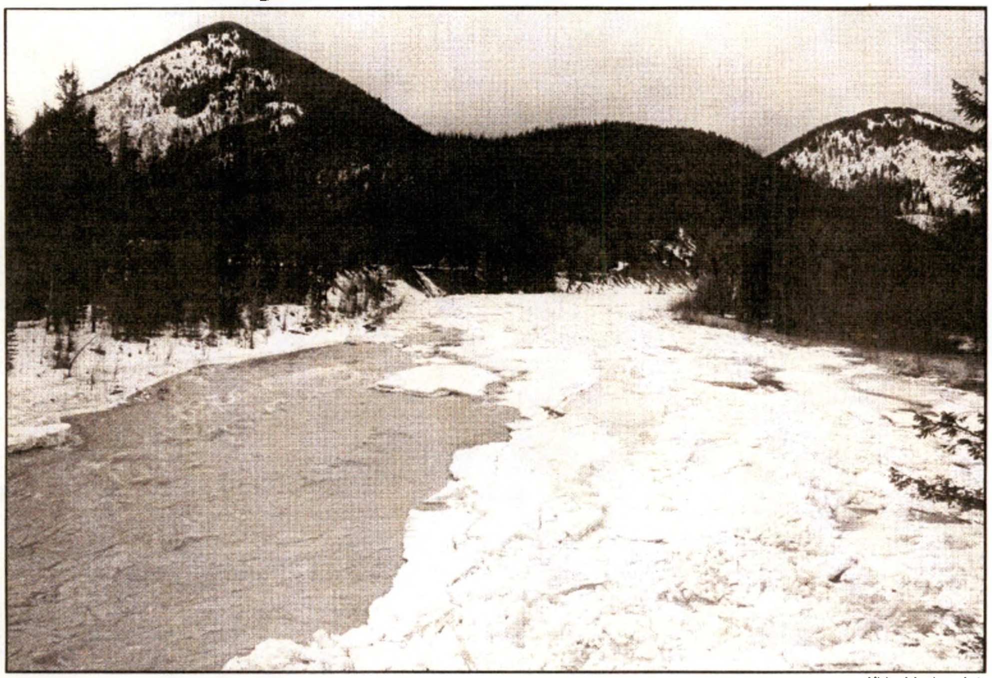


Figure 13. Discharge and Daily Precipitation – 1979 Event.

1996 Ice Jam

A series of upper-air disturbances produced extremely cold temperatures and a large amount of snow in January of 1996. Exceptionally cold conditions prevailed for several weeks causing the Middle Fork of the Flathead River and its tributaries to freeze to a great depth. District rangers estimated the ice was 3 – 5 meters thick. Weather conditions changed dramatically on February 8^{th} and 9^{th} as a Pacific front moved in, bringing unseasonably warm temperatures and with it, widespread rain. In some places temperatures rose more than 40°C in a 24-hour period (Butler and Wilkerson, 2001). "The warm temperatures and rain onto the frozen surface of the river and its tributaries initiated widespread break-up conditions on February 9^{th} " (Butler and Wilkerson 2001, 58). Rain and snowmelt runoff led to a rapid rise in water levels in the river and streams, causing them to approach bankfull conditions. The rising water broke apart the ice cover and began moving the ice downstream. Ice jamming occurred due to the numerous constrictions in the deeply incised canyon of the Middle Fork. The ice jam was estimated to be two kilometers long at its height (Figure 14). When the jam broke loose, tabular-shaped chunks of ice more than 2-meters deep were deposited on the riverbanks. This in turn heavily impacted the riparian forest lining the river channel (Butler and Wilkerson, 2001).

Middle Fork jam



Michael Jamison photo

A mile-long ice jam on the Flathead River's Middle Fork broke loose last week, sending tons of hardpack snow, ice and debris downstream. The mass of ice clogged McDonald Creek, damaging Quarter Circle Bridge in Glacier Park. Longtime residents could not remember an ice jam of this size ever clogging the Middle Fork.

Figure 14. Middle Fork jam (Jamison, 1996).

One large meander bend became especially choked with ice. Ice moving downstream was displaced and forced up McDonald Creek where it smashed into the Quarter Circle Bridge, ripping out bridge pilings and leaving 10-15 meters of the bridge completely unsupported and literally hanging in the air (Butler and Wilkerson, 2001).

At the mouth of Lincoln Creek, "ice jamming along the Middle Fork of the Flathead River temporarily impounded the meltwater coming down Lincoln Creek, until the water burst through the ice dam and flowed into the river in an outburst flood channel" (Butler and Wilkerson 2001, 59). Outburst floods are particularly dangerous because they can catch people downstream unaware, leading to potential tragedy (Butler and Wilkerson, 2001).

The average discharge for the period examined (January 25th – February 24th) was 58.64 m³ / s (2071 cfs). Discharge remained below average until February 8th when it rose from 43.89 m³ / s (1550 cfs) to 110.15 (3890 cfs) on February 9th. Discharge peaked at 181.51 m³ / s (6410 cfs) on February 10th, the day after the ice jam was first reported. The below average discharge data from the USGS support the Hungry Horse News reports that the Middle Fork of the Flathead River was frozen to great depth. More water was locked in as ice until breakup was initiated on February 9th, also supported by the USGS data. The 1996 hydrograph produced the most visually dramatic "spike" in discharge. This dramatic rise in discharge is closely linked to rising temperatures and precipitation runoff.

Air temperatures remained below freezing January 25th through February 5th, with temperatures plummeting to -26.11°C (-15°F) on January 30th. Temperatures rose to above freezing starting February 6th leading up to the jam date, February 9th. Figure 15 shows the strong direct relationship between rising temperatures and increased discharge levels.

In 1996, snowpack levels at high elevations were well above average for the state. The mountain snow water content across western Montana was 14% above average (Friend, 1996). Intermittent rain events likely melted the snowpack. The NCDC reported snow and rain events February 4th through 7th followed by rain only events on the 8th and 9th. Rain and snowmelt runoff in turn increased river discharge, as shown in Figure 16. The discharge spiked to 181.51 m³ / s (6410 cfs) days after the larger rain event occurred. Again, it is important to note that the rising limb and peak of the hydrograph are slightly delayed because it takes time for runoff from the farthest reaches of the drainage basin to reach the river.

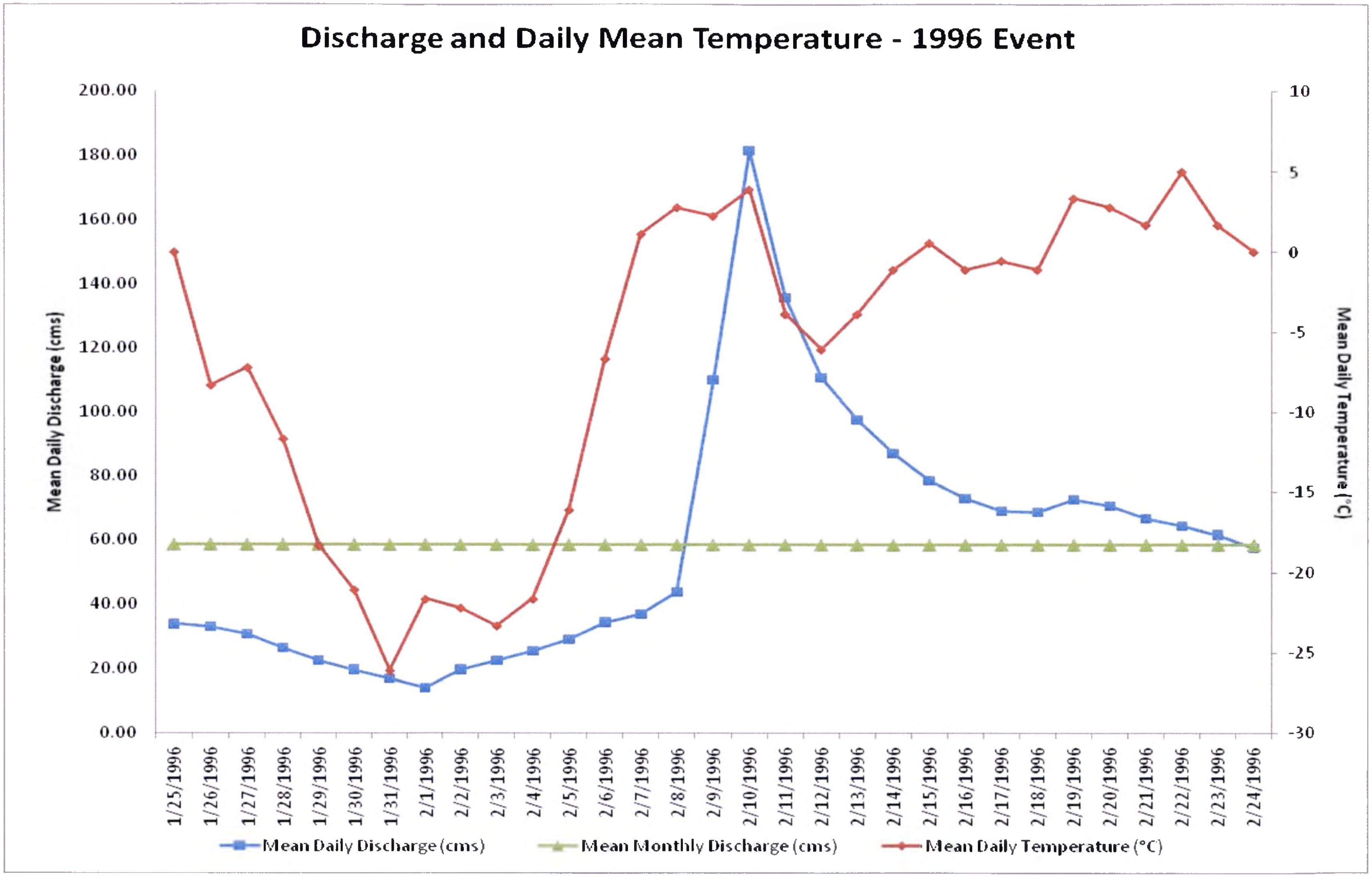


Figure 15. Discharge and Daily Mean Temperature – 1996 Event.

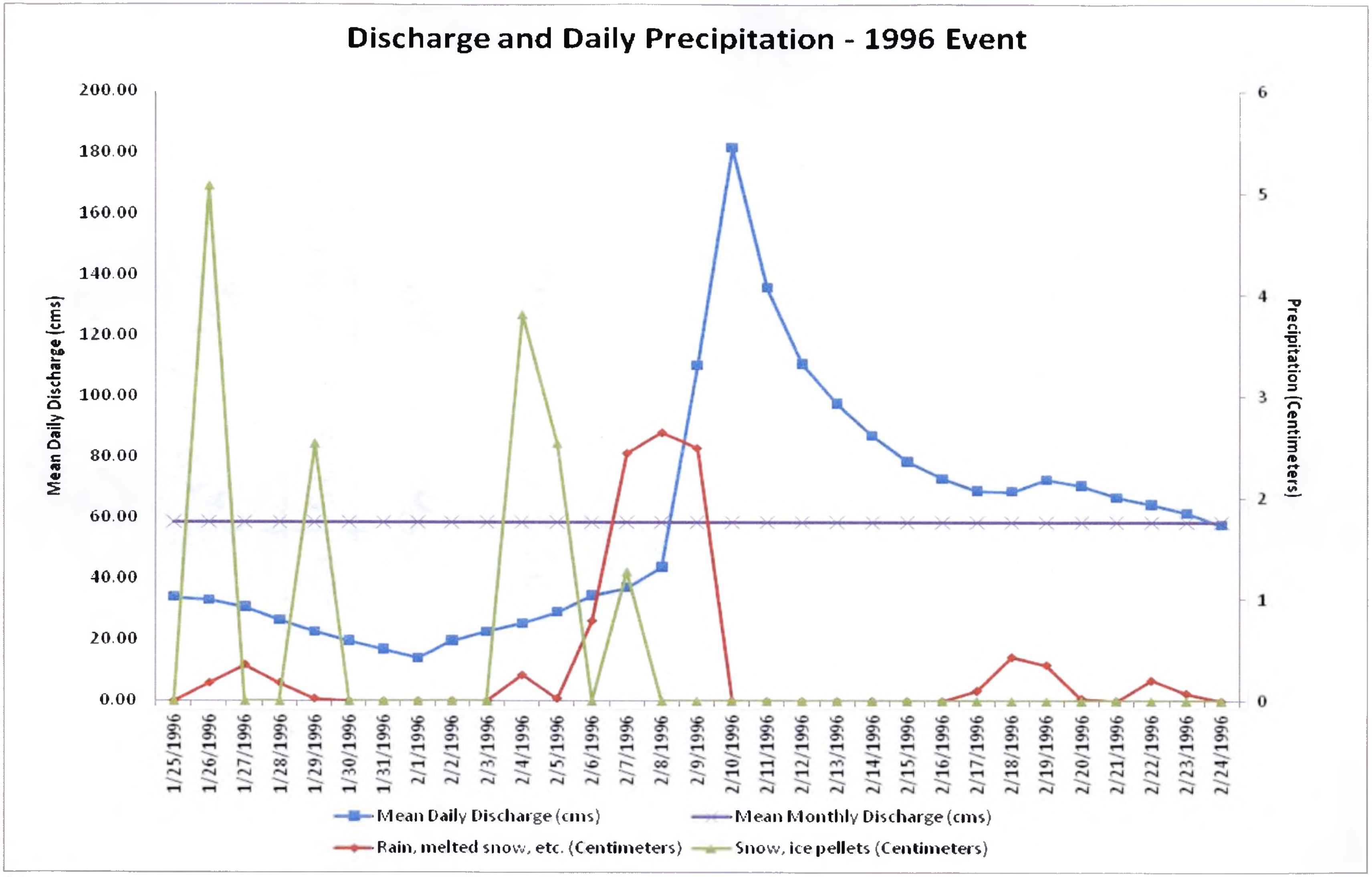


Figure 16. Discharge and Daily Precipitation – 1996 Event.

CHAPTER VI

FINDINGS AND CONCLUSIONS

The main objective of this study was to determine if there are signature river discharge, air temperature, and precipitation characteristics that lead to the formation of ice jams and ice-jam breakup events. While signature characteristics in terms of a threshold or specific number could not be identified from the three events, commonalities were discovered between ice jam types and will be discussed within the context of the two hypotheses underlying this study.

Findings

The two hypotheses were:

1. During freezing temperatures, the lower the river discharge, the higher the probability that freeze-up ice jams will develop; and consequently, the higher the river discharge, the lower the probability that freeze-up ice jams will develop.

The freeze-up ice jam reported on February 1st 1979 supported this hypothesis. January was the coldest month since weather records were kept in 1897 (Crandell, 1979; Ruder, 1979b) and river discharge was the lowest on January 31st and February 1st, at 9.34 m^3 / s (330 cfs) and 9.63 m^3 / s (340) respectively. Periods of intense, prolonged cold were experienced alongside low discharge values with reports of freeze-up having the lowest discharge values. Freeze-up jams were not reported when discharge was high; it would take substantially more extreme conditions to freeze more amounts of water.

2. Periods of intense cold followed by drastic warming can trigger the break-up of ice cover that leads to breakup ice jam events. Such temperature deviations are often experienced alongside precipitation changes from snow to rain, which will significantly amplify the event.

The breakup jams of 1963 and 1996 occurred during winters in which periods of intensely cold air temperatures were followed by a period of rapid warming. "Strong meridional flow causing bitterly cold temperatures, followed by a rapid warming, produces the conditions appropriate for ice-jam development" (Butler and Wilkerson 2001, 62). Both breakup jams showed a strong, direct relationship between air temperature and river discharge (Figures 8 and 15).

The 1996 ice jam occurred in almost the exact location as in 1963, on almost the exact date. In both cases, mid-channel bars were completely submerged by ice slabs; to a lesser extent in 1996 than in 1963. Both years had considerable preexisting snowpacks that were melted rapidly by rain events.

Conclusions

Beltaos (2002) argued that the flow hydrograph, the thickness of winter ice cover, and stream morphology are the main factors governing the occurrence and severity of river ice jams. This study found flow hydrograph, air temperature, and precipitation to be the governing factors for this locale. Precipitation is the primary factor while precipitation, if secondarily so, is not a driving factor. It was hoped that signature hydrological and meteorological conditions leading to ice jam formation and breakup could be established by analyzing past events. Future studies should try predicting discharge using local weather forecasts; instead of analyzing past ice-jamming events, trying to predict future ice jams. Similar meteorological conditions surrounding ice jam breakup events are known to cause avalanching; future studies could also further analyze this relationship.

There are a lot of unresolved questions surrounding river ice science and therefore future research is needed in a variety of fields. As previously mentioned, forecasting and prediction through modeling, especially in the context of climate change, could prove to be an invaluable tool for local land use managers and emergency planners. Future research is also needed in analyzing the effectiveness of mitigation, adaptation, and management strategies. For example, an agreement with Hungry Horse Dam keeps warm water from the reservoir flowing into the South Fork of the Flathead River. This keeps the river flowing at constant levels and the warm water helps prevent ice jam formation (Friend, 1996). There are a variety of ice jam management options that must be studied to determine the best option for the local community.

APPENDIX A. 1963 Data

Date	Discharge cfs (Mean)	Mean Daily Discharge (cms)	Mean Daily Temp (°F)	Mean Daily Temp. (°C)	Rain/melted snow (Inches)	Rain/melted snow (Centimeters)	Snow/ice pellets (Inches)	Snow/ice pellets (Centimeters)
1/24/1963	664 [A]	18 80	4	-15.56	0.18	0.46	4	10.16
1/25/1963	672 [A]	19.03	-10	-23.33	0	0 00	0	0.00
1/26/1963	680 [A]	19 26	-7	-21.67	0	0.00	0	0.00
1/27/1963	664 [A]	18.80	7	-13.89	0.04	0.10	0.5	1.27
1/28/1963	656 [A]	18.58	5	-15 00	0.15	0.38	1.5	3.81
1/29/1963	656 [A]	18.58	10	-12.22	0	0 00	0	0.00
1/30/1963	640 [A]	18.12	-13	-25.00	0	0.00	0	0.00
1/31/1963	616 [A]	17.44	2	-16.67	0.44	1.12	5.3	13.46
2/1/1963	648 [A]	18 35	0	-17.78	0.85	2.16	14.4	36.58
2/2/1963	672 [A]	19.03	11	-11 67	0	0.00	0.1	0 25
2/3/1963	720 [A]	20.39	32	0.00	1.54	3.91	0	0.00
2/4/1963	940 [A]	26.62	42	5.56	0	0.00	0	0.00
2/5/1963	1,500 [A]	42.48	39	3 89	0	0 00	0	0 00
2/6/1963	1,900 [A]	53.80	33	0.56	0	0.00	0	0.00
2/7/1963	2,200 [A]	62.30	36	2.22	0.09	0.23	1.1	2.79
2/8/1963	2,300 [A]	65 13	31	-0 56	0	0.00	0	0.00
2/9/1963	2,200 [A]	62.30	28	-2 22	0	0.00	0	0 00
2/10/1963	2,100 [A]	59.47	27	-2.78	0	0.00	0	0.00
2/11/1963	1,950 [A]	55.22	26	-3.33	0	0.00	0	0.00
2/12/1963	1,880 [A]	53.24	23	-5.00	0	0.00	0	0.00
2/13/1963	1,770 [A]	50.12	22	-5 56	0	0.00	0	0.00
2/14/1963	1,700 [A]	48.14	21	-6 11	0	0.00	0	0.00
2/15/1963	1,660 [A]	47.01	33	0 56	0	0.00	0	0 00
2/16/1963	1,600 [A]	45.31	33	0.56	0	0 00	0	0.00
2/17/1963	1,480 [A]	41.91	34	1 11	0.08	0 20	0 7	1.78
2/18/1963	1,390 [A]	39.36	33	0.56	0	0.00	0	0 00
2/19/1963	1,340 [A]	37 94	33	0.56	0.24	0.61	1 1	2.79
2/20/1963	1,320 [A]	37.38	38	3.33	0.19	0.48	1	2.54
2/21/1963	1,260 [A]	35.68	34	1.11	0	0.00	0	0.00
2/22/1963	1,200 [A]	33.98	32	0 00	0	0.00	0	0.00
2/23/1963	1,160 [A]	32.85	38	3.33	0	0.00	0	0.00

APPENDIX B. 1979 Data

Date	Discharge cfs (Mean)	Mean Daily Discharge (cms)	Mean Daily Temp (°F)	Mean Daily Temp. (°C)	Rain/melted snow (Inches)	Rain/melted snow (Centimeters)	Snow/ice pellets (Inches)	Snow/ice pellets (Centimeters)
1/17/1979	480 [A]	13 59	-3	-19.44	0	0	0	0
1/18/1979	475 [A]	13 45	14	-10 00	0	0	0	0
1/19/1979	470 [A]	13 31	8	-13.33	0	0	0	0
1/20/1979	460 [A]	13 03	12	-11.11	0	0	0.3	0.76
1/21/1979	470 [A]	13 31	18	-7.78	0.1	0.25	1	2.54
1/22/1979	430 [A]	12.18	7	-13.89	0.19	0.48	2	5.08
1/23/1979	420 [A]	11.89	1	-17 22	0	0	0	0
1/24/1979	440 [A]	12.46	13	-10 56	0.41	1 04	2	5 08
1/25/1979	420 [A]	11.89	14	-10.00	0	0	0	0
1/26/1979	400 [A]	11 33	6	-14 44	0	0	0	0
1/27/1979	390 [A]	11 04	10	-12.22	0	0	0	0
1/28/1979	380 [A]	10.76	11	-11 67	0	0	0.3	0.76
1/29/1979	380 [A]	10.76	3	-16.11	0	0	0	0
1/30/1979	350 [A]	9.91	-2	-18.89	0	0	0	0
1/31/1979	330 [A]	9.34	0	-17.78	0	0	0	0
2/1/1979	340 [A]	9.63	-4	-20.00	0	0	0	0
2/2/1979	345 [A]	9.77	-4	-20 00	0	0	0	0
2/3/1979	350 [A]	9.91	-4	-20.00	0	0	0	0
2/4/1979	360 [A]	10.19	5	-15.00	0	0	0	0
2/5/1979	370 [A]	10.48	11	-11 67	0.12	0.30	0 5	1 27
2/6/1979	370 [A]	10 48	28	-2.22	0	0	0	0
2/7/1979	380 [A]	10 76	24	-4.44	0.72	1.83	10	25.4
2/8/1979	390 [A]	11.04	14	-10.00	0	0	0	0
2/9/1979	400 [A]	11.33	14	-10.00	0 11	0.28	1	2 54
2/10/1979	450 [A]	12.74	35	1.67	0 3	0 76	0	0
2/11/1979	490 [A]	13.88	33	0.56	0.35	0 89	0	0
2/12/1979	540 [A]	15 29	36	2 22	0.35	0.89	0	0
2/13/1979	600 [A]	16 99	39	3.89	0.7	1.78	0	0
2/14/1979	690 [A]	19.54	30	-1.11	0	0	0	0
2/15/1979	720 [A]	20 39	6	-14.44	0	0	0	0
2/16/1979	730 [A]	20.67	9	-12.78	0	0	0	0

APPENDIX C. 1996 Data

Date	Discharge cfs (Mean)	Mean Daily Discharge (cms)	Mean Daily Temp (°F)	Mean Daily Temp. (°C)	Rain/melted snow (Inches)	Rain/melted snow (Centimeters)	Snow/ice pellets (Inches)	Snow/ice pellets (Centimeters)
1/25/1996	1,200 [A]	33.98	17	-8 33	0	0	0	0
1/26/1996	1,170 [A]	33.13	19	-7.22	0 07	0 18	2	5.08
1/27/1996	1,090 [A]	30.87	11	-11.67	0 14	0 36	0	0
1/28/1996	937 [A]	26.53	-1	-18 33	0.07	0.18	0	0
1/29/1996	800 [e A]	22 65	-6	-21 11	0.01	0.03	1	2.54
1/30/1996	700 [e A]	19 82	-15	-26.11	0	0.00	0	0
1/31/1996	600 [e A]	16.99	-7	-21.67	0	0.00	0	0
2/1/1996	500 [e A]	14.16	-8	-22.22	0	0.00	0	0
2/2/1996	700 [e A]	19.82	-10	-23.33	0	0.00	0	0
2/3/1996	800 [e A]	22.65	-7	-21 67	0	0 00	0	0
2/4/1996	900 [e A]	25.49	3	-16.11	0.1	0.25	1 5	3.81
2/5/1996	1,030 [A]	29.17	20	-6.67	0.01	0.03	1	2.54
2/6/1996	1,220 [A]	34 55	34	1.11	0 31	0.79	0	0
2/7/1996	1,310 [A]	37.10	37	2 78	0 96	2 44	0.5	1.27
2/8/1996	1,550 [A]	43 89	36	2 22	1.04	2 64	0	0
2/9/1996	3,890 [e A]	110 15	39	3.89	0.98	2.49	0	0
2/10/1996	6,410 [A]	181.51	25	-3 89	0	0.00	0	0
2/11/1996	4,790 [A]	135.64	21	-6.11	0	0.00	0	0
2/12/1996	3,910 [A]	110 72	25	-3.89	0	0 00	0	0
2/13/1996	3,450 [A]	97.69	30	-1 11	0	0.00	0	0
2/14/1996	3,080 [A]	87.22	33	0.56	0	0 00	0	0
2/15/1996	2,780 [A]	78.72	30	-1.11	0	0.00	0	0
2/16/1996	2,580 [A]	73 06	31	-0 56	0	0.00	0	0
2/17/1996	2,440 [A]	69.09	30	-1.11	0.04	0.10	0	0
2/18/1996	2,430 [A]	68.81	38	3.33	0.17	0.43	0	0
2/19/1996	2,570 [A]	72 77	37	2 78	0.14	0.36	0	0
2/20/1996	2,500 [A]	70 79	35	1.67	0.01	0.03	0	0
2/21/1996	2,360 [A]	66.83	41	5.00	0	0 00	0	0
2/22/1996	2,280 [A]	64.56	35	1 67	0.08	0.20	0	0
2/23/1996	2,180 [A]	61.73	32	0 00	0 03	0 08	0	0
2/24/1996	2,040 [A]	57 77	27	-2 78	0	0 00	0	0

REFERENCES

Anonymous. 1963a. Spring thaw. *Hungry Horse News* 17 (27): 4.

Anonymous. 1963b. Flathead's Middle Fork. *Hungry Horse News* 17 (28): 1.

Ashton, G. D. 1978. River Ice. *Annual Review of Fluid Mechanics* 10: 369-92.

Bailey, R. G., P. E. Avers, T. King, and W. H. McNab, eds. 1994. *Ecoregions and Subregions of the United States* (map). Washington, DC, U.S. Geological Survey. Accompanied by a supplementary table of map unit descriptions compiled and edited by W.H. McNab and R.G. Bailey. Prepared for the U.S. Department of Agriculture, Forest Service.

Beltaos, S. 1995. *River Ice Jams.* Highlands Ranch, CO.: Water Resources Publications, LLC.

Beltaos, S. 1997. Onset of river ice breakup. *Cold Regions Science and Technology* 25: 183-96.

Beltaos, S. 2000. Advances in river ice hydrology. *Hydrological Processes* 14: 1613-25.

Beltaos, S. 2002. Effects of climate on mid-winter ice jams. *Hydrological Processes* 16: 789-804.

Beltaos, S. 2007. River ice breakup processes: recent advances and future directions. *Canadian Journal of Civil Engineering* 34: 703-16.

Beltaos, S., and B. C. Burrell. 1998. Transport of metals on sediment during the spring breakup of river ice. *Proceedings, 14th International Ice Symposium* 2: 793-800.

Beltaos, S., and B. Burrell. 2003. Climatic change and river ice breakup. *Canadian Journal of Civil Engineering* 30: 145-55.

Beltaos, S., and B. Burrell. 2005. Field measurements of ice-jam-release surges. *Canadian Journal of Civil Engineering* 32: 699-711.

Beltaos, S., and T. D. Prowse. 2001. Climate impacts on extreme ice-jam events in Canadian rivers. *Journal of Hydrological Sciences* 46: 157-81.

Blackburn, J., and F. Hicks. 2003. Suitability of dynamic modeling for flood forecasting during ice jam release surge events. *Journal of Cold Regions Engineering* 17: 18-36.

Butler, D. R., and F. D. Wilkerson. 2001. Hazardous ice jams in northwestern Montana: their prediction and effects on the landscape. *Papers and Proceedings of the Applied Geography Conferences* 24: 57-63.

Carey, K. L., G. D. Ashton, and G. E. Frankenstein. 1973. *Ice Engineering for Civil Works*. Hanover, NH: Corps of Engineers, U.S. Army, CRREL.

Carrara, P.E. 1990. Surficial Geologic Map of Glacier National Park, Montana. US Geological Survey Miscellaneous Investigations Series Map I-1508-D.

Confederated Salish and Kootenai Tribes [CSKT] and Montana Fish, Wildlife, and Parks [MFWP]. 2003. *Flathead River Subbasin Executive Summary 10/110/04: A report Prepared for the Northwest Power and Conservation Council.*

Crandell, S. 1979. Past 12 days coldest in Flathead history. *Hungry Horse News* 33 (24): 1.

Department of Emergency Services [DES]. 2004. *The State of Montana Multi-Hazard Mitigation Plan and Statewide Hazard Assessment.*

Dixon, R. W., D. R. Butler, L. M. DeChano, and J. A. Henry. 1999. Avalanche hazard in Glacier National Park: an El Niño Connection? *Physical Geography* 20 (6): 461-67.

Doyle, C. J. 1987. *Hydrometeorological aspects of ice jam formation at Fort McMurray, Alberta.* Alberta, Canada: University of Alberta – Department of Geography.

Fagre, D. B. 2000. Changing Mountain Landscapes in a Changing Climate: Looking into the Future. *Changing Landscapes*: University of Montana, Missoula, MT.

Fagre, D. B., P. L. Comanor, J. D. White, F. R. Hauer, and S. W. Running. 1997. Watershed responses to climate change at Glacier National Park. *Journal of the American Water Resources Association* 33 (4): 755-65.

Flathead Transboundary Network. 1999. State of the Crown of the Continent Ecosystem: Flathead/Castle Transboundary Region (Draft). Calgary: Miistakis Institute for the Rockies.

Friend, M. 1996. Flood waters spill across frozen Flathead; wash out roads, homes. *Hungry Horse News* 50 (29): 7.

Hall, M. H. P., and D. B. Fagre. 2003. Modeled climate-induced glacier change in Glacier National Park, 1850-2100. *Bioscience* 53 (2): 131-40.

Healy, D. 2006. *Experimental Observations on river ice accumulations*. Alberta, Canada: University of Alberta.

Healy, D., and F. E. Hicks. 2006. Experimental Study of Ice Jam Formation Dynamics. *Journal of Cold Regions Engineering* 20: 117-39.

Jamieson, B. 2002. Background information on the natural resources and compensation issues in the area of interest for a national park reserve in the southwest portion of the Flathead drainage in B.C. BioQuest International. TaTa Creek B.C.

Jamison, M. 1996. Middle Fork jam. *Hungry Horse News* 50 (29): 5.

Jasek, M. 2003. Ice jam release surges, ice runs, and breaking fronts: field measurements, physical descriptions, and research needs. *Canadian Journal of Civil Engineering* 30: 113-27.

Mahabir, C., F. E. Hicks, C. Robichaud, and A. R. Fayek. 2006. Forecasting breakup water levels at Fort McMurray, Alberta, using multiple linear regression. *Canadian Journal of Civil Engineering* 33: 1227-38.

Mock, C. J. 1991. Historical evidence of a cold, dry summer during 1849 in the northeastern Great Basin and adjacent Rocky Mountains. *Climatic Change* 18: 37-66.

Montana Natural Resource Information System. 2003. Middle Fork Watershed of the Flathead River, Montana. http://nris.mt.gov/ (last accessed 5 March 2010).

Montana Natural Resource Information System. 2003. North Fork Watershed of the Flathead River, Montana. http://nris.mt.gov/ (last accessed 5 March 2010).

Morse, B., and F. Hicks. 2005. Advances in river ice hydrology 1999-2003. *Hydrological Processes* 19: 247-63.

Patterson, J. L. 1966. Magnitude and frequency of floods in the United States. Part 6-1: Missouri River Basin above Sioux City, Iowa. USGS Water Supply Paper 1679.

Pfly. 2007. Flathead River. http://www.google.com/imgres?imgurl=http://upload.wikimedia.org/wikipedia/commons/2/21/Flathead_River_Map.png&imgrefurl=http://commons.wikimedia.org/wiki/File:Flathead_River_Map.png&h=628&w=813&sz=100&tbnid=SUgRADVO21K3VM:&tbnh=111&tbnw=144&prev=/images%3Fq%3Dflathead%2Briver&hl=en&usg=__QhMU40CLKVltYBD_GnbV1sPyfzU=&ei=XqXyS52rC4SClAfT6Y3pDA&sa=X&oi=image_result&resnum=4&ct=image&ved=0CD0Q9QEwAw (last accessed 5 March 2010).

Prowse, T. D., and S. Beltaos. 2002. Climatic control of river-ice hydrology: a review. *Hydrological Processes* 16: 805-22.

Prowse, T. D., and J. M. Culp. 2003. Ice breakup: a neglected factor in river ecology. *Canadian Journal of Civil Engineering* 30: 128-44.

Robichaud, C. 2003. *Hydrometeorological factors influencing breakup ice jam occurrence at Fort McMurray, Alberta.* Alberta, Canada: University of Alberta.

Ruder, M. 1979a. Chunks of Ice. *Hungry Horse News* 33 (26): 16.

Ruder, M. 1979b. Coldest January. *Hungry Horse News* 33 (27): 6.

Smith, D. G., and C. M. Pearce. 2000. River ice and its role in limiting woodland development on a sandy braid-plain, Milk River, Montana. *Wetlands* 20: 232-50.

Smith, D. G., and C. M. Pearce. 2002. Ice jam-caused fluvial gullies and scour holes on northern river flood plains. *Geomorphology* 42: 85-95.

Stermitz, F., T. F. Hanly, and C. W. Lane. 1963. Mineral and Water Resources of Montana. *Montana Bureau of Mines and Geology Special Publication No. 28.*

USACE. 1998. Ice Jams in Montana. *Information Exchange Bulletin*: Hanover, NH: Corps of Engineers, U.S. Army, CRREL.

USGS. 2002. Flow data for Flathead. US Geological Survey Water Resources Website. Surface Water Data. www.usgs.gov (last accessed 5 March 2010).

Western Regional Climate Center [WRCC]. 2010. Climate of Montana.

White, K. D. 1996. Predicting breakup ice jams using logistic regression. *Journal of Cold Regions Engineering* 10: 178-90.

White, K. D. 2003. Review of prediction methods for breakup ice jams. *Canadian Journal of Civil Engineering* 30: 89-100.

White, K. D., and H. J. Eames. 1999. CRREL Ice Jam Database. *CRREL Report 99-2*: Hanover, NH: Corps of Engineers, U.S. Army, CRREL.

White, K. D., A. M. Tuthill, and L. Furman. 2007. *Studies of Ice Jam Flooding in the United States*. Hanover, NH; Corps of Engineers, U.S. Army, CRREL.

Woessner, W., D. F. Potts, S. W. Running, J. S. Kimball, T. H. DeLuca, D. B. Fagre, S. Makepeace, M. S. Hendrix, J. N. Moore, M. S. Lorang, and B. K. Ellis. 2004. Flathead River Basin Hydrologic Observatory, Northern Rocky Mountains. University of Montana: Missoula.

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