A CLIMATOLOGY OF STREAMFLOW FOR GLACIER NATIONAL PARK

MONTANA, U S.A

THESIS

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by

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CHAPTER I

INTRODUCTION

A glacier is a mass of granular snow and ice formed by the compaction and recrystallization of snow that amasses over time Glaciers are being used as monitors of global climate change to determine pre-industrial variability energy exchanges between the earth and atmosphere. Anthropogenic causes of retreating glaciers are seen as a very recent development and may only affect glaciers on a small scale (Haeberli et al 1999) Observations have been made about glaciers to determine what condition they may be in by repeat photography, stream flow measurements, climate change and modeling (Hall and Fagre 2003). Most of these observations have shown that glaciers are receding from past places where they used to dominate the landscape. Through these studies, it is possible to verify the volume of meltwater that these glaciers have lost over time by the increased stream flow and measured recession of the glaciers.

Glacier National Park, Montana has been the site where several glacial studies have taken place that record the changing and shrinking of glaciers (Fountain et al. 1997). The park is named for the effects of the Pleistocene glaciation on display there. Glacier research and ongoing studies have been a prominent theme since its creation in 1910. Dyson (1948) clarified some of the early shrinkage of Sperry and Grinnell glaciers, stating that they have been reduced in surface and total area since the National Park Service measured recession in 1931

In this study, available repeat photography has been utilized to visually represent the drastic changes of glacier retreat, which has been used in the past to show the recession of Sperry and Grinnell glaciers in the 20^{th} century (Johnson 1980). All major streams associated with the Hudson Bay Basin watershed will be used to correlate the amount of increased stream flow in recent years with the rise of yearly temperatures provided by weather station Babb 6 NE and West Glacier in Montana. The total area of the glaciers is already known to be shrinking. With this knowledge it is then possible to determine what effect glacial melt has on other fluvial processes. What is the relationship between temperature and streamflow in this study area? Is there a significant correlation between temperature and streamflow to prove that the glaciers are responsible for an increase of water flow? These are the objectives of this study.

The Hudson Bay Basin area, where the glaciers are located, is comprised of high and rugged terrain Most of the research that has been done in conjunction with the glaciers has been the measuring of physical retreat of the glaciers and observing how it may affect the surrounding area.

This research was done following systems theory. A system is a set of two or more elements that satisfy three conditions (Ackoff 1981):

- The behavior of the individual elements has an effect on the whole system.
- The behavior of the individual elements and effects on the system are interdependent
- Subgroups of the individual elements are formed and have an effect on the behavior of the system, but none has an independent effect on the system

Using systems as the basis of this research, the entire mountain environment where the glaciers are located is the system. The temperatures, glaciers and streamflow are elements, and the streamflow may also be considered a subgroup. The behavior of the temperature, increasing since the advent of global warming, or changing decadal climate patterns, has caused the glaciers to recede Increased streamflow from the glacial melt then affects the environment near the streams and contributes to further processes in the system.

Another attribute of systems theory is the concept of output and negative entropy (Katz and Kahn 1966). Open systems often output a product, in this case one of the outputs is meltwater from the receding snow and ice which allows the vegetation to be sufficiently nourished to creep further up the mountain slopes Positive entropy is the process when all parts of an organization are moving toward disorganization and death. Some systems can allow this to go on for extended periods of time to conserve energy, but more often a large number of systems die, just like the glaciers in Glacier National Park.

The data collected and analyzed in this research have been used to indicate if a relationship exists between increased temperature and possible increased streamflow because of receding glacier movement in Northwestern Montana, now and in past decades. Repeat photography of certain glaciers in the study area complements the statistical analysis of these data sets.

CHAPTER II

LITERATURE REVIEW

The literature supported the research and methods of this study The literature is classified into three sections: climate, glacial studies and repeat photography.

Glaciers are a part of the landscape that have been observed and recorded for many years, but recently these observations have been so dramatic as to warrant some concern. Key et al. (2002) state that when glaciers in Glacier National Park are compared with their historical areas, they are excellent examples of glacier retreat occurring in the Rocky Mountains Most of the glaciers in the area only exist because of their well-placed orientation to snow storms and wind-blown deposits, not because they are sheltered from insolation.

Climate

The beginning of glacial retreat is tied to severe climatic conditions. The Little Ice Age, which lasted from the 14^{th} to the middle of the 19^{th} centuries, was a time when the heaviest snowfall has been recorded in Europe and North America. Many glaciers in the Alps advanced, and small towns and farms were engulfed by ice. Since then, entire glaciers have been lost and snow accumulation rates have lowered.

Several studies have looked into global warming and climate change (White et al 1998) and its affects on glaciers, not only in Montana but around the world.

Global warming is seen as a force that is melting glaciers and causing the sea level to rise Some scientists believe if the planet is warming and causing a further increase in the hydrologic cycle, then snowfall will increase (Grosvenor et al. 2004). But so far, observations around the world have shown a greater decrease in snowfall because of shorter cold periods (Houghton 2004). Overall, future scenarios predict will indicate more winter floods, shorter winters and drier, longer summer weather (Loaiciga et al 1996).

Much of the information about past climates and ice ages is found by inspecting the earth's topography for glacial landforms (Wilson et al. 2000). In Glacier National Park, Montana, the changes from the Little Ice Age can be seen through the seasons when the snow recedes. Places that were once covered with glaciers are now bare of any snow accumulation. Global warming may be one of the causes of the decrease in colder temperatures, and the other could be the Pacific decadal oscillation (PDO) (Selkowitz et al. 2002). PDO is somewhat like an El Nino-southern-oscillation pattern. Off the western coast of the United States the Aleutian Low will increase, which causes storms to travel further south When this occurs, atmospheric pressures increase across northwestern North America, resulting in higher than normal winter temperatures and less winter precipitation (Meier et al. 2003). This interdecadal climate regime shift occurred in 1976-77.

Glacier balances have been strongly affected in western North America by other Pacific Basin climatic conditions. Maritime Alaskan glaciers have been influenced by colder conditions in the North Pacific and then tropical Pacific conditions in the summer (Hodge et al. 1997). Arctic sea ice has seen a decrease and has been melting more since the 1976-77 climate regime shift which ended in 1988. Since 1988, many glacier termini in Canada have retreated. The rise in snowline has created smaller glacier areas, leading to decreased meltwater and less total streamflow runoff (Moore 2001).

Climate variability and possibly PDO may relate to SWE, Snow Water Equivalent, of the early spring months inside the park. SWE is lower in spring because vegetation and topography serve to keep snow blocked between rock outcrops, trees or small shrubs, so that it is less susceptible to increased melting rates than glaciers that are more exposed to solar radiation (Geddes et al. 2005). With a lowered SWE, streamflow may not show a dramatic increase in discharge By correlating annual temperature and annual streamflow discharge for this study area, a more concise data set will be utilized to provide a better understanding of climatic change for a smaller area.

Glacial Studies

Glacial observations have been considered to be indicators of a changing climate (T.J Chinn 1996). Records of the glacial recession from 1965-1967 detail some of the strange relationships between greater precipitation and lower summer temperatures that are influencing the size and area of glaciers in the park (Arthur Johnson 1965) One such example is Grinnell Glacier. During the winter of 1964 and through to the summer of 1965, the mean temperature for August was below the average for 6 years. The surface elevation of Grinnell Glacier decreased from 1950 to 1965 by an increment of 25 feet. The most glacial melting takes place at the edges of the glacier. Ablation during this period was measured with stakes and also showed a steady decline that averaged between 30 to 50 feet per year (Arthur Johnson 1965). The 1966-1967 report of Arthur Johnson showed a high rate of ablation. The highest recession rate between 1965-1966 was 7 feet, and 16.4 feet between 1966-1967 These reports show a rapid decline in glacier size that relates to increased temperatures.

As the edges of the glacier melt and high summer temperatures follow low accumulation rates, the runoff from glacier-fed streams in mountain ecosystems usually increases (Birsan et al 2005). But it can be difficult to obtain completely accurate glacial hydrology measurements for an area, because some criteria in mountain ecosystems can not be accounted for, such as blowing snow (Meier 1969).

In western North America, many alpine glaciers are reaching peak runoff rates during early summer because of their decrease in size Peak solar intensity on glaciers affects the degree of snow melt (Conovitz et al 1998) These glacier basins are then prone to increased drought, but glaciers that are covered in surface debris are melting at slower rates (Basagic et al. 2004). Many of the glacial studies in the western United States predict a decrease in streamflow because of smaller glacial areas. But other obstructions to melt, such as sediment or woody debris, may be the cause of lower stream discharges.

Repeat photography

Repeat photography has been used in geography to monitor the changes in landscape by many people (Butler and DeChano 2001). In Glacier National Park, Montana, many photographs have been taken to chart the progress of alpine treeline (Butler et al 1994), vegetation types (Brown 1994), different ecotone environments (Butler et al. 2003) and the changes of glaciers (Pederson et al. 2004). Repeat photography is a simple data collection technique that shows the physical changes of the landscape in a dramatic and non-quantitative way. Factors that might influence the correct interpretation of these photos would be if glacial debris covered parts of the exposed snow and a definite line delineating the glacier boundary was unable to be seen (Champoux and Ommanney 1986).

The United States National Park Service has been categorizing and collecting photos of glaciers in Glacier National Park since the 1900's. These photos provide the evidence needed to examine glacial recession. Finding the exact photo points to match the pictures directly to different years is the most challenging obstacle. If the photos are not aligned, it could lead to inaccuracies with interpretation, and if these photos were used for mapping, further errors would be made.

CHAPTER III

STUDY AREA

This research covered the eastern side of the Continental Divide, in the Hudson Bay watershed. All of the study area is inside Glacier National Park, Montana, which is in the northern Rocky Mountains and covers 4078 sq km. It is just south of its sister park, Waterton Lakes National Park, Canada, which was designated as the Waterton-Glacier Peace Park in 1932. The area is characterized by pronounced U-shaped valleys with lithology almost exclusively Precambrian (Whipple 1992). All of the 21 glaciers considered in this research are located at or near the Continental Divide.

The climate of Glacier National Park is temperate with cold winters and warm summers. Changing dry and wet climate periods with low and high snowpack decades have been a cause of ecosystem processes such as forest fires and glacial dynamics (Pederson et al. 2006). 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 also affect the SWE which has shown a decrease, with earlier melting times and a decline in snow cover (Fagre et al 1997). The data used in this study area are from the glaciers (Key et al. 1998) in table 1

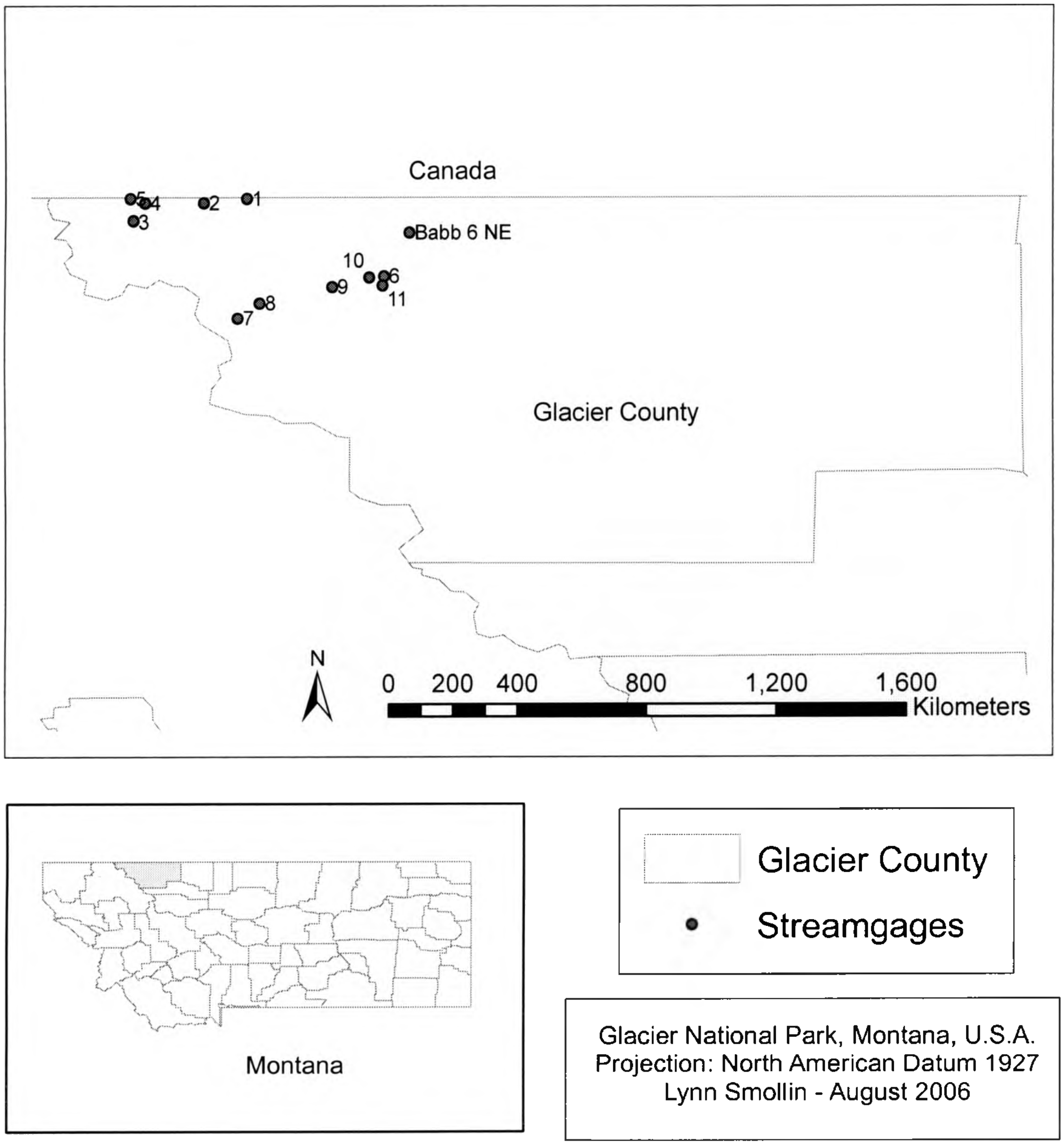
Table 1- Glaciers in Study Area.

Glaciers in the Hudson Bay Basin	Area of Glacier in sq. km.
Logan	0 43
Red Eagle	0 15
Blackfoot	1 74
Jackson	1.02
Sexton	0 4
Gem	0 02
Grinnell	0 88
Swiftcurrent	0 14
Ahern	0 59
Ipasha	0 32
Chaney	0 54
Whitecrow	0 24
Shephard	0 2
Carter	0 47
Miche Wabun	0 2
Old Sun	0 42
Dixon	0 29
Thunderbird	0 19
Hudson	0 09
Herbst	0 14
Siyeh	0 22

Table 2 – Gage, Weather Station and Associated Watershed.

Gage Number and Name	USGS Gage Site Number (each number begins with)	Weather Station	Watershed
1 Belly River at International Boundary	5010000	Babb 6 NE	Belly
2 North Fork Belly River at International Boundary	5010500	Babb 6 NE	Belly
3 Waterton River near International Boundary	5011500	Babb 6 NE	Belly
4 Street Creek at International Boundary	5012000	Babb 6 NE	Belly
5 Boundary Creek at International Boundary	5012500	Babb 6 NE	Belly
6 St Mary River near Swiftcurrent C nr Babb	5013700	Babb 6 NE	St Mary
7 Grinnell Creek nr Many Glacier MT	5014000	Babb 6 NE	St Mary
8 Swiftcurrent Creek at Many Glacier MT	5014500	Babb 6 NE	St Mary
9 Swiftcurrent Creek at Sherburne MT	5016000	Babb 6 NE	St Mary
10 Swiftcurrent Creek near Babb MT	5016500	Babb 6 NE	St Mary
11 St Mary River near Babb MT	5017500	Babb 6 NE	St. Mary

Figure 1 - Map of Streamgages.



CHAPTER IV

METHODS

To determine if a relationship exists between shrinking glacier areas, temperature and possible increased streamflow, the non-parametric statistical test of Spearman's rho correlation and repeat photography have been utilized. Spearman's rho is very similar to the Pearson r Coefficient. Pearson r reflects the degree to which two variables make a linear relationship. The range of correlation is between -1 and +1. When a correlation of +1 is calculated, a perfect positive linear relationship exists between the two variables. Spearman's rho is different from Pearson r in that the variables are ranked before calculation

- Spearman's rho= $1-\frac{6\Sigma D^2}{N(N^2-1)}$

Stream flow data and temperature data from the years 1900 to 2004 were used in this research because these are the years that have the most streamflow data, which were gathered from the USGS website and the NCDC website. The data were then used in this study to determine a connection involving changing climates which affects stream flow through the melting of glaciers. The annual mean temperatures in (˚F) and the annual peak streamflow in cubic feet per second (cfs) data were the variables used in the Spearman's rho calculations.

The collected data were entered into Microsoft Excel and then moved into the statistical package SPSS for further manipulation The maximum annual temperatures for the month of July in degrees Fahrenheit were used with the annual streamflow in cfs. Scatter plots were then created to visually show the temperature and streamflow data. A complete, consistent record of stream gage data or temperature data for the 105 year time period for this study does not exist. This may account for possible negative correlations. Streamflow data were collected from 11 gages around the study area and were close to one weather station, Babb 6 NE in Glacier County, Montana. The stream gages are clustered around the Continental Divide close to the glaciers in this study. Table 3 shows the locations of the streams and the number of years data were available.

Only three stream gages had long and most consistent data available. Gage 7, 8 and 11 were used for the Spearman's rho calculations in the warmest summer month, July, when peak streamflow is at its highest.

Repeat photography was used to visually represent the change in glacier size and the amount of retreat that has taken place. The photographs used to confirm glacial melt are from the USGS and part of the Repeat Photography Project for Glacier National Park, Montana to record landscape change.

Table 3 – Glaciers Listed with Repeat Photography.

Glacier	Years Photographed (-) Indicates one photo from each year
1 Grinnell Glacier Trail	1900-1998
2 Grinnell Glacier Trail	1910-1998
3 Grinnell Glacier Trail	1911-1998
4 Grinnell Glacier Overlook	1940-2004
5 Grinnell Glacier Trail Footbridge	1920-1998
6 Chaney Glacier Notch	1911-2005
7 Blackfoot and Jackson Glacier	1914-2001
8 Shephard Glacier	1913-2005
9 Swiftcurrent Glacier Trail	1900-1998
10 Swiftcurrent Glacier Lookout	1930-2002

Table 4 – Location of Stream Gages. County.

County	Elevation (ft)	Number of Years
Glacier	4500	1948-1956 9 yrs.
Glacier	5100	1948-1951 4 yrs
Glacier	4200	1948-1956 9 yrs
Glacier	4400	1950-1951 2 yrs
Glacier	4300	1948-1956 9 yrs
Glacier	4460	1902-1914 13 yrs
Glacier	4920	1950-1976 27 yrs
Glacier	4876 78	1918-1919 1959-2004 48 yrs.
Glacier	4370 26	1917-1922 6 yrs
Glacier	4490	1903-1909 7 yrs
Glacier	4468 13	1911-1924

Table 5 – Location of Stream Gages. Latitude and Longitude.

Gage Name & Number	Latitude	Longitude
1 Belly River at International Boundary	48°59'50"	113°40'50"
2 North Fork Belly River at International Boundary	48°59'20"	113°45'5"
3 Waterton River near International Boundary	48°57'20"	113°54'0"
4 Street Creek at International Boundary	48°59'20"	113°52'40"
5 Boundary Creek at International Boundary	48°59'50"	113°54'20"
6 St Mary River at Swiftcurrent C nr Babb MT	48°51'03 17"	113°24'58 23"
7 Grinnell Creek nr Many Glacier MT	48°46'14"	113°41'53"
8 Swiftcurrent Creek at Many Glacier MT	48°47'57"	113°39'21"
9 Swiftcurrent Creek at Sherburne MT	48°49'49"	113°30'59"
10 Swiftcurrent Creek near Babb MT	48°50'55 06"	113°26'39 67"
11 St Mary River near Babb MT	48°50'00"	113°25'08"

CHAPTER V

ANALYSIS AND RESULTS

Expected results would be finding a positive correlation between temperature and streamflow values. The repeat photography would enforce this belief. If streamflow becomes greater in time it may be attributed to glacial melt and a rising trend in temperatures from the Little Ice Age to present day. Since there is no previous research in Glacier National Park to connect these variables, further monitoring would show that increased streamflow is an indicator of climate change.

Only a limited number of photographs for the eastern side of the continental divide exist, but they do show the differences between glacier mass and the recent glacial recession in the 20th and 21st centuries. Figure 2 shows Grinnell Glacier from the view of Grinnell Glacier Trail. This glacier has receded into two separate glaciers, the upper right glacier mass is called the Salamander. Gem Glacier, the park's smallest glacier, is the small mass in the upper left corner of the photo. It doesn't seem to have receded to the extent that Grinnell has. Figure 3 is Grinnell Glacier in 1910 when the park was established. The stream that runs down from the glacier narrows into two much broader streams in 1998. Figure 4 shows Grinnell Glacier just one year after the park's opening. The lower glacier seems to have decreased just slightly compared to the photography of Grinnell Glacier in 1910. Grinnell Glacier of Figure 4 shows the glacier from the viewpoint of the Highline Trail where a proglacier lake has formed at the terminus of the glacier.

Figure 2 – Grinnell Glacier Trail. 1900- 1998.

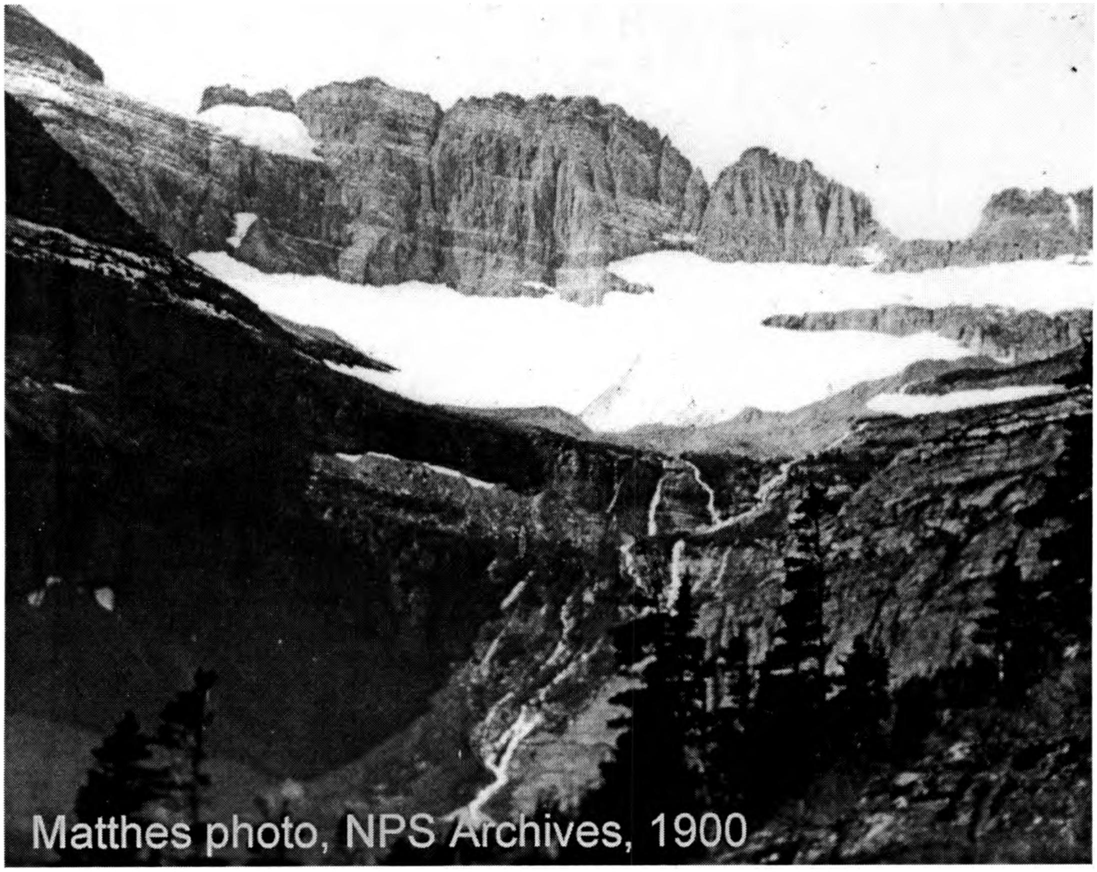


Figure 3 – Grinnell Glacier Trail. 1910-1998.

Figure 4 – Grinnell Glacier Trail. 1911-1998.

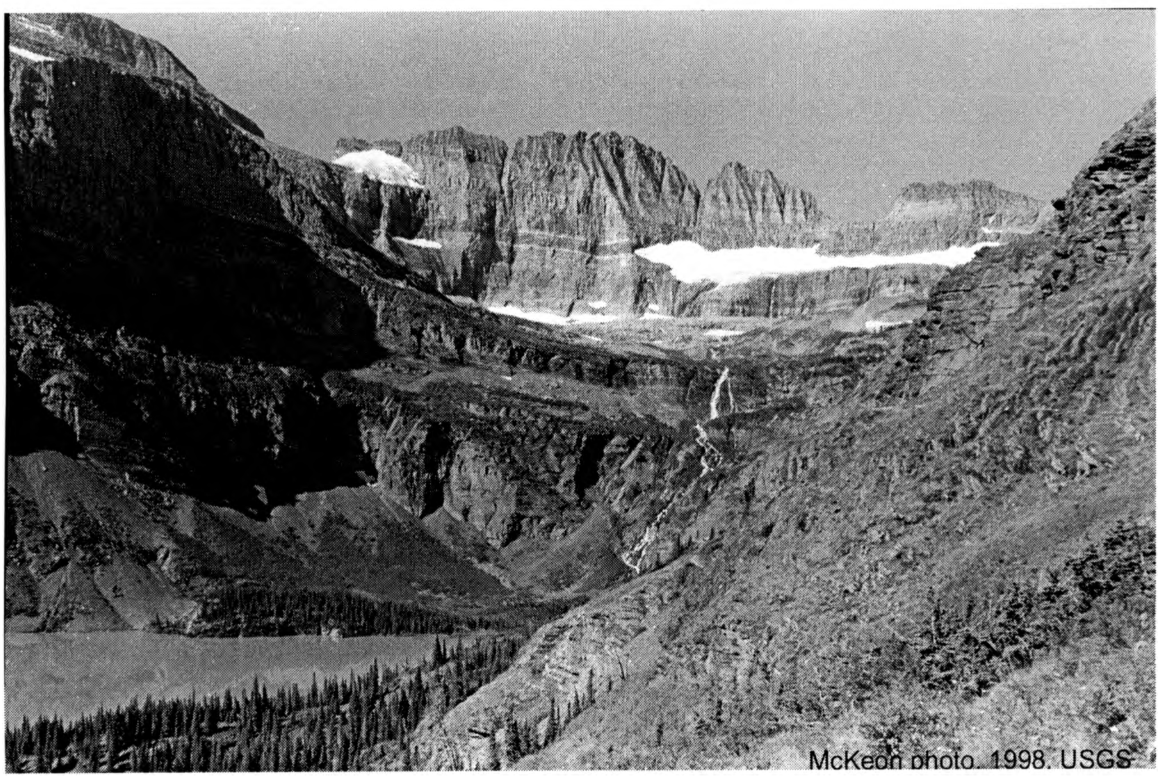


Figure 5 – Grinnell Glacier Overlook. 1940-2004.

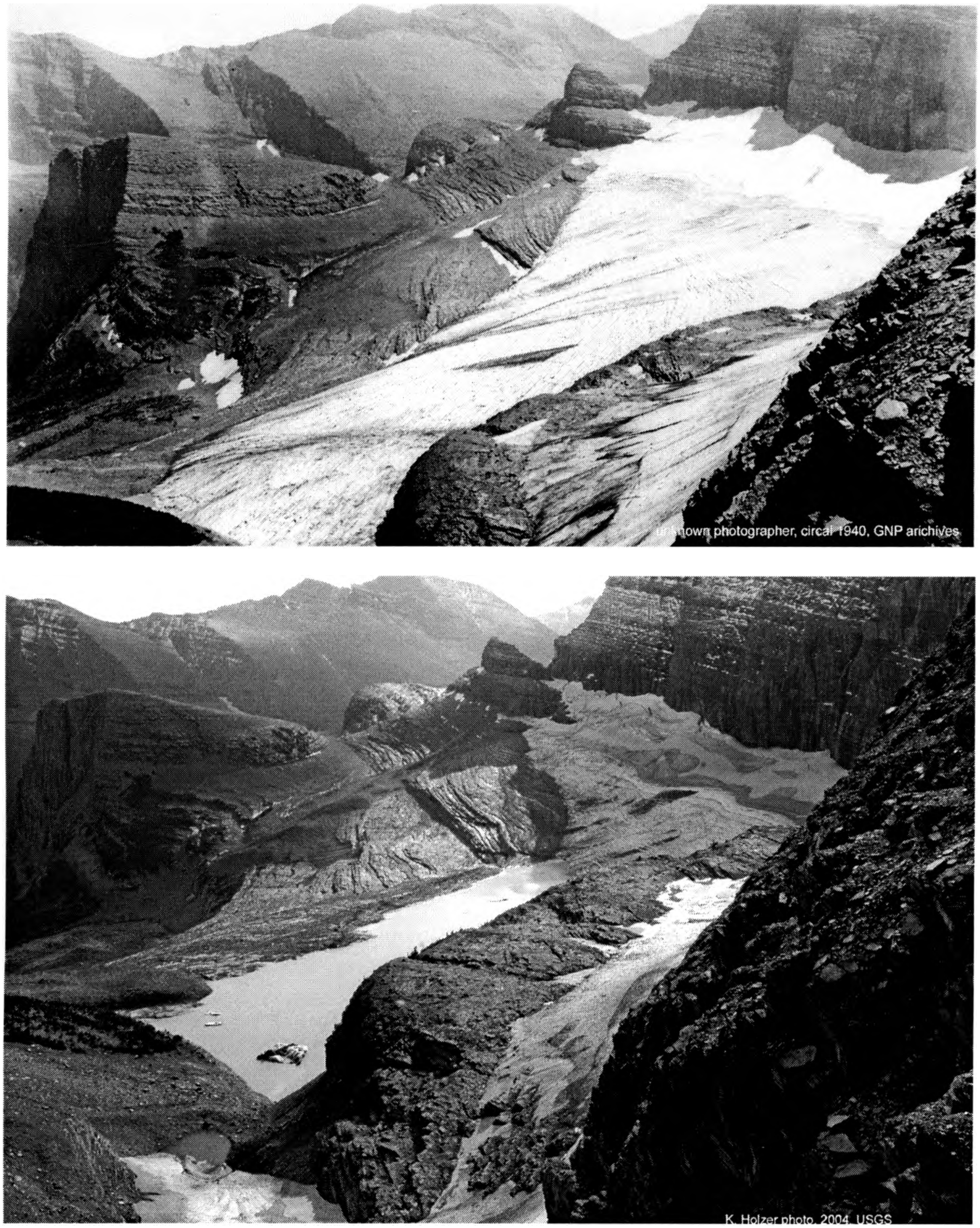


Figure 6 – Grinnell Glacier Trail Footbridge. 1920-1998.

Figure 7 – Chaney Glacier Notch. 1911-2005.

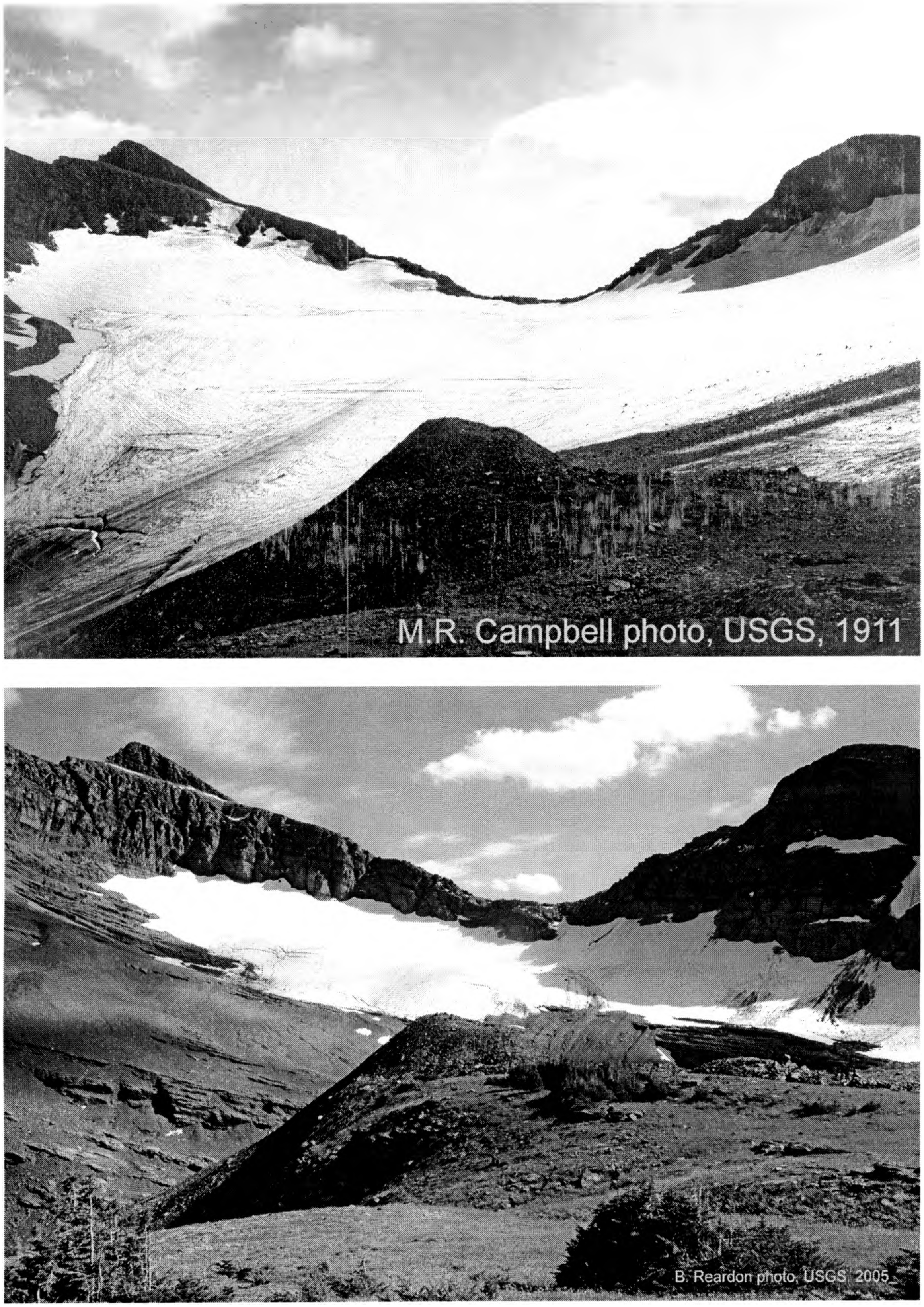


Figure 8 – Blackfoot and Jackson Glacier. 1914-2001.

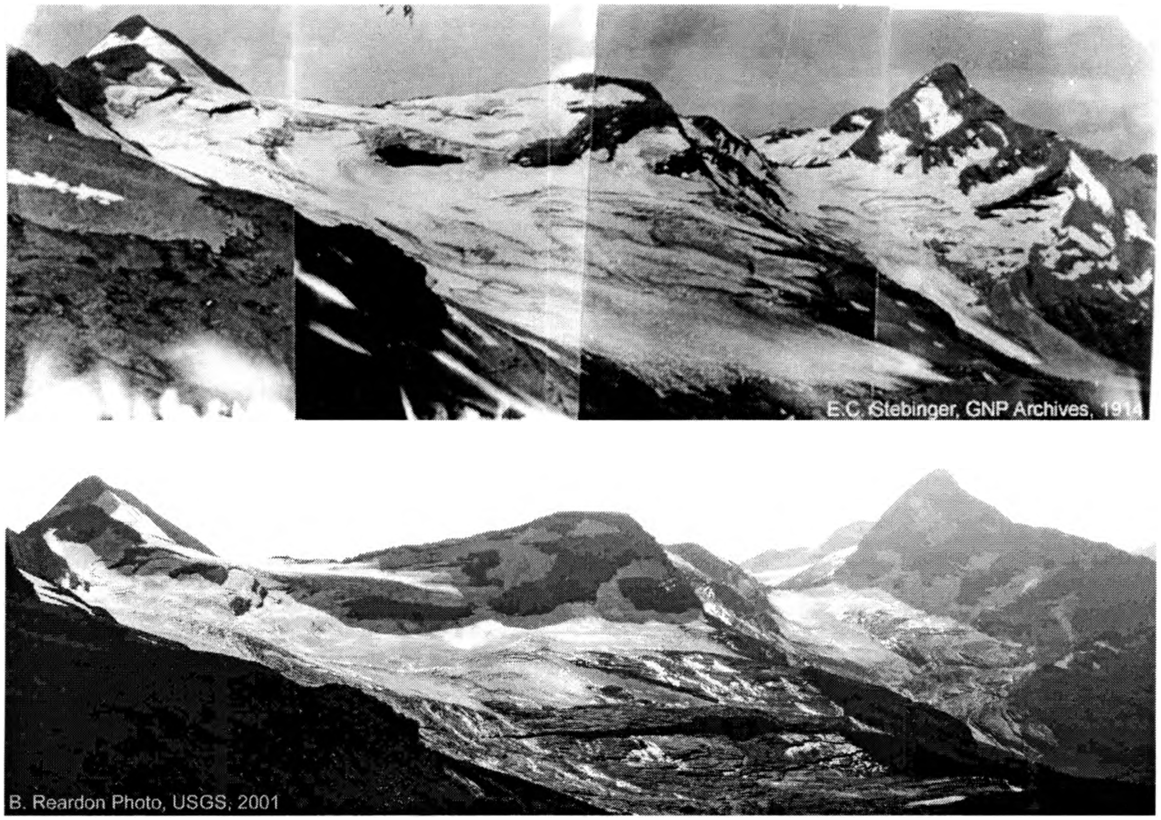


Figure 9 – Shepard Glacier. 1913-2005.

Figure 10 – Swiftcurrent Glacier Trail. 1900-1998.

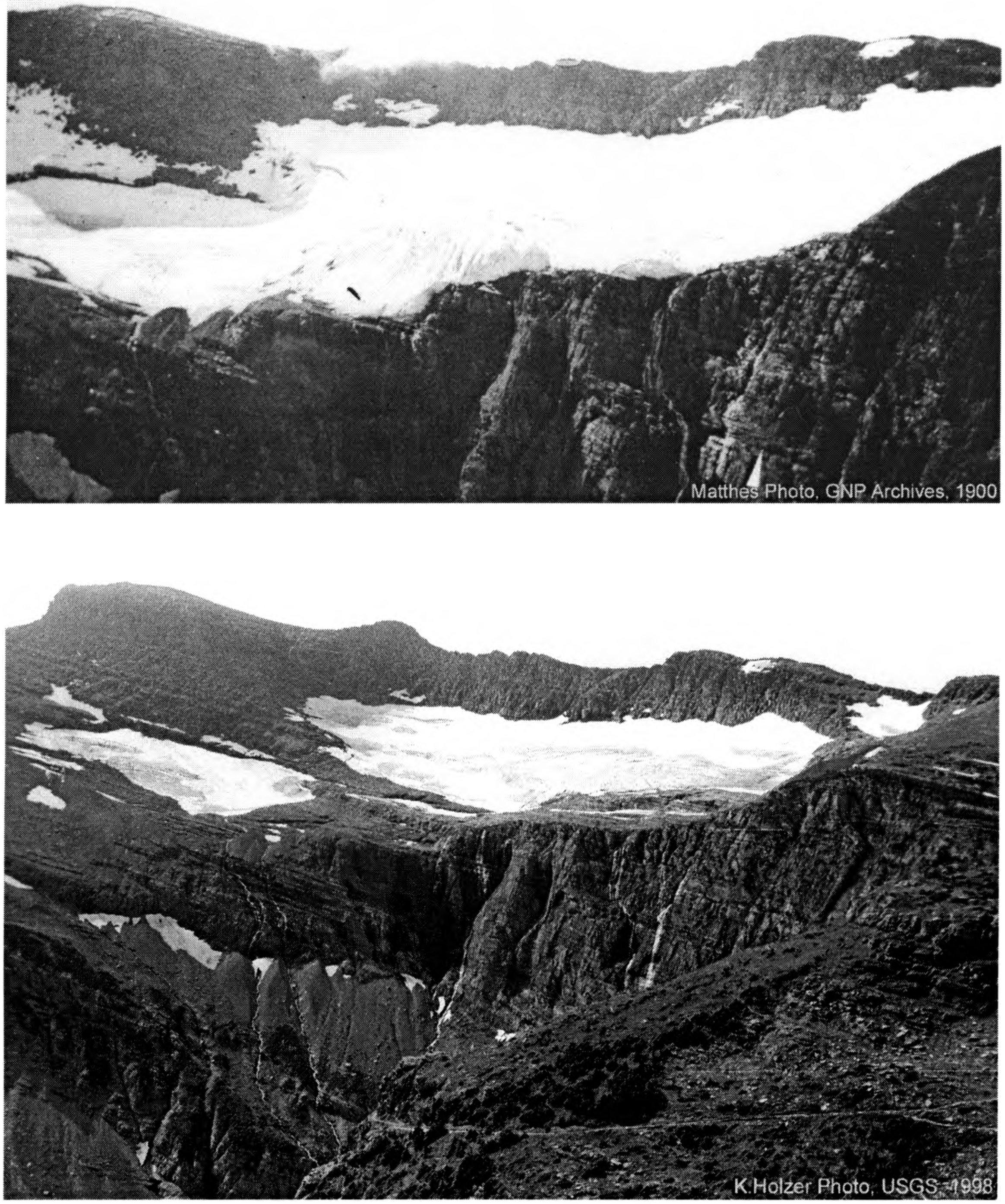
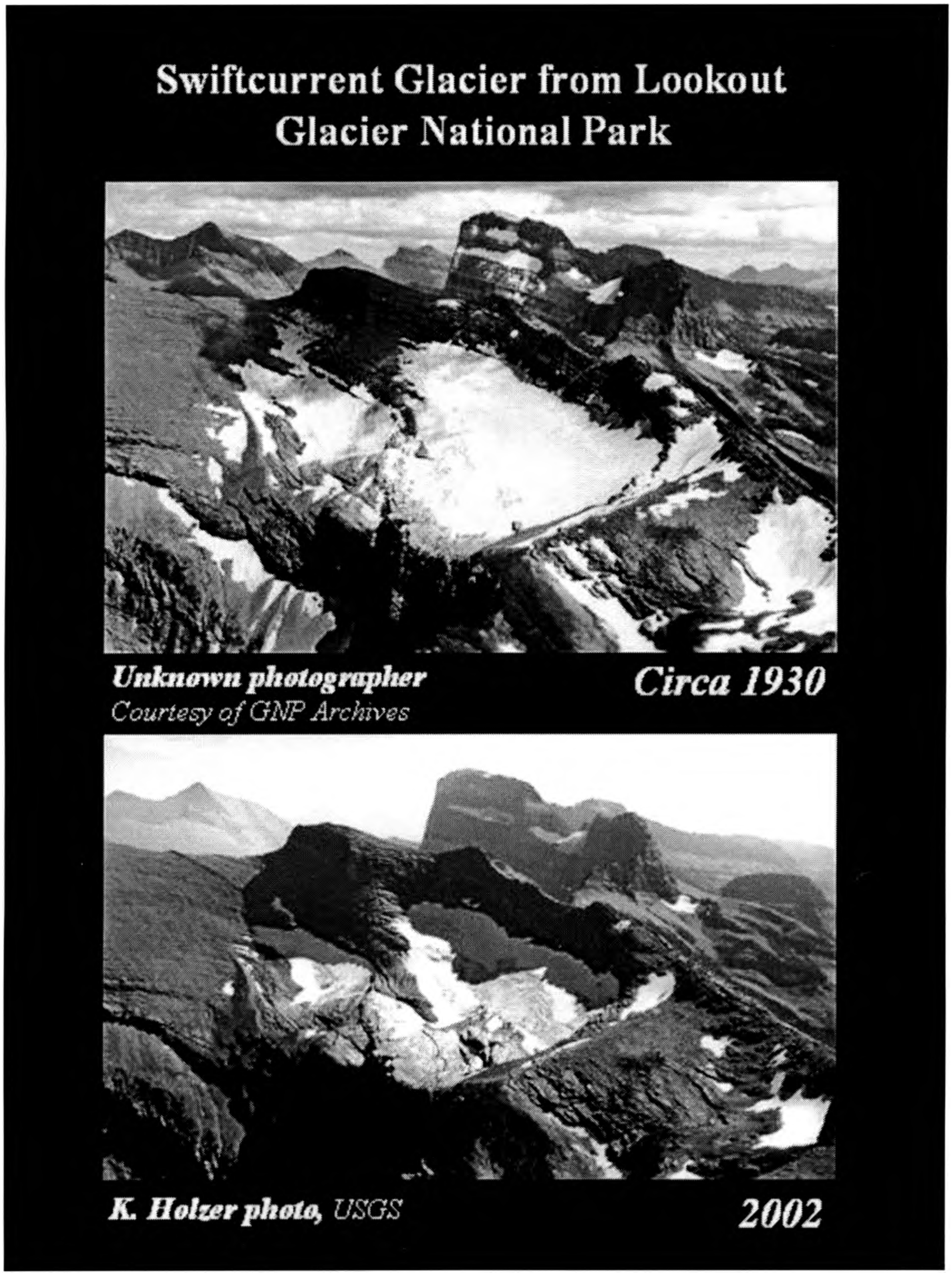


Figure 11 – Swiftcurrent Glacier Lookout. 1930-2002.



The 2004 photograph shows an increase in glacial melt by the greater size of the lake Figure 6 is Grinnell Glacier from the footbridge at the head of Lake Josephine. It is clear that the stream in the foreground has increased vegetation surrounding it and the glacier in the background has retreated up the mountain. Grinnell Glacier is the most visited and frequently photographed glacier in the park. The other photographs of glaciers inside the park give an obvious visual representation that streams fed by glaciers may have raised levels of streamflow.

The statistical analysis of this thesis does not support the research question. According to the calculations of Spearman's rho there is a negative correlation with Swiftcurrent Creek, gage 8. Correlations with Grinnell Creek, gage 7 and St. Mary's River, gage 11 are not significant enough to attach a relationship between temperature and streamflow. These results have determined that annual temperature may not have a major affect on glaciers or an increased rate of streamflow.

Streamflow may not be increasing because of the natural process of evapotranspiration, debris, possible tributary streams that carry water away from the main stream, and beaver dams in the park. Table 6 shows the correlations for this research. Figures 12 through 14 represent the cubic feet per second of the streamflow and the period of years for the stream gages.

Table 6 - Spearman's rho Correlation.

Spearmans's rho	ST MARY R	SC CREEK	G CREEK
Correlation Coefficient	0	-0.001507	0.265615
Sig. (2-tailed)	0	0.991121	0.163732
N	14	92	29

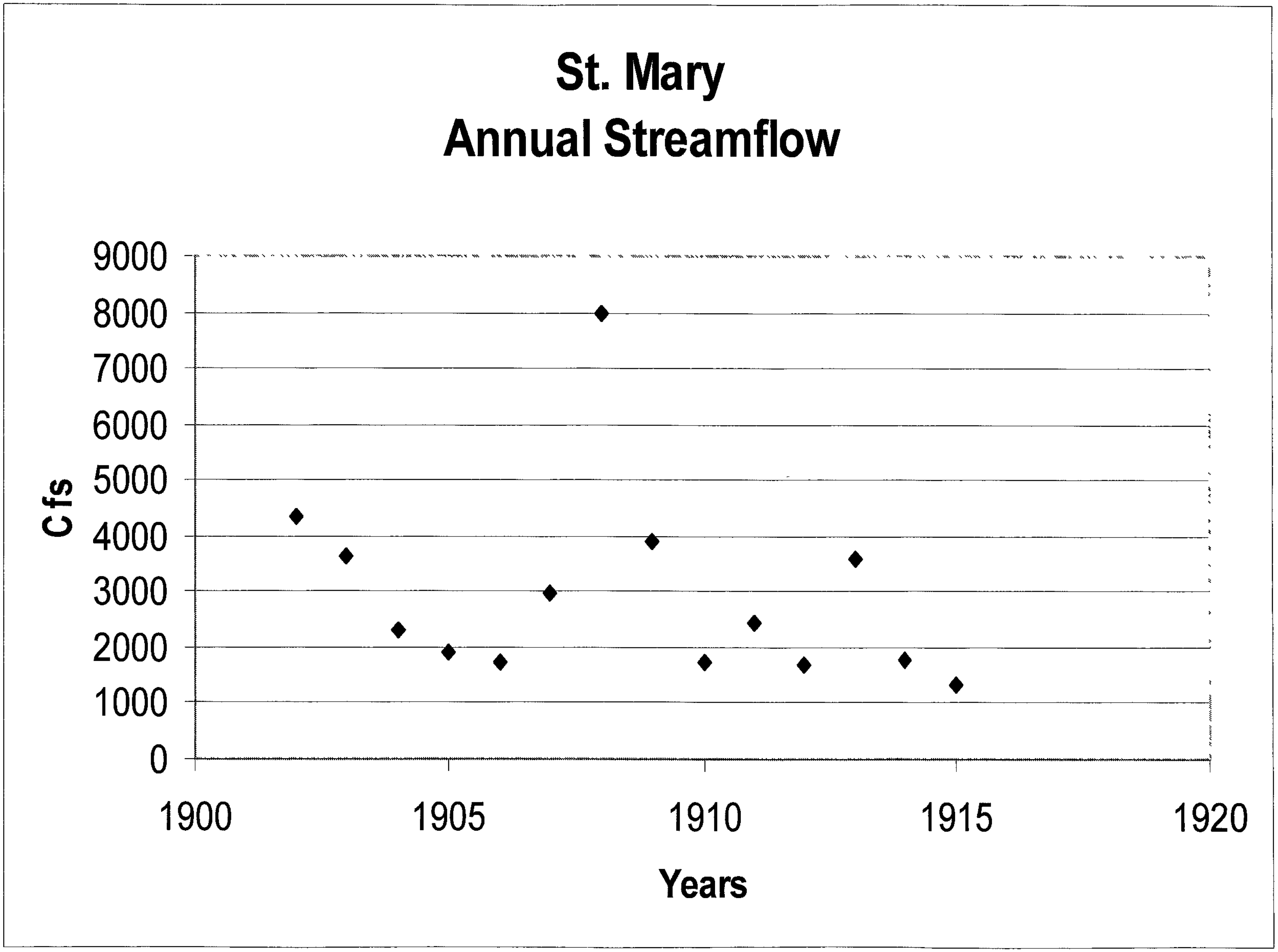


Figure 12 – Gage 11. St. Mary River.

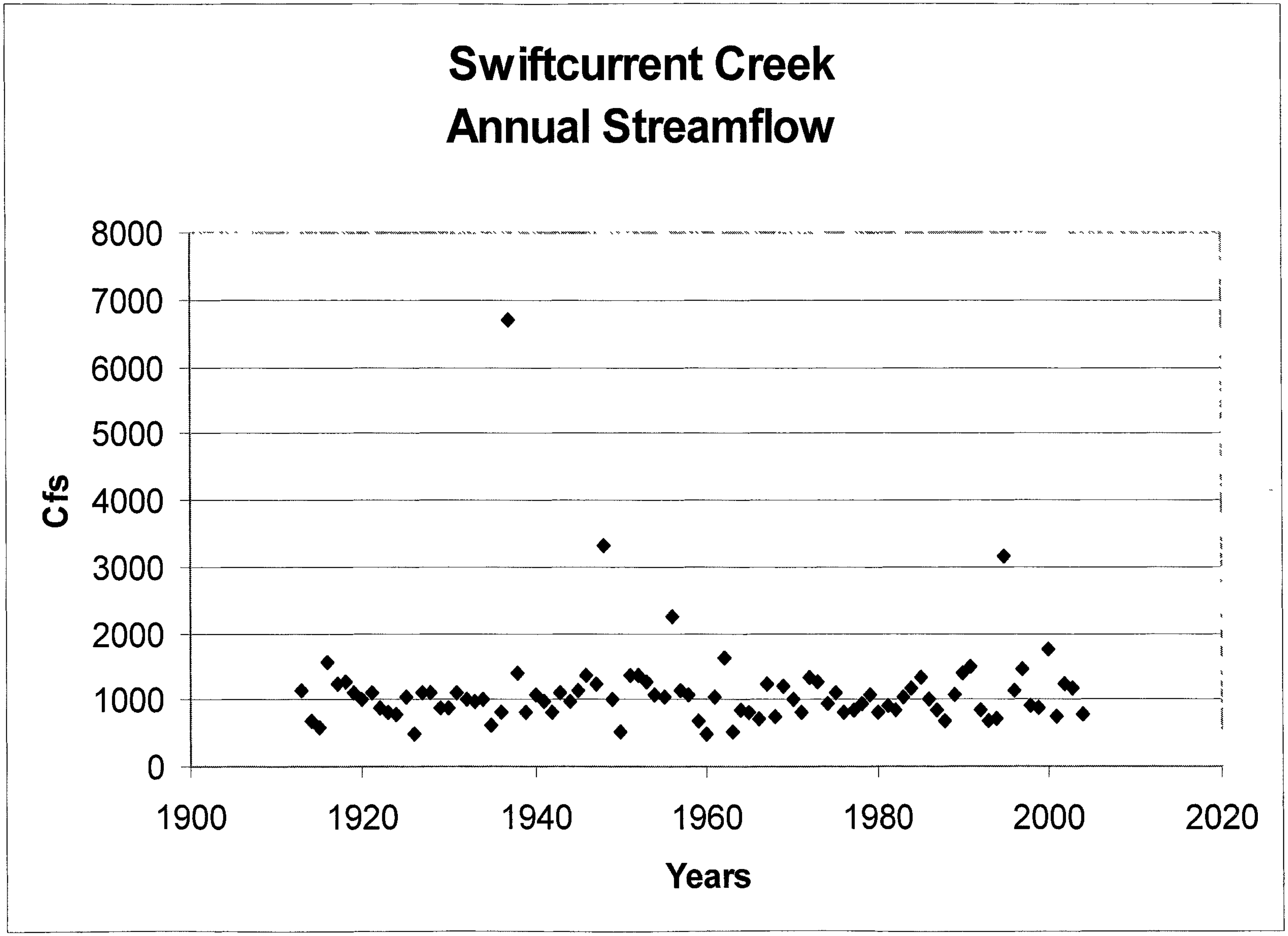


Figure 13 – Gage 8. Swiftcurrent Creek.

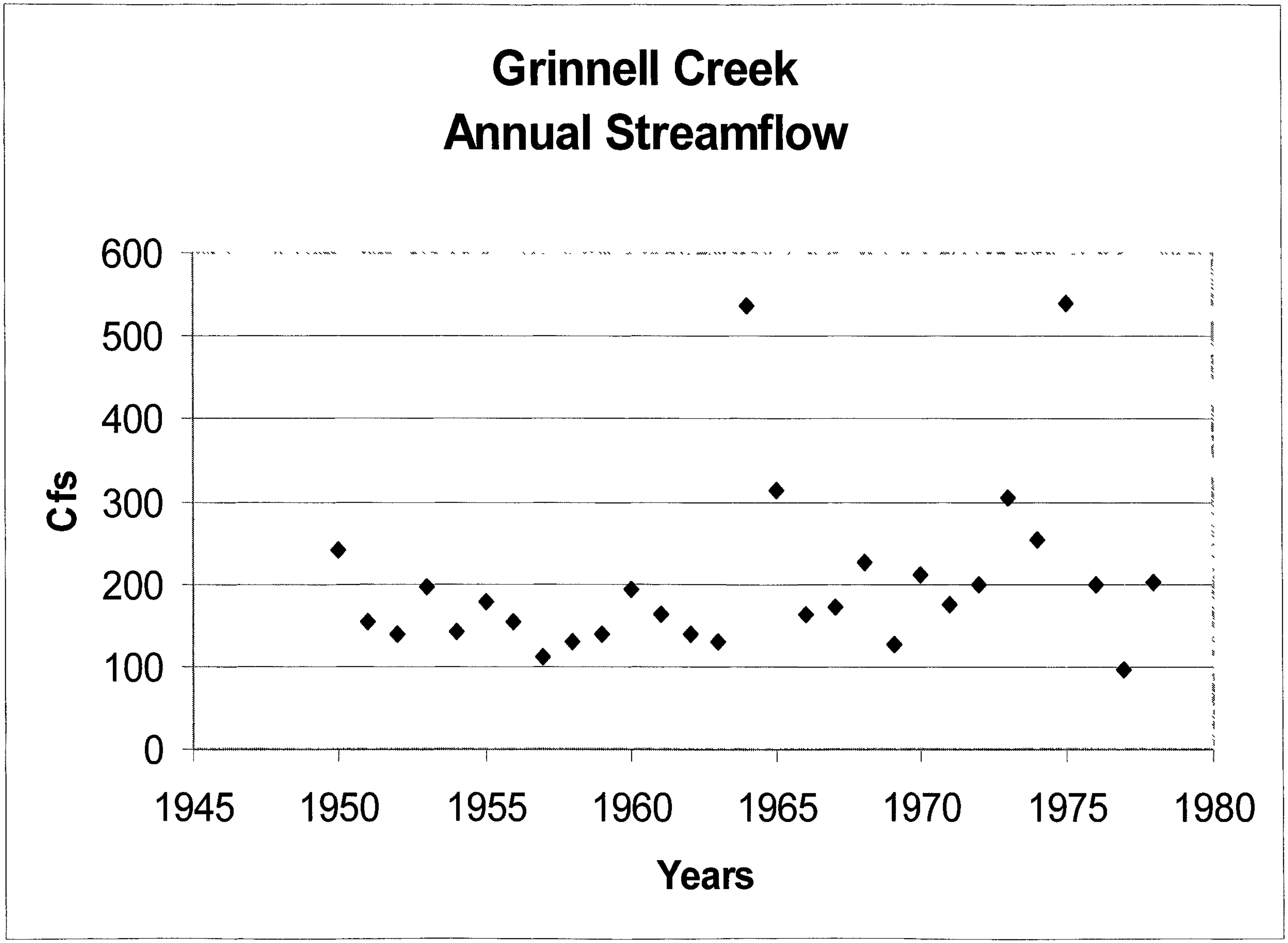


Figure 14 – Gage 7. Grinnell Creek.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Previous research in the Western United States has investigated climate variability coinciding with glacial dynamics. For Glacier National Park, correlations were run to determine if a relationship between glacial melt and streamflow over a 105 year period exists

If a positive correlation exists between the temperature and streamflow variables, it is most likely that temperature affects glaciers which causes accelerated melting and retreat. The disappearing glaciers influence nearby streams with greater discharge as a result of melt.

The Spearman's rho correlation did not show significance between annual temperature and annual peak steamflow. While increased temperature may be responsible for glacial melt, the statistics in this work show that there is not a strong relationship between temperature and streamflow. The melt rate of the glaciers might not be fast enough to affect streamflow, but other factors do. Such factors are beaver dams, evapotranspiration, debris, and possible small tributaries that divert water from the main channel. Does an increase in annual temperature melt the glaciers enough to cause an increase in peak streamflow? The calculations of this work show that it does not and also shows that increased streamflow is not a good indicator of climate change.

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