

USING REMOTE SENSING TO EXAMINE CHANGES OF CLOSED-
BASIN SURFACE WATER AREA IN INTERIOR ALASKA FROM
1950 – 2002

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BASIN SURFACE WATER AREA IN INTERIOR ALASKA FROM
1950 – 2002

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Abstract

Over the past fifty years Alaska has experienced an increase in mean annual temperature. This warming may be causing significant changes in hydrology and permafrost dynamics. In recent decades, Native Americans and land managers have reported losses of water bodies and surface water area in interior Alaska. We conducted a study to determine the degree to which these informal observations were representative of a regional trend in surface water area loss. This study examines closed-basin water bodies in nine regions across Alaska: 1) Copper River Basin, 2) Talkeetna, 3) Tetlin National Wildlife Refuge, 4) Denali National Park, 5) Innoko Flats National Wildlife Refuge, 6) Minto Flats State Game Refuge, 7) Stevens Village, 8) Yukon Flats National Wildlife Refuge, and 9) Prudhoe Bay/Arctic Coastal Plain. The study included approximately 850,000 hectares and over 40,000 water bodies. To conduct such a large-scale study, GIS and Remote Sensing techniques were applied. Water body change detection was conducted over a fifty-year time period. A minimum of three time periods were used for each area. Imagery included black and white aerial photography (1950 -1957), color infrared aerial photography (1978 -1982), Landsat TM (1986 - 1995), and Landsat ETM+ (1999 - 2002). Based on these images, water body polygons were digitized for each time period. Area was calculated for each polygon and compared to corresponding ponds from images at later times. Of the nine regions, six showed substantial reductions in surface water area: Copper River Basin, Minto Flats, Innoko Flats, Yukon Flats, Stevens Village, and Denali National Park. The Innoko Flats and Copper River Basin regions showed the most loss at 31% and 28% respectively. There are several mechanisms possible for reductions of surface water in a warming climate including increased formation of taliks, increased soil water holding capacity, increased evapotranspiration, and terrestrialization.

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1 Introduction and Review

1.1 CLIMATIC HISTORY

Recent effects of climate warming have been observed in the northern latitude regions (Committee on Permafrost, 1983; Serreze et al., 2000). In Fairbanks, Alaska, the number of days where temperatures drop below -50°C are now half of what they were in 1950 (International Arctic Science Committee, 1999). The most severe environmental stressors in Alaska at present are climate-related (National Assessment Synthesis Team, 2000). Four key issues are associated with warming in Alaska: permafrost and sea ice melting, increased risk of fire, implications for marine environments and fisheries, and stress on tribal life (National Assessment Synthesis Team, 2000).

Since the 1950s there has been a significant increase of 2°C in Alaska's mean annual temperature, with an increase of 4°C in interior Alaska during the winter (National Assessment Synthesis Team, 2000). Global circulation models estimate an increase of $2\text{-}3^{\circ}\text{C}$ in global surface temperature resulting from trace atmospheric gases (IPCC, 2001, Jorgenson et al., 2001, Zhang & Osterkamp, 1993). In Alaska, mean annual temperatures may increase by $4\text{-}6^{\circ}\text{C}$ over the next hundred years (National Assessment Synthesis Team, 2000). The effect of greenhouse warming is amplified in northern latitudes because of feedbacks that are strongly influenced by variations in sea ice extent and snow cover, the thawing of permafrost, and the stability of the lower troposphere (Serreze et al., 2000).

Some effects of a warming climate (Stone 1997, Chapman and Walsh, 1993) in northern regions include a decrease in sea ice (Serreze et al., 2000) and glacier mass balance (Meir et al., 2003); warming of permafrost (Osterkamp and Romanowsky, 1999); increase in plant growing season and productivity (Keyser et al., 2000; Stone et al., 2002; Jia et al., 2004); and expansion of shrubs in the arctic tundra (Sturm et al., 2001). While precipitation in Alaska has not changed substantially in recent decades, warming temperatures have led to increases in potential evapotranspiration (PET) for Alaska interior and coastal tundra regions (Oechel et al., 2000). In subarctic interior Alaska, the increases in potential evapotranspiration since the 1970s have led to

dramatic increases in summer water deficits (Oechel et al., 2000) that caused a decrease in tree growth (Lloyd and Fastie, 2002), and temperature-induced drought stress (Barber et al., 2000).

1.2 PERMAFROST

1.2.1 Permafrost

Permafrost incorporates 20-25% of the land surface on earth and approximately 75% of the land surface area in Alaska (Figure 1.1) (Committee on Permafrost, 1983; Serreze et al., 2000). The permafrost environment consists of three primary components: permafrost, the active layer, and taliks. Permafrost is defined as ground that remains at a temperature below 0°C for a period of two consecutive years or more (Committee on Permafrost, 1983; Davis, 2001). Permafrost can be further classified into two regional types; continuous and discontinuous.

These regions of permafrost are distinguished on the basis of location, depth, and average temperature. The active layer is a dynamic zone above the permafrost that annually freezes and thaws. This layer ranges from several meters deep in southern Alaska to several centimeters deep on the Arctic Coastal Plain (Davis, 2001). There is an inverse relationship between active layer thickness and permafrost thickness. Taliks are zones of unfrozen soil between blocks of frozen soil or zones that resided between the permafrost and active layer. Taliks begin to develop under a water body when the water body does not fully freeze during the winter. This in turn leads to year-round degradation of the permafrost and growth of the talik (Burn & Smith, 1988; Burn & Smith, 1990). This process results from water's relatively high heat conductance. These taliks may be responsible for lake drainage during the winter (Yoshikawa and Hinzman, 2003; Fraver, 2003).

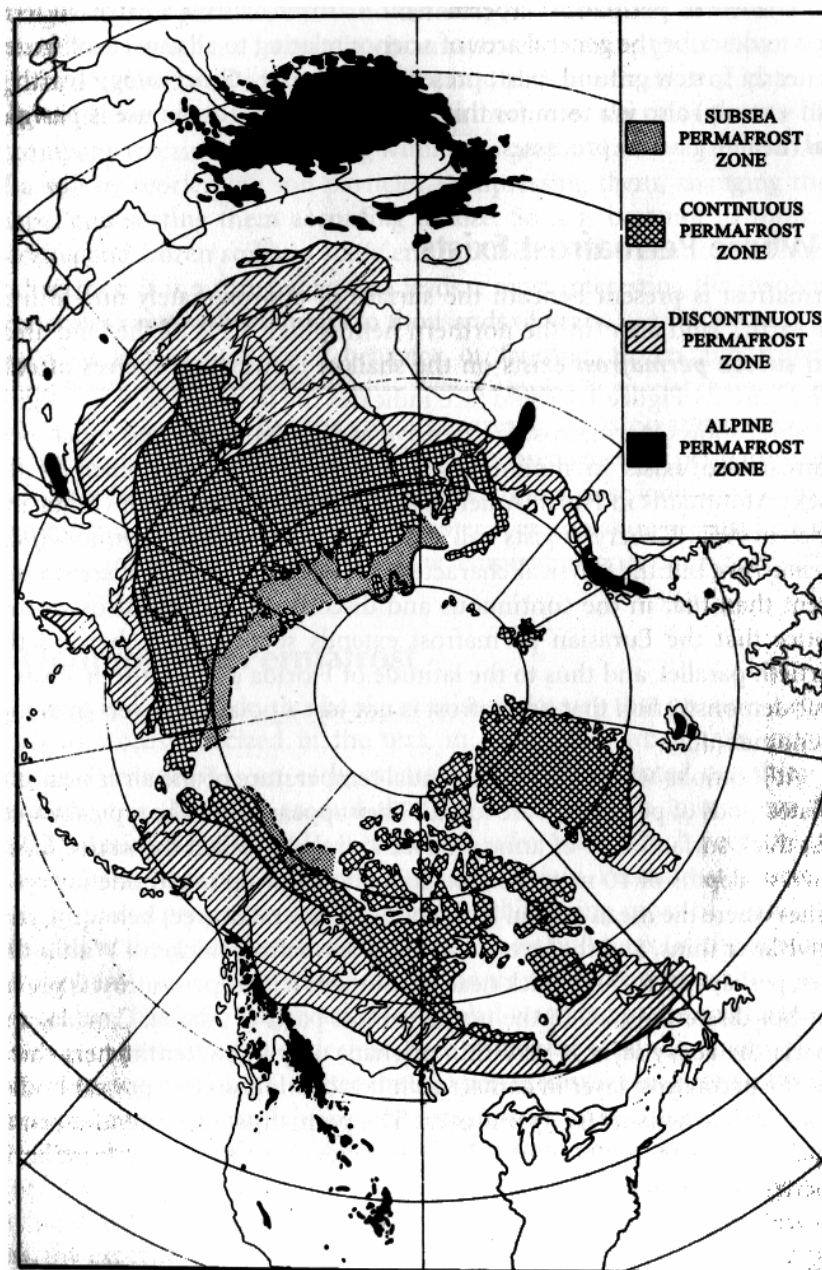


Figure 1.1 Permafrost extent in the northern hemisphere (Pewe, 1975a; Davis, 2001).

Continuous permafrost often extends to depths of 400 m (Committee on Permafrost 1983) in Arctic ecosystems. The Arctic is defined as the region above the 14°C July isotherm, and is referred to as a Periglacial environment (Woodin, S.J. and Marquiss, M. 1997).

Discontinuous permafrost is predominately found in subarctic regions; where mean annual temperatures are warmer than in the Arctic. Discontinuous permafrost temperatures are generally warmer than -5°C (Osterkamp and Romanovsky, 1999), and have seen an increase of 0.5°C - 1.5°C from the 1980s to the 1990s (Osterkamp and Romanovsky, 1999). Discontinuous permafrost ranges in depth from 30 m in Fairbanks, Alaska, to a few tenths of a cm near the southern coast of Alaska (Committee on Permafrost, 1983). With thin layers of permafrost and increasing permafrost temperatures, degradation is unavoidable (Figure 1.2). Southern regions of Alaska are some of the first areas to show signs of permafrost degradation resulting from climatic change (Osterkamp and Romanovsky, 1999).

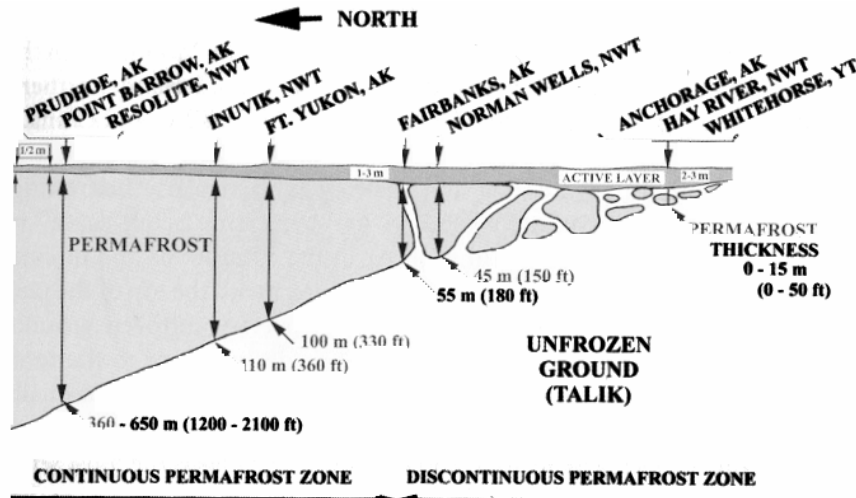


Figure 1.2 Permafrost zone progression from south to north in Alaska (Brown, 1975; Davis, 2001; Pewe, 1982; Washburn 1980).

1.2.2 Permafrost Hydrology

Permafrost is the primary control for hydrology in northern regions (Yoshikawa and Hinzman, 2003). Warming permafrost temperatures may bring dramatic hydrological changes to the interior of Alaska. Warming and thawing of discontinuous permafrost is common in interior Alaska (Osterkamp and Romanovsky, 1999). The thawing of permafrost may affect many hydrological processes, including decreased summer peak Alaska flows (Bolton et al., 2002), increased winter stream flow (Yang et al., 2002), and changes in water chemistry (Petrone et al., 2000). Permafrost permeability varies with ice content in the soil, active layer depth, and depth of the permafrost. Permafrost is either semi-permeable or totally impervious to water movement

(Woodin and Marquiss, 1997). As warming occurs, the active layer will increase in width allowing for an increase in water holding capacity and water movement. This process also tends to cause pooling from snowmelt or near-surface ground water (Wright, 1981). Pooling can have significant effects on the underlying permafrost (Johnston and Brown, 1966). This process creates large tracts of permafrost land that are covered with many small ponds and lakes. These are called thaw lakes or thaw ponds. They are common across Alaska where terrain is flat and the ground is underlain by continuous permafrost (Wallace, 1948; Detterman, et al., 1959; Tedrow, 1962; and others).

1.3 POTENTIAL SURFACE WATER CHANGES DUE TO CLIMATE WARMING

There are four ways that surface water area may change in response to a changing climate: drainage through taliks, increased soil water holding capacity, increased evapotranspiration, and succession.

1.3.1 Drainage from Expanding Taliks

Hopkins (1949) detailed two processes for thaw pond drainage on the Seward Peninsula. The first is lateral drainage via thermokarst channels above ice wedges. The second process is through growth of taliks that could pierce through the permafrost layer and into a bedrock layer. Warming of the water body and ground will result in the growth of taliks below the water bodies. As taliks grow they can merge with nearby taliks or completely penetrate the permafrost soil beneath the water, creating an open talik (Yershov, 1998; Yoshikawa and Hinzman, 2003). This provides a path for the retained water to use as it travels horizontally above the permafrost layer and below the active layer (Figure 1.3). This horizontal water movement allows water to move from the water body to nearby streams, rivers, or wetlands.

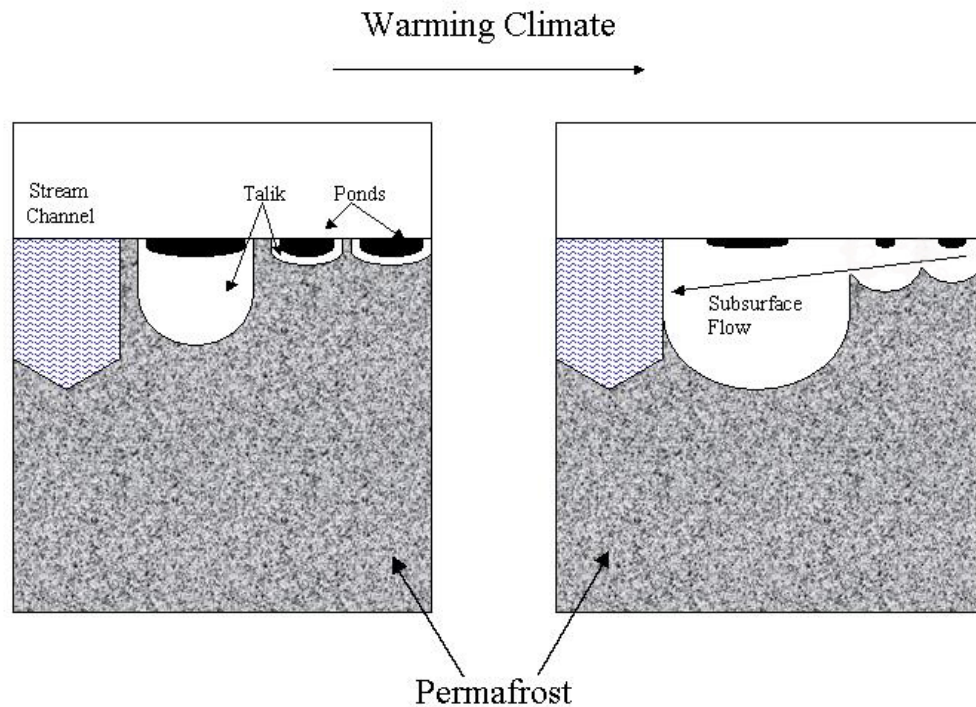


Figure 1.3 Example of talik drainage in response to climatic warming.

1.3.2 Increased Soil Water Holding Capacity

The active layer is the key component in soil water holding capacity. Warming in subarctic and arctic regions will increase the size of the active layer, thus increasing the potential for water holding capacity (Figure 1.4) (Kane et al., 1991). Wetlands have a large storage capacity for water, and studies have shown that there is a large amount of water transfer between wetlands and ponds (Fraver, 2003). Therefore, transitions from water bodies to wetlands and large active layers will allow for more water movement between water bodies and soil.

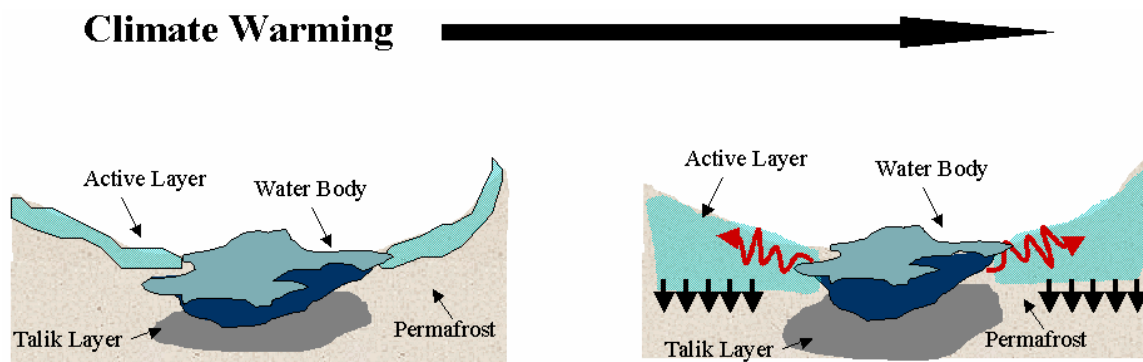


Figure 1.4 Examples of increase in soil water holding capacity in response to climatic warming

1.3.3 Increased Evapotranspiration

With climatic warming more energy is available to drive evaporation and plant transpiration. If there is not a corresponding increase in precipitation, a reduction in water bodies could occur (Figure 1.5). There have been increases in surface water deficit in both Alaska interior moist-tussock tundra and Alaska coastal wet-sedge tundra (Oechel et al., 2000).

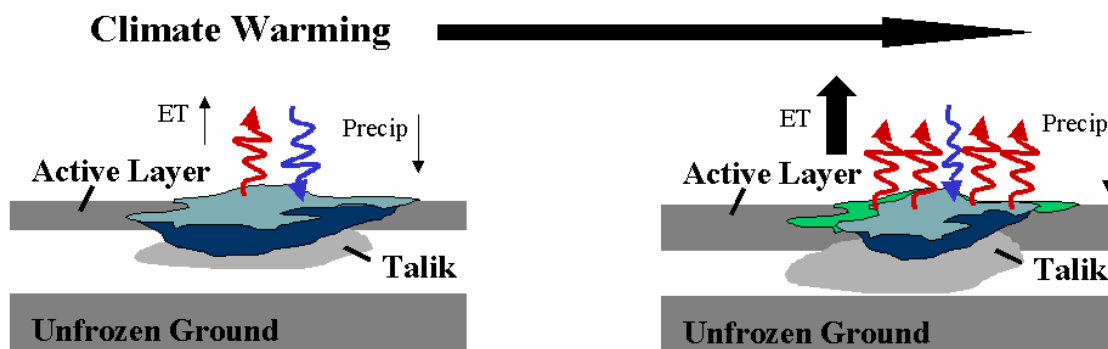


Figure 1.5 Increased evapotranspiration with climatic warming

1.3.4 Terrestrialization

With climate warming vegetation may change substantially in and near water bodies. Water bodies may naturally succeed from aquatic ferns to sphagnum/spruce bogs, with bogs succeeding to an upland vegetation type (Thormann et al., 1998) (Figure 1.6). Peat is the foundation for progression from pond to bog, and peat growth is enhanced on the shores of

receding water bodies (Mitsch, 1993). This successional process, known as terrestrialization, may be accelerated by climatic warming.

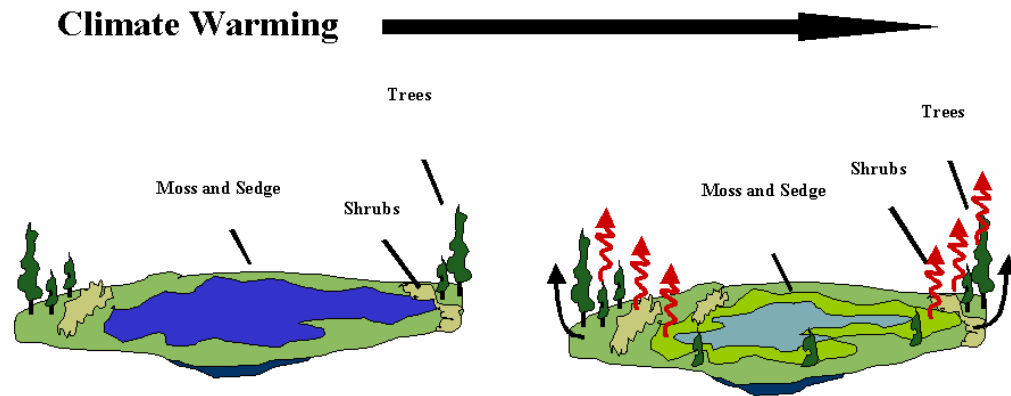


Figure 1.6 Succession example in response to climatic warming

1.4 OBJECTIVES

The objective of this study is to use remotely sensed images from 1950 - 2002, to analyze the aerial change of closed-basin ponds and lakes across nine regions of interior Alaska (Figure 1.7). I hypothesize climate change is causing a reduction in surface area through one or all of the mechanisms described. If this is true, I expect to find that recent climatic warming has caused a substantial decrease in the number of water bodies and area of surface water in interior Alaska.

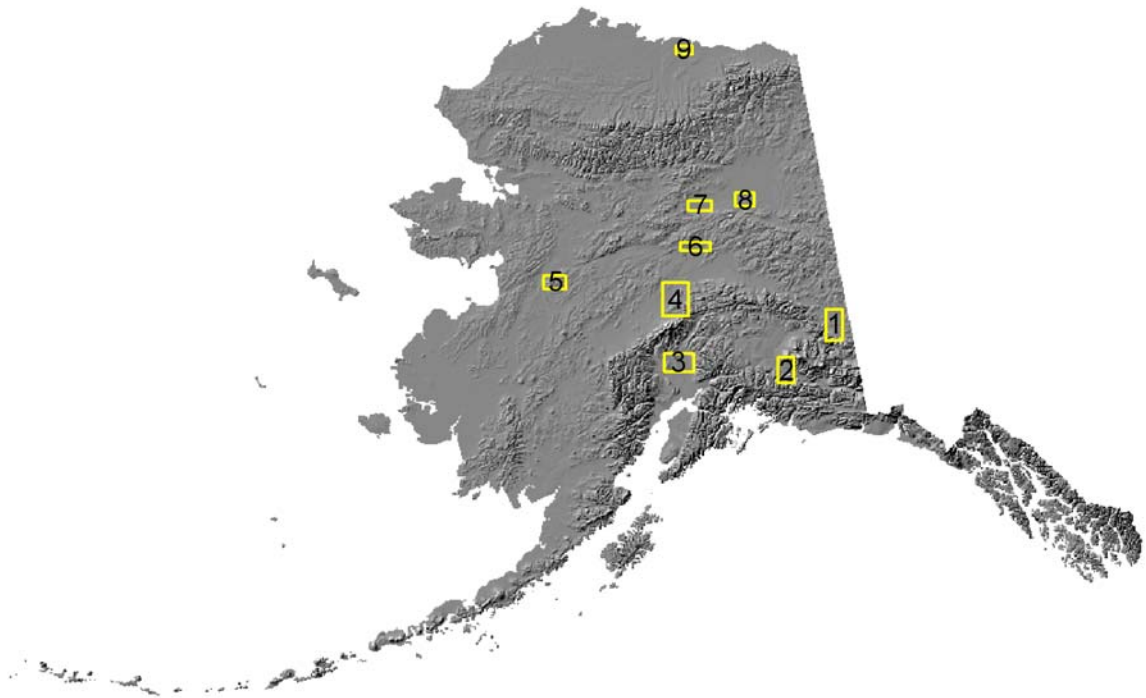


Figure 1.7 Nine study regions across Alaska from south to north: 1) Tetlin National Wildlife Refuge, 2) Copper River Basin, 3) Talkeetna, 4) Denali National Park, 5) Innoko Flats National Wildlife Refuge, 6) Minto Flats State Game Refuge, 7) Stevens Village, 8) Yukon Flats National Wildlife Refuge, and 9) Prudhoe Bay, Arctic Coastal Plain.

This study focuses only on closed-basin water bodies because open-basin water bodies may have changes not related to climate warming, such as changes in beaver dams or stream channels. Closed-basin water bodies are defined as having no direct influx of water and no direct outlet for water (Figure 1.8).

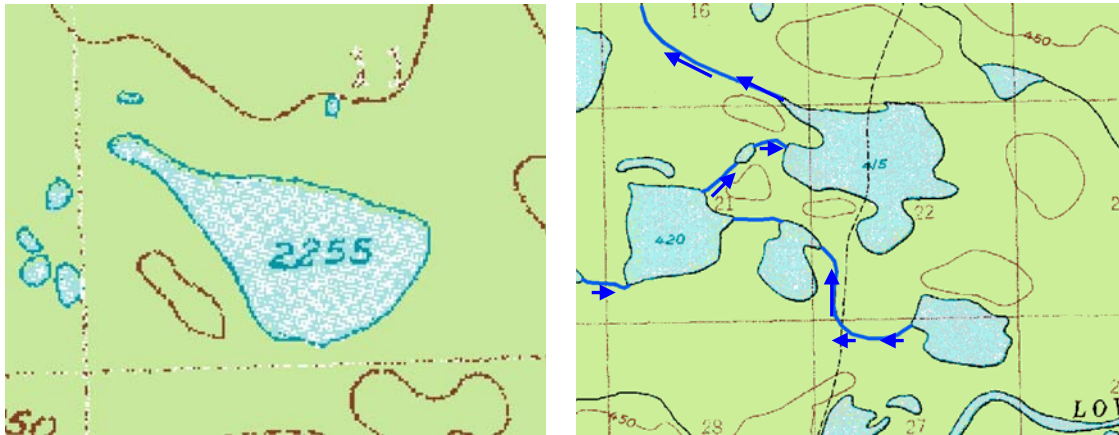


Figure 1.8 The water body on the left is an example of a closed-basin water body. There is no direct in-flow and outflow for surface water to affect lake water levels. The water bodies on the right are open-basin water bodies; and there is a direct inflow and outflow for water to move between water bodies as symbolized by arrows in the figure.

2 Study Regions and Weather Station Locations

2.1 STUDY REGIONS

2.1.1 Study Regions and Weather Station Locations

This study includes nine study regions, eight of which are located in subarctic Alaska, the largest region is Yukon Flats National Wildlife Refuge with over 200,000 ha. The smallest region is the Copper River Basin with just over 30,000 ha (Table 2.1).

Table 2.1 Study regions general information

Study Region	Mean Annual Temp	Mean Annual Precip (mm)	Weather Station Used	Area (ha)	Number of Water Bodies	Elevation (m)
Prudhoe Bay, Arctic Coastal Plain	-12°C	106mm	Barrow Airport	26,242ha	1,426	31m
Yukon Flats National Wildlife Refuge	-5°C	411mm	Bettles Airport	202,244ha	1,370	107 - 274m
Tetlin National Wildlife Refuge	-4.9°C	238mm	Northway Airport	95,286ha	2,152	533 - 686m
Minto Flats State Game Refuge	-2.9°C	262mm	Fairbanks Airport	80,937ha	1,390	107 - 152m
Stevens Village	-2.9°C	262mm	Fairbanks Airport	107,330ha	1,825	107 - 137m
Denali National Park	-2.9°C	262mm	Fairbanks Airport	82,131ha	876	152 - 244m
Innoko Flats National Wildlife Refuge	-2.8°C	445mm	McGrath Airport	62,655ha	1,205	31m
Copper River Basin	-2.8°C	290mm	Gulkana Airport	30,311ha	153	396 - 914m
Talkeetna	1°C	715mm	Talkeetna Airport	176,666ha	1,000	91 - 284m

Reliable weather stations that date back more than thirty-years in Alaska are scarce, leaving researchers with few options in choosing weather data to represent a remote study region. I used six first order weather stations to provide the weather data for the study regions. The weather station locations, mean temperature, and mean annual precipitation (including snow) are listed in Table 2.1. Table 2.2 provides detailed information about the imagery used for each study region, Appendix A contains even more detailed information.

Table 2.2 Study regions image information

Study Region	Image Date	Images Used
Prudhoe Bay/ Arctic Coastal Plain	<ul style="list-style-type: none"> · 1954 · 1978 · 8/3/99 	<ul style="list-style-type: none"> · Black and White Aerial Photography (1:20,000) · Color Infrared Aerial Photograph (1:60,000) · Landsat 7 ETM+ Satellite Image (15m)
Yukon Flats National Wildlife Refuge	<ul style="list-style-type: none"> · 6/14/52; 6/24/52; 7/5/52; 7/18/52; 8/21/52; 9/13/52 · 1979 · 8/16/00 	<ul style="list-style-type: none"> · Black and White Aerial Photography (1:40,000) · Orthophotographs created from mosaic (1:120,000) · Landsat 7 ETM+ Satellite Image (15m)
Tetlin National Wildlife Refuge	<ul style="list-style-type: none"> · 8/22/54 · 7/1/78; 8/1/81 · 8/4/99 	<ul style="list-style-type: none"> · Black and White Aerial Photography (1:40,000) · Color Infrared Aerial Photograph (1:60,000) · Landsat 7 ETM+ Satellite Image (15m)
Minto Flats State Game Refuge	<ul style="list-style-type: none"> · 6/27/51; 7/11/51; 8/7/54 · 7/1/80 · 6/29/91 · 8/16/00 · 8/6/02 	<ul style="list-style-type: none"> · Black and White Aerial Photography (1:40,000) · Color Infrared Aerial Photograph (1:60,000) · Landsat 5 ETM+ Satellite Image (30m) · Landsat 7 ETM+ Satellite Image (15m)

Table 2.2 continued

Stevens Village	<ul style="list-style-type: none"> · 6/27/51; 7/11/51 · 7/1/78 · 6/29/91 · 8/16/00 · 8/6/02 	<ul style="list-style-type: none"> · Black and White Aerial Photography (1:40,000) · Color Infrared Aerial Photograph (1:60,000) · Landsat 5 ETM+ Satellite Image (30m) · Landsat 7 ETM+ Satellite Image (15m)
Denali National Park	<ul style="list-style-type: none"> · 8/28/51; 7/20/52; 8/5/52; 8/7/54 · 8/1/79; 8/23/81 · 8/16/2000 	<ul style="list-style-type: none"> · Black and White Aerial Photography (1:40,000) · Color Infrared Aerial Photograph (1:60,000) · Landsat 7 ETM+ Satellite Image (15m)
Innoko Flats National Wildlife Refuge	<ul style="list-style-type: none"> · 6/14/52; 6/24/52 · 7/1/80 · 8/18/01 	<ul style="list-style-type: none"> · Black and White Aerial Photography (1:40,000) · Color Infrared Aerial Photograph (1:60,000) · Landsat 7 ETM+ Satellite Image (15m)
Copper River Basin	<ul style="list-style-type: none"> · 7/29/57; 7/5/55 · 8/28/78 · 8/8/95 · 8/7/01 	<ul style="list-style-type: none"> · Black and White Aerial Photography (1:40,000) · Color Infrared Aerial Photograph (1:60,000) · Landsat 5 TM Satellite Image (30m) · Landsat 7 ETM+ Satellite Image (15m)
Talkeetna	<ul style="list-style-type: none"> · 7/3/51; 7/3/54; 7/11/53; 6/17/54 · 8/1/80 · 8/16/00 	<ul style="list-style-type: none"> · Black and White Aerial Photography (1:40,000) · Color Infrared Aerial Photograph (1:60,000) · Landsat 7 ETM+ Satellite Image (15m)

2.1.3 Copper River Basin Region and Gulkana Airport Weather Station

The Copper River flows to the south, and Mount Drum is situated north of the region (Figure 2.1). The Valdez D-3 USGS topographic map covers the entire area. The Copper River Basin is the smallest region in the study. This area, near the town of Gulkana, Alaska, is on the edge of the discontinuous permafrost zone and was expected to be the first area to show signs of permafrost degradation in response to climatic change.

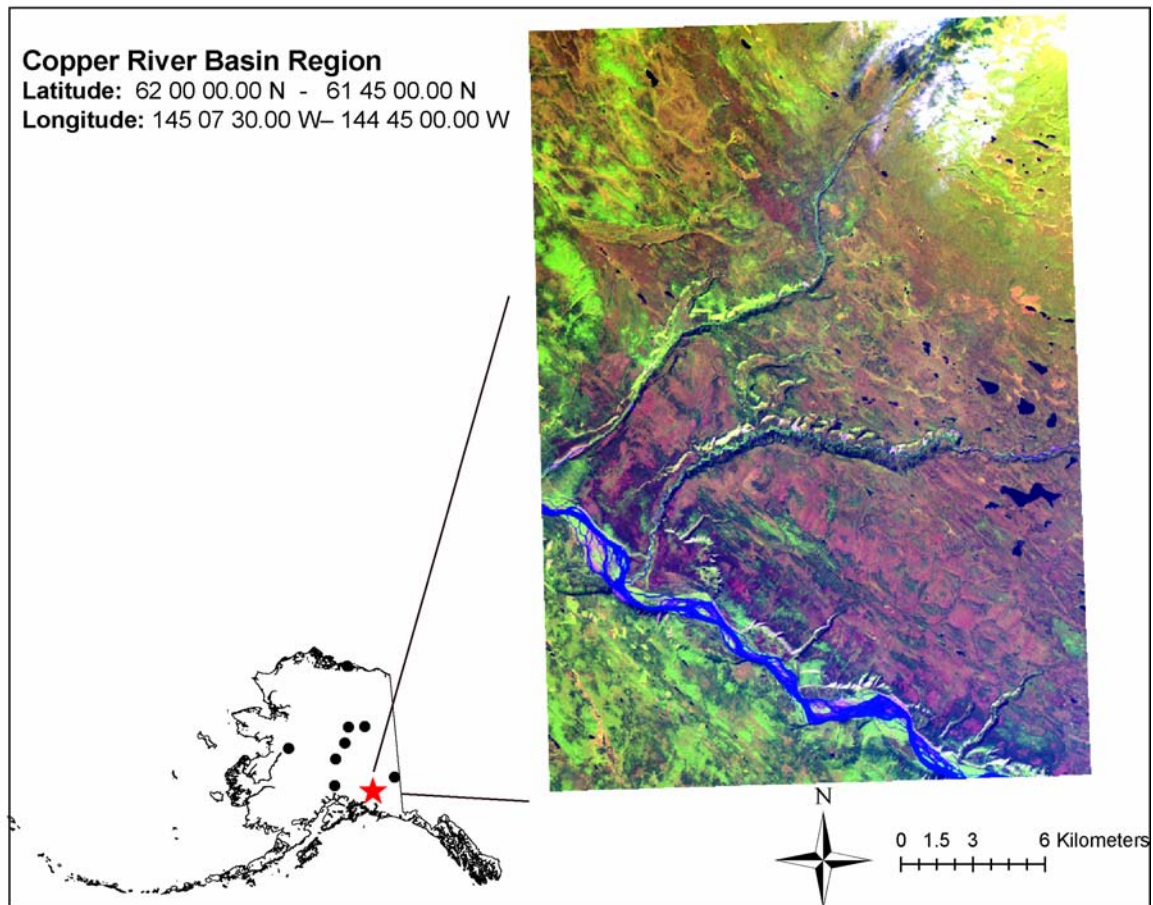


Figure 2.1 Landsat 7 ETM+ displayed in bands 5, 4, and 1 of the Copper River Basin study region.

The Gulkana weather station is at 62 °10' N, 145°27' W, elevation 479m, in the Copper River Basin. The weather station is 35 kilometers from the center of the study region (Figure 2.2). This weather station has good continuity from 1942 - present.

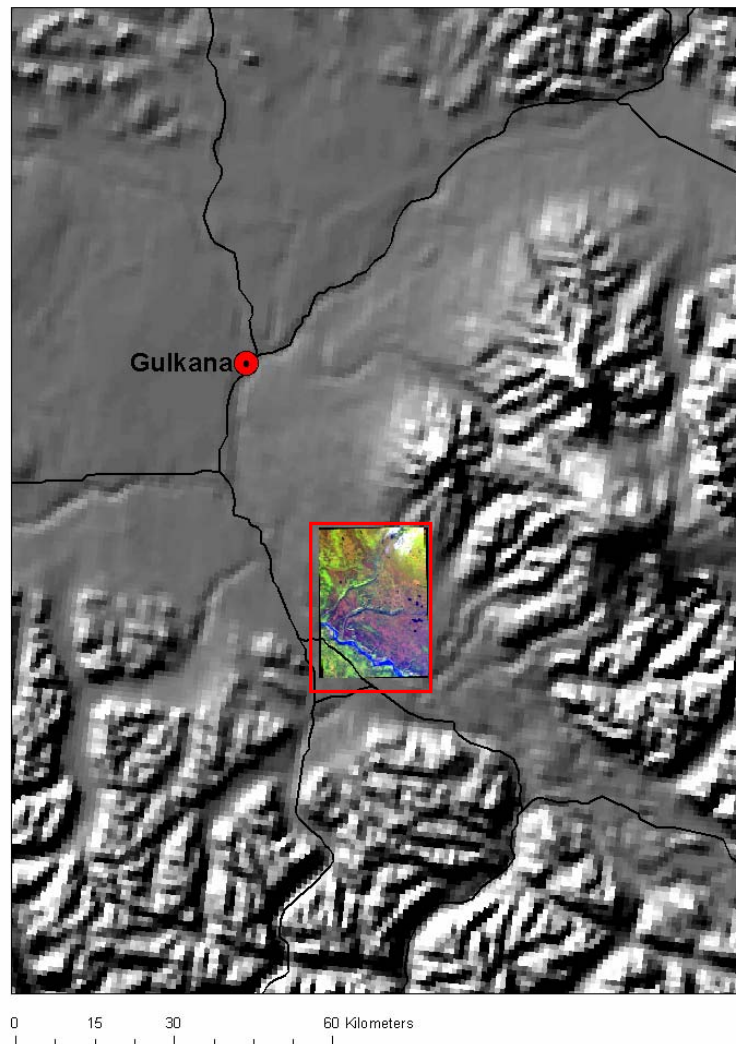


Figure 2.2 Gulkana airport weather station in relation to Copper River Basin region.

2.1.4 Yukon Flats National Wildlife Refuge Region and Bettles Airport Weather Station

There are two study regions located in the Yukon Flats National Wildlife Region: Yukon Flats National Wildlife Refuge and Stevens Village. This region is in the center of the Yukon Flats Wildlife Refuge (Figure 2.3), while the Stevens Village region is located in the northwest corner of the refuge. It has an elevation change of less than 30 m. The closest town is Fort Yukon, Alaska. Thousands of small ponds comprise this ecosystem, which is home to diverse

populations of migratory waterfowl. The region is inhabited by the Athabaskan Indians, who have reported a decrease in local water bodies over the last fifty years. Discontinuous and continuous permafrost underlie this region.

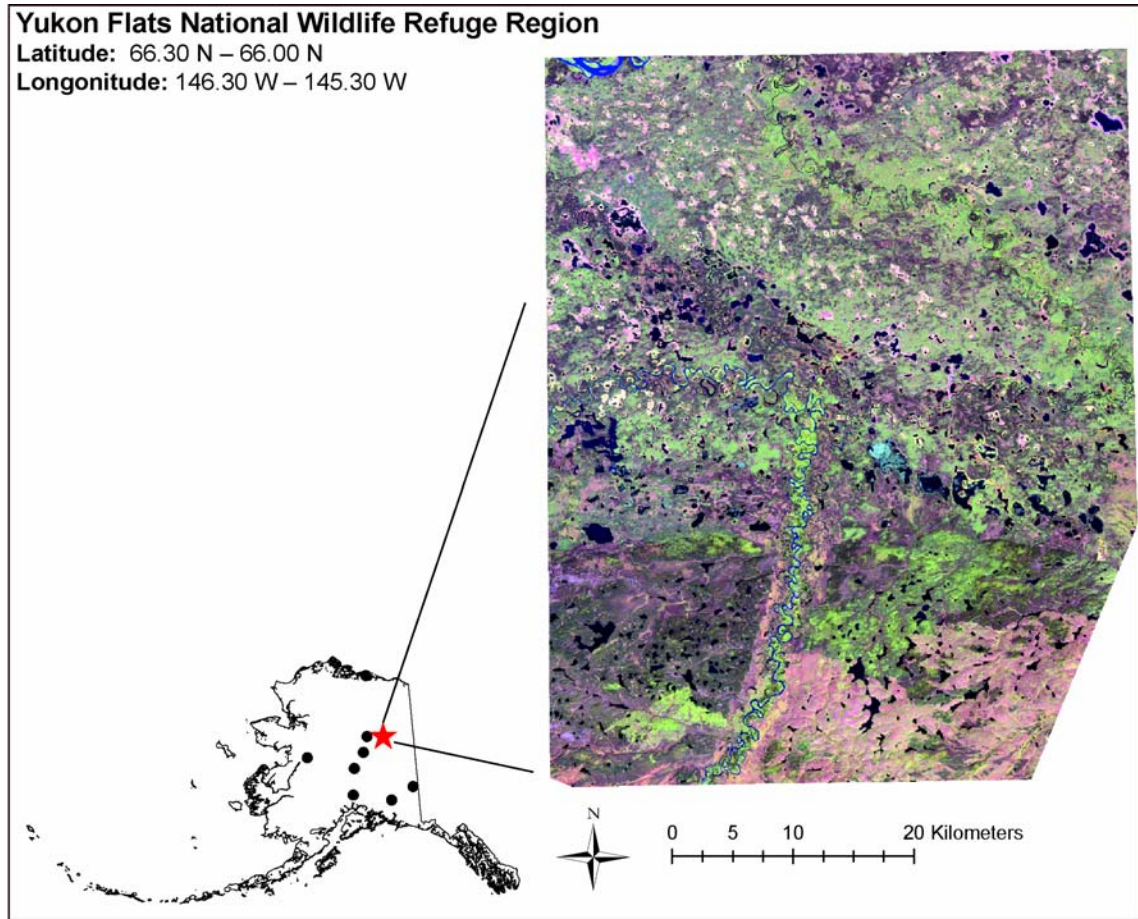


Figure 2.3 Landsat 7 ETM+ displayed in bands 5, 4, and 1 of the Yukon Flats National Wildlife Refuge study region.

The Bettles airport weather station is at 66 ° 55' N, 151 ° 31' W, elevation 196 m (Figure 2.4). The Brooks Range borders the station to the north. The weather station is 257 kilometers from the center of the Yukon Flats National Wildlife Refuge. The continuity of weather records dates back to 1944, with an excellent record from 1951-present.

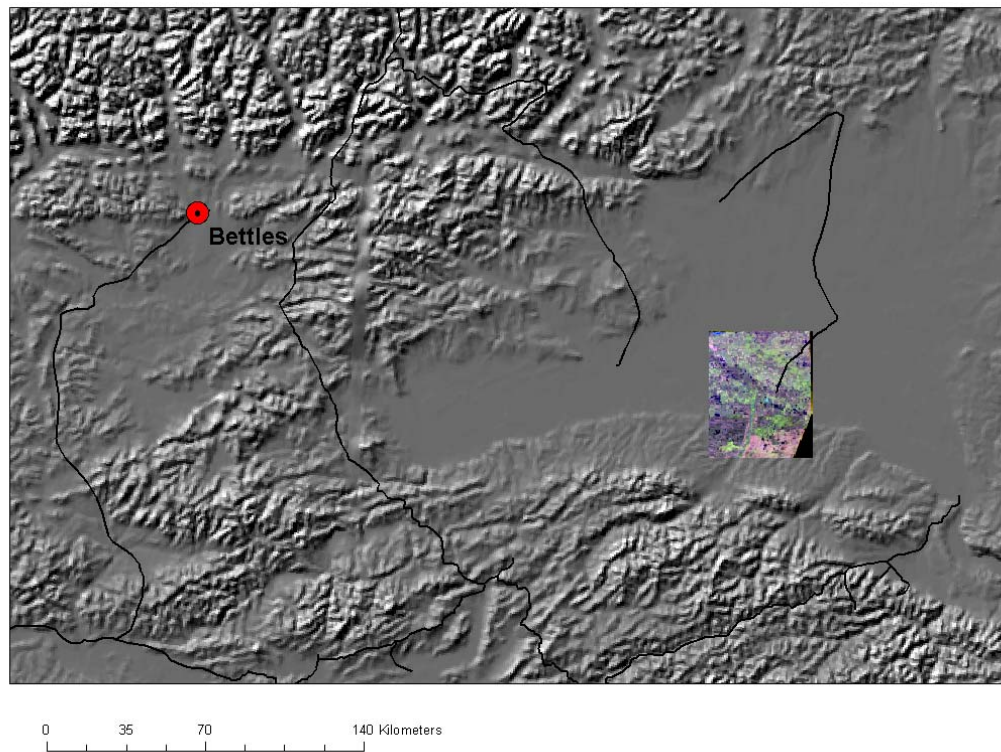


Figure 2.4 Bettles airport weather station in relation to Yukon Flats National Wildlife Refuge study region.

2.1.5 Minto Flats State Game Refuge, Stevens Village, Denali National Park, and Fairbanks Weather Station

Minto Flats State Game Refuge is largely composed of ponds, oxbows, stream channels, and wetlands (Figure 2.5). This area is often recharged by several rivers and streams in the region. These include the Tanana, Chatanika, and Tolovanva rivers. The closest fifty-year weather record is in Fairbanks, which is 56 kilometers to the east. The study region can be located within three USGS Quadrangle maps: Livengood A4, Livengood A5, and Livengood A6.

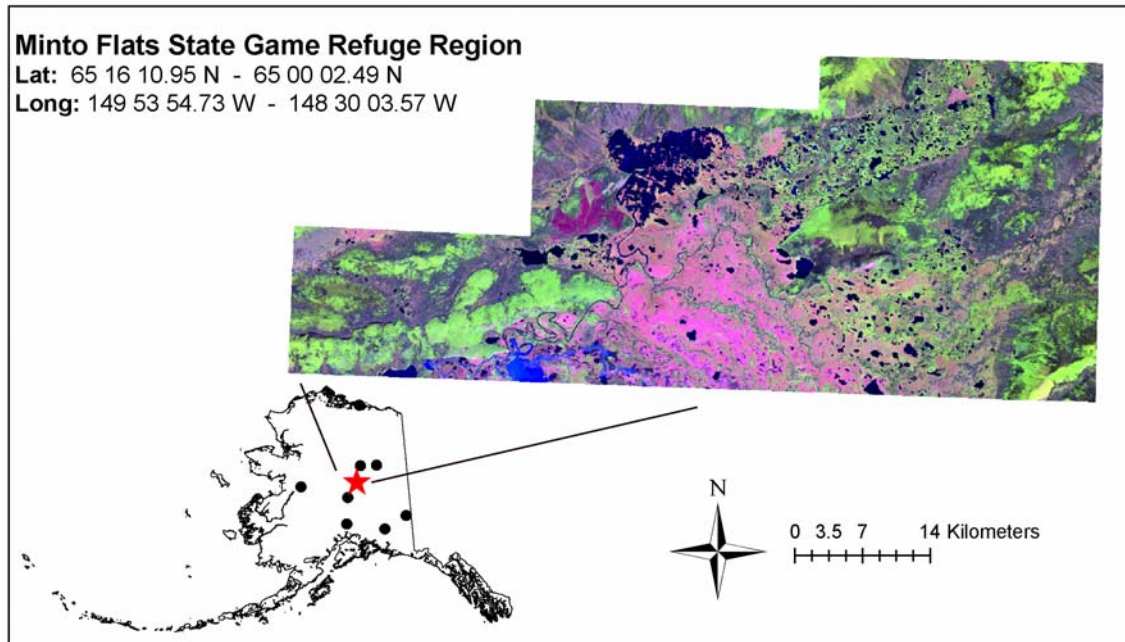


Figure 2.5 Landsat 7 ETM+ displayed in bands 5, 4, and 1 of the Minto Flats State Game Refuge study region.

The Stevens Village region is located in the northwest corner of the Yukon Flats National Wildlife Refuge. Located approximately 161 kilometers north of Fairbanks, the refuge covers over 4,800,000 hectares and follows the Yukon River for 322 kilometers along a large flood plain (Figure 2.6). There are over 40,000 lakes and wetlands within the Yukon Flats National Wildlife Refuge.

This study region is on six USGS Quadrangle maps: BeaverA3, Beaver A4, Beaver A5, Beaver B3, Beaver B4, and Beaver B5. In relation to the entire refuge, this region is in the upper left corner near Stevens Village. Missing photographs from the 1950s generated a mosaic pattern in this region.

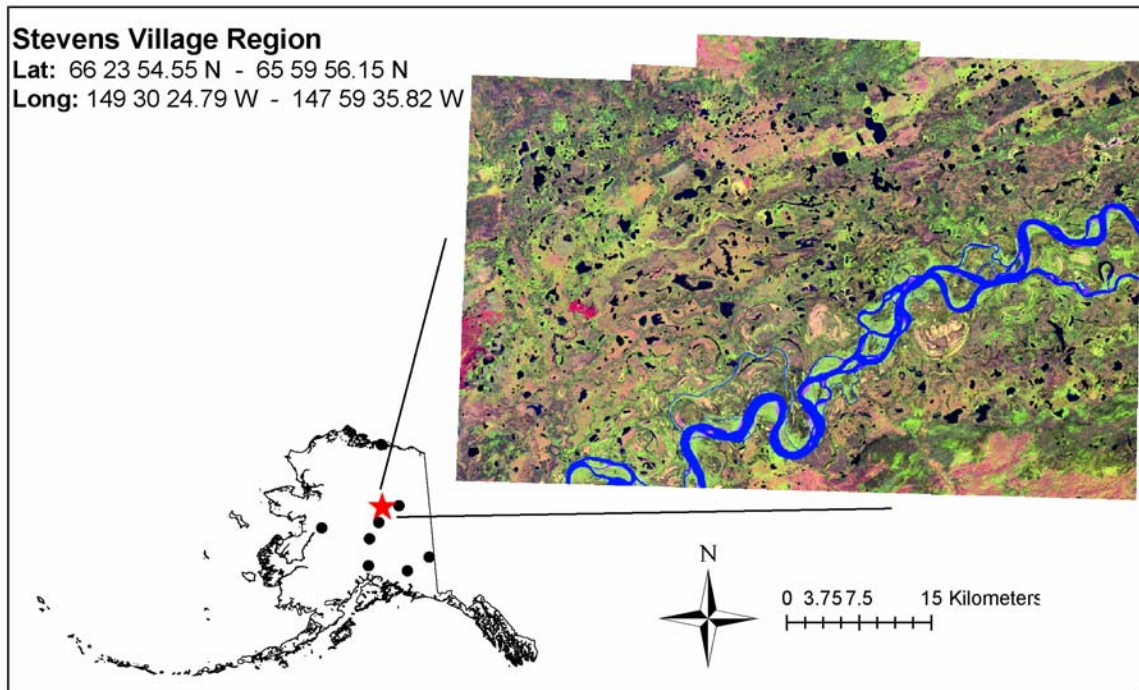


Figure 2.6 Landsat 7 ETM+ displayed in bands 5, 4, and 1 of the Stevens Village study region.

The Denali National Park region is on the northern boundary of Denali National Park, with the Kastishna River running through it, the Kuskokwim Mountains to the west, and the Toklat River bordering it the east (Figure 2.7). The closest long-term weather station is in Fairbanks, Alaska.

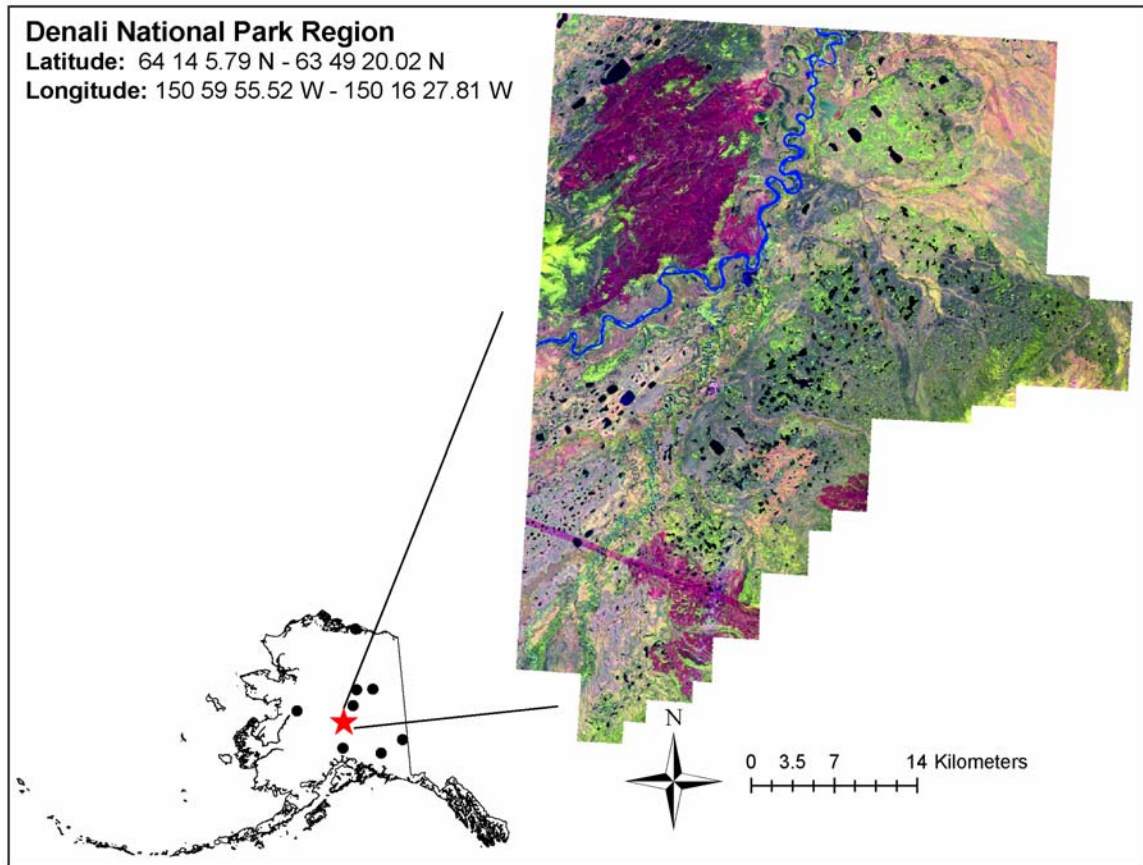


Figure 2.7 Landsat 7 ETM+ displayed in bands 5, 4, and 1 of the Denali National Park study region.

The Fairbanks station is in the town of Fairbanks (Figure 2.8); current coordinates 64 ° 51' N, 147 ° 52' W, elevation 145 m. I used the Fairbanks weather station: Denali National Park is 166 kilometers to the south west, Minto Flats State Game Refuge is 69 kilometers to the west, and Stevens Village is 156 kilometers to the NW.

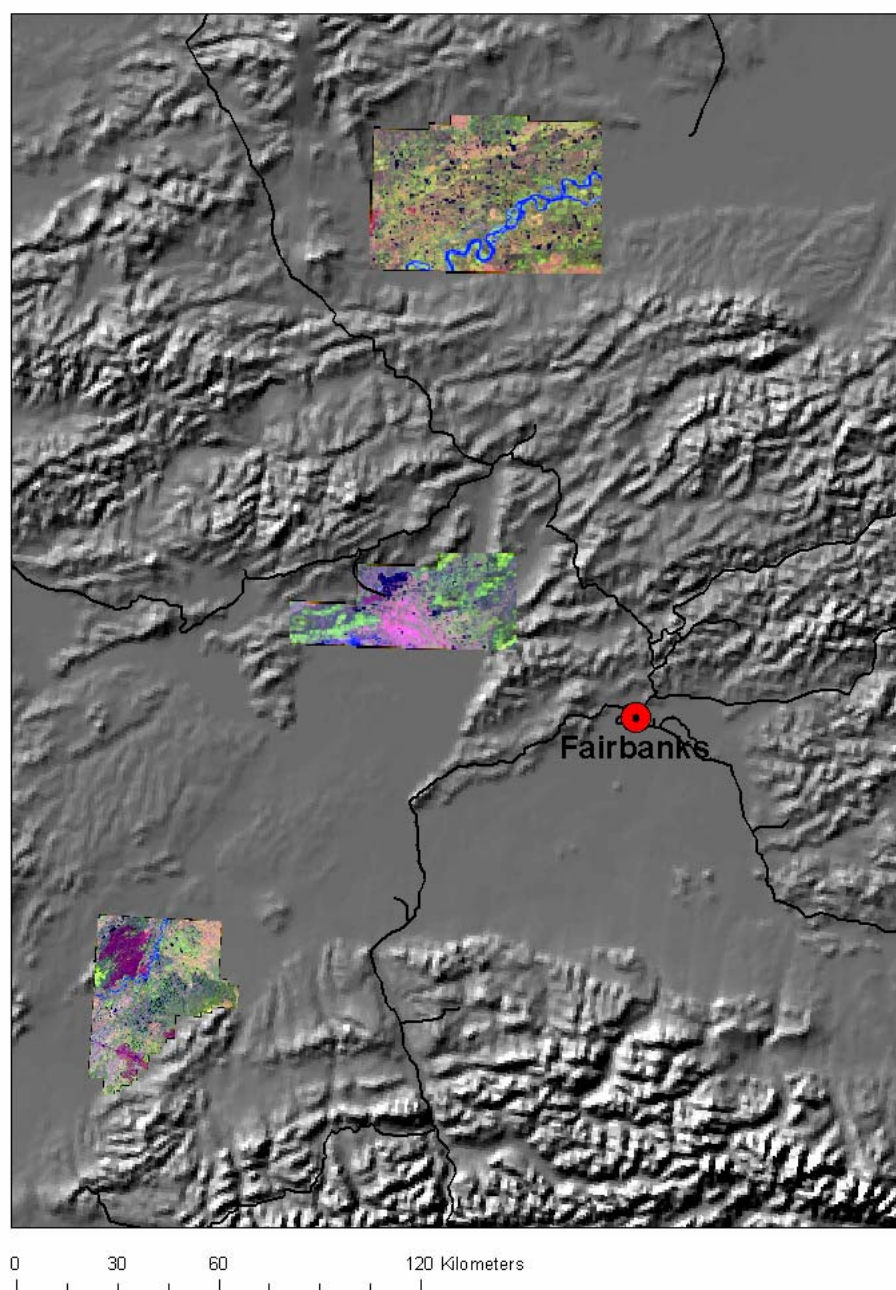


Figure 2.8 Fairbanks weather station in relation to Denali National Park, Minto Flats State Game Refuge, and Stevens Village study regions.

2.1.6 Tetlin National Wildlife Refuge Region and Northway Weather Station

The Tetlin National Wildlife Refuge was established in 1980. It covers roughly 295,424 hectares and is located 32 kilometers west of the Canadian border in the Upper Tanana Valley. The refuge has some of the coldest winter temperatures in North America. (Figure 2.9) This study region is within the USGS Quadrangle maps of Nabesna C2 and Nabesna D2. The Alaska Highway (Route 2) borders it to the east and north, and the Alaska Range to the west. The Chisana River runs through the study region.

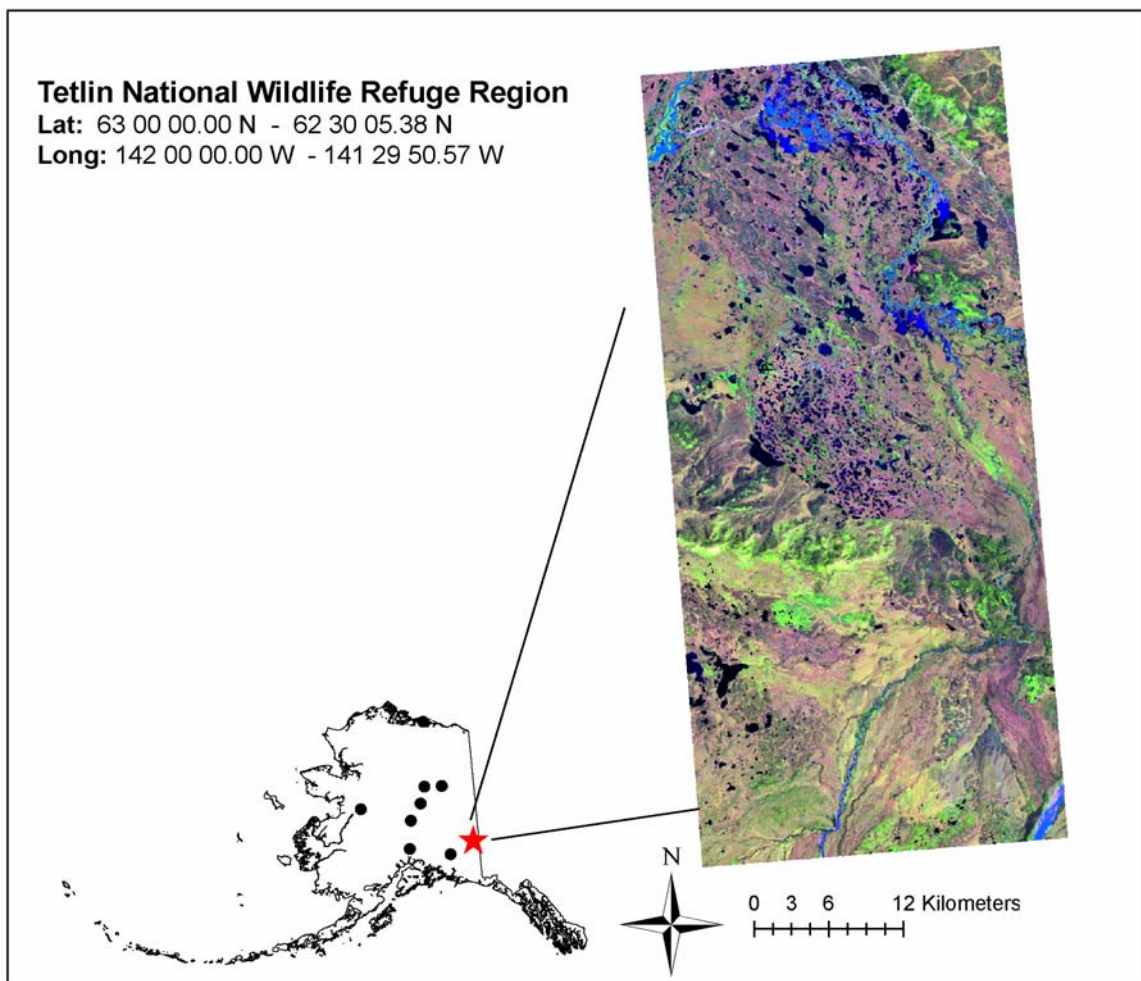


Figure 2.9 Landsat 7 ETM+ displayed in bands 5, 4, and 1 of the Tetlin National Wildlife Refuge study region.

The Northway station is in the town of Northway in the upper Tanana Valley. The weather station is at 62° 58' N, 141° 56' W, elevation 522 m (Figure 2.10). Climate data are available from 1942 – present, with few missing values.

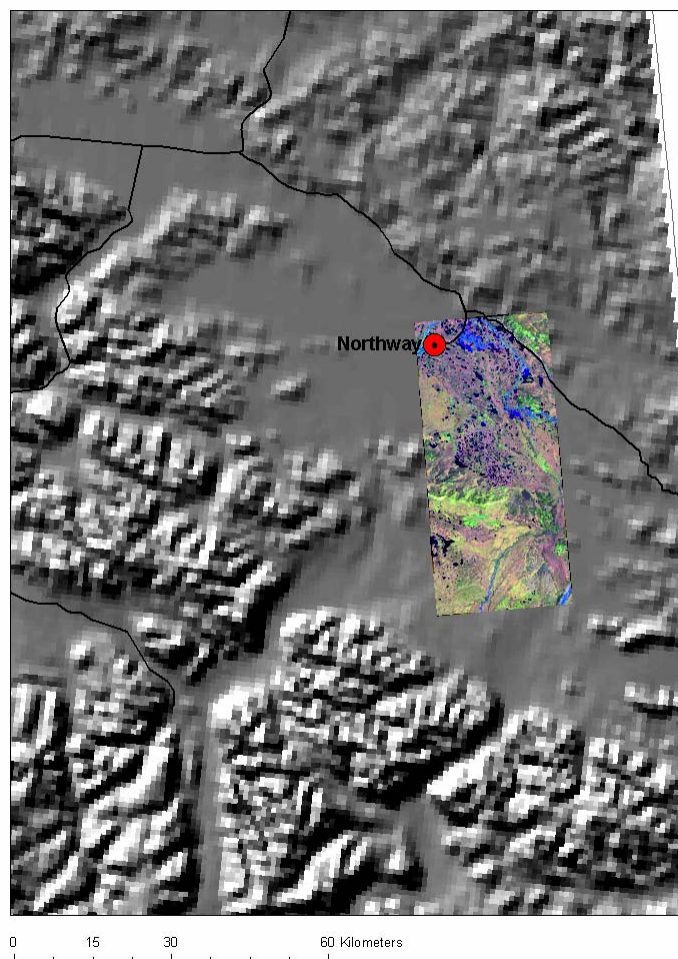


Figure 2.10 Northway Weather Station in relation to Tetlin National Wildlife Refuge region.

2.1.7 Innoko Flats National Wildlife Refuge Region and McGrath Airport Weather Station.

The Innoko Flats National Wildlife Refuge study region spans the USGS Quadrangle maps of Nulato B4 and Nulato B5 (Figure 2.11). The closest weather station is at Holy Cross. However, incomplete records at Holy Cross required the use of the weather station data from McGrath, Alaska.

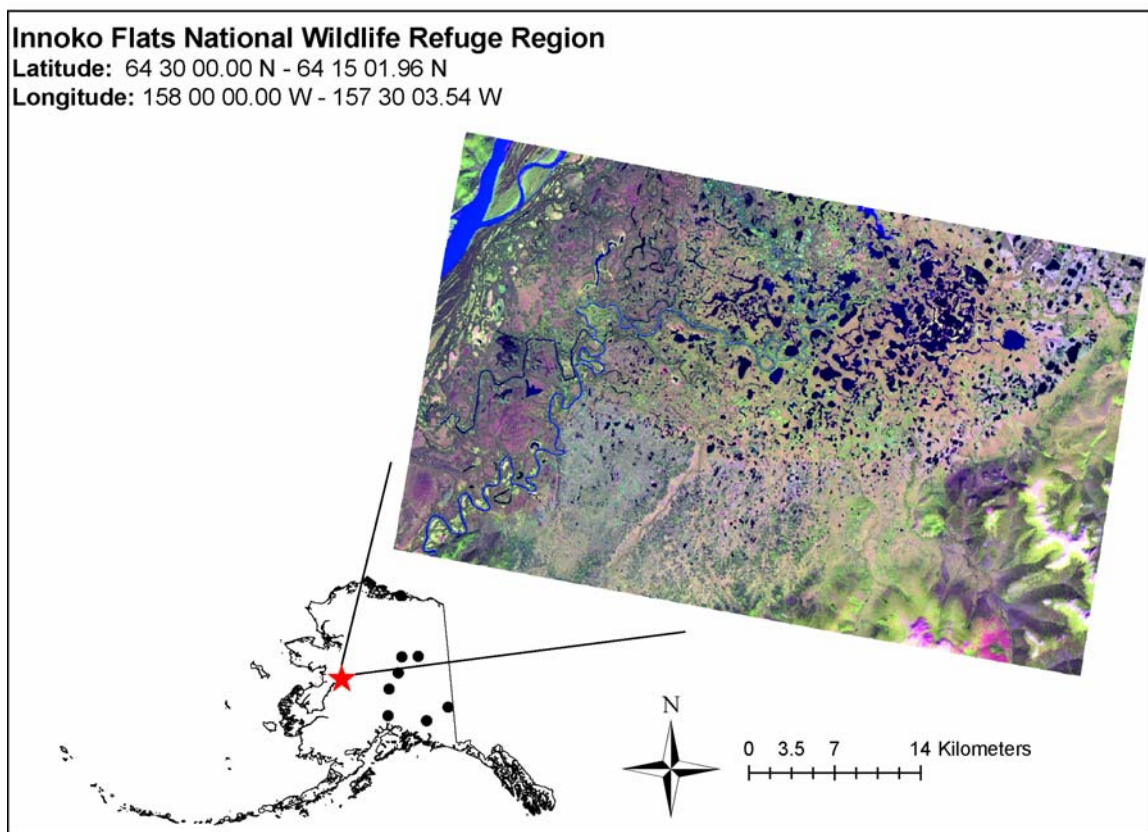


Figure 2.11 Landsat 7 ETM+ displayed in bands 5, 4, and 1 of the Innoko Flats National Wildlife Refuge study region.

The McGrath airport is in the town of McGrath, on the Kuskokwim River, between Fairbanks and the Yukon-Kuskokwim delta (Figure 2.12). The weather station is at coordinates 62 ° 57' N, 155 ° 36' W, elevation 101.5m. It is 201 kilometers from the middle of the Innoko Flats National Wildlife Refuge study region. There are few missing values between 1941-present. The

Fairbanks National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) office considers this possibly the best station in interior Alaska.

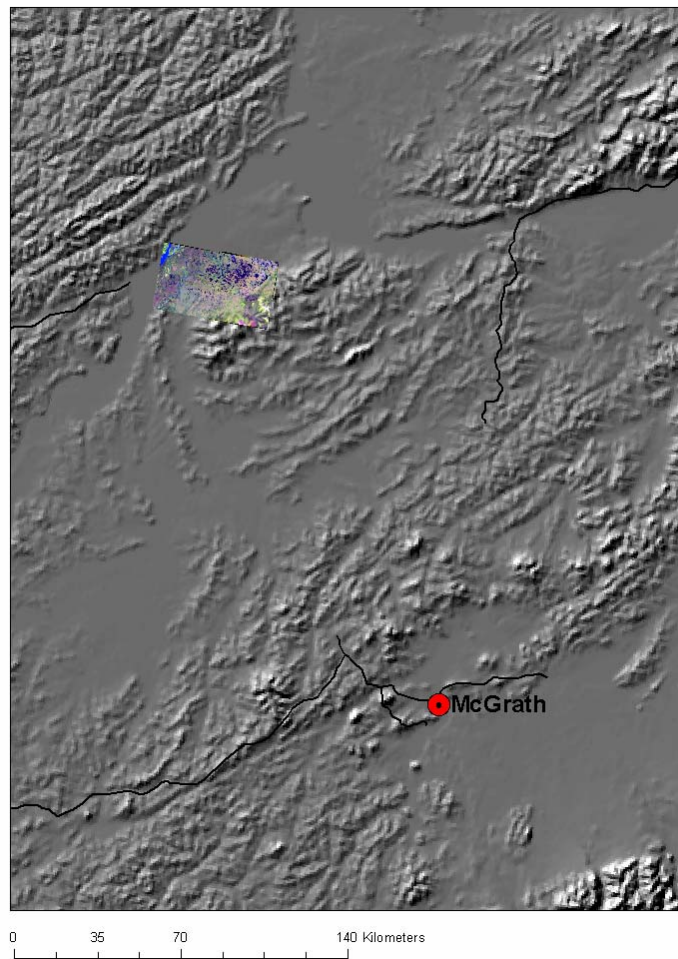


Figure 2.12 McGrath Weather Station in relation to Innoko Flats National Wildlife Refuge study region.

2.1.8 Talkeetna Region and Talkeetna Airport Weather Station

Four USGS Quadrangle maps define the boundaries of the Talkeetna study region: Talkeetna A1, Talkeetna A2, Talkeetna B1, and Talkeetna B2 (Figure 2.13). The George Parks

Highway (Route 3) on the east and the foothills of Denali National Park to the north and west border the region. The town of Talkeetna is the location of the closest weather station.

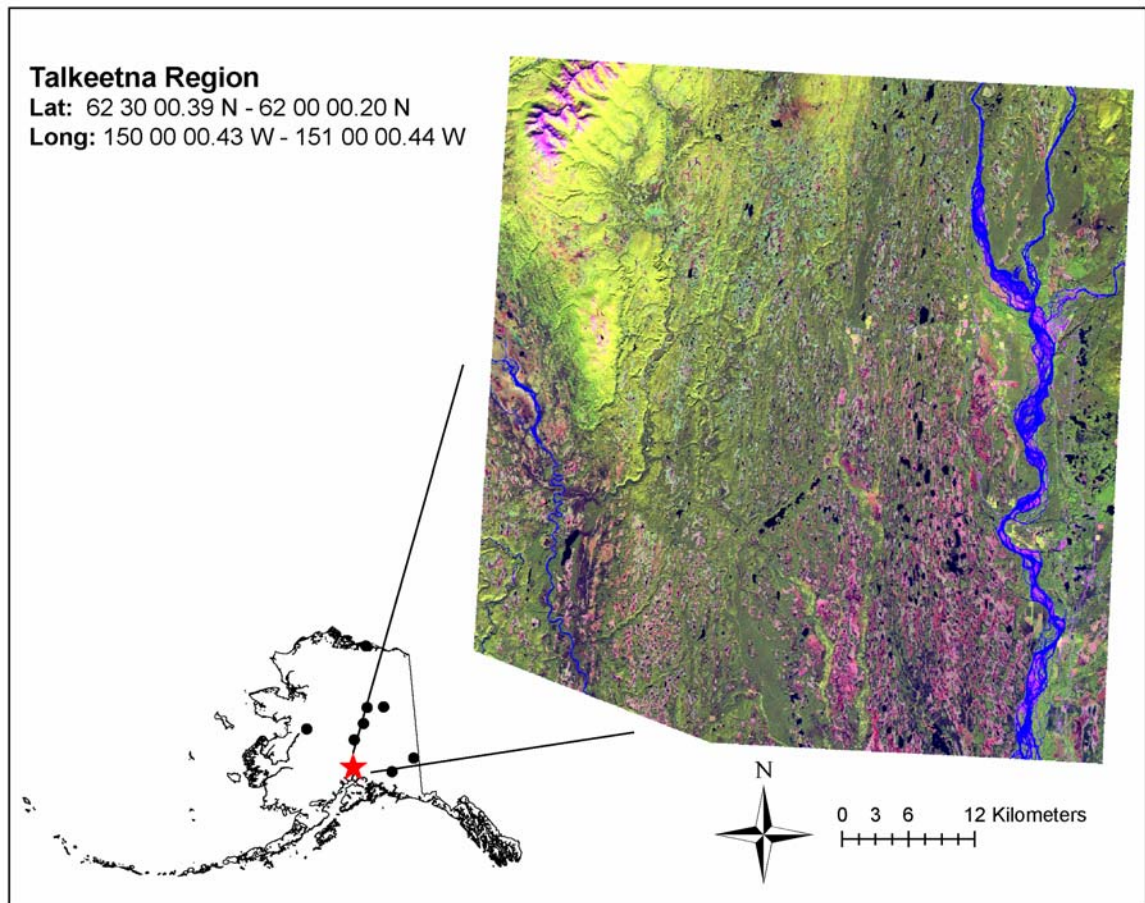


Figure 2.13 Landsat 7 ETM+ displayed in bands 5, 4, and 1 of the Copper River Basin study region.

The Talkeetna airport is in the upper Susitna Valley (Figure 2.14). The weather station is at coordinates 62°19'N, 150°06'W, elevation 106.7m. This station opened 3/16/1917 at the Alaska Railroad Depot and was relocated to the Talkeetna Airport June 1, 1940.

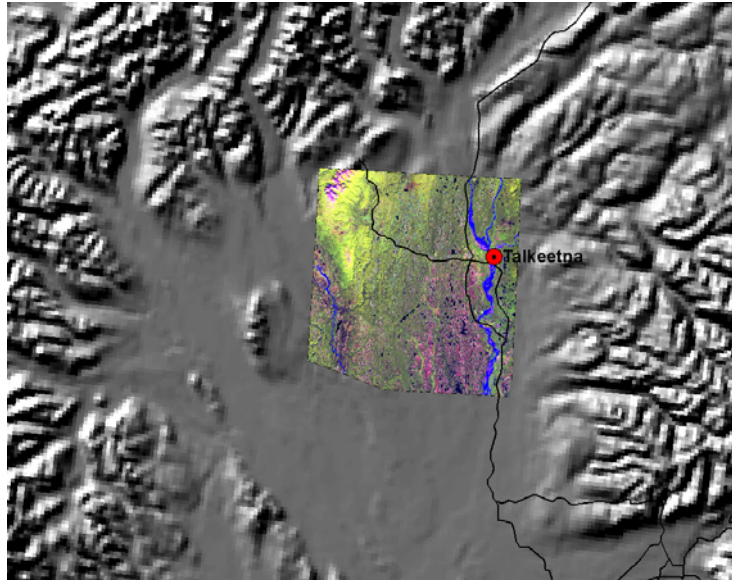


Figure 2.14 Talkeetna weather station in relation to the Talkeetna study region.

2.1.9 Prudhoe Bay/Arctic Coastal Plain Region and Barrow Weather Station

The Prudhoe Bay/Arctic Coastal Plain region is located on the northern slope of Alaska. Thousands of thaw ponds, underlain by continuous permafrost, make up this landscape (Figure 2.15). With mean annual temperatures of permafrost in this region cooler than the permafrost temperatures near Fairbanks, it is expected that water bodies have not substantially changed in this region. Three study areas are used to sample the arctic coastal plain region (Figure 2.16), and they are located to the west and southwest of Prudhoe Bay, Alaska.

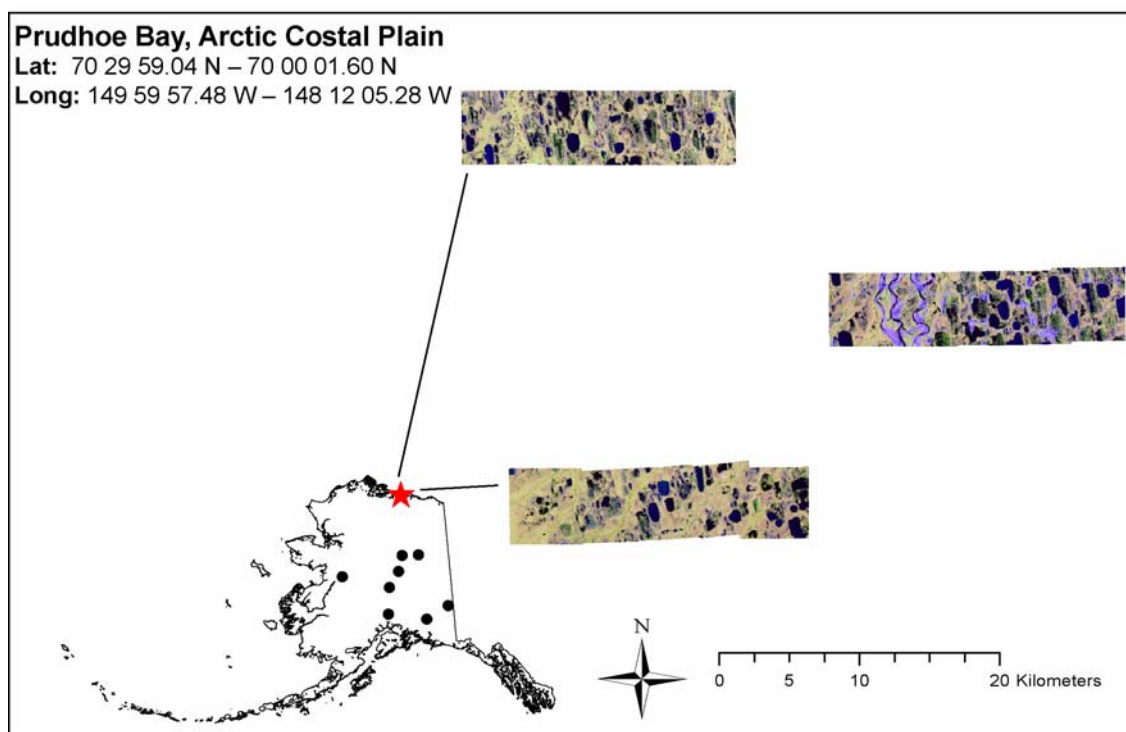


Figure 2.15 Landsat 7 ETM+ displayed in bands 5, 4, and 1 of the Prudhoe Bay/Arctic Coastal Plain study region.

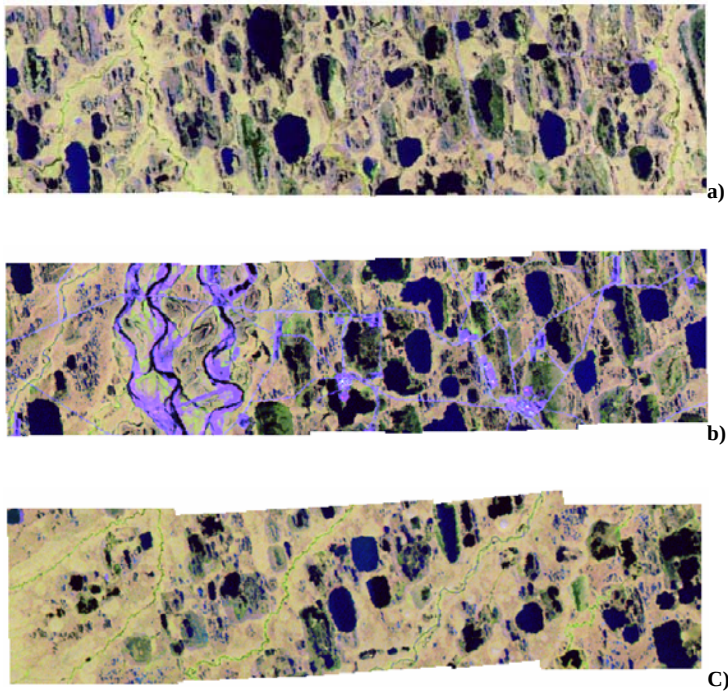


Figure 2.16 Three areas of the Arctic Coastal Plain study region.

The Arctic Coastal Plain has two weather stations, one at Barrow and the other at Barter Island. Barter Island is 177 kilometers from the study regions and would be the better choice for the weather station, but the dataset is short and of unreliable quality. Therefore, Barrow was used as the source for temperature and precipitation data.

The Barrow station is at coordinates 71 °18' N, 156 ° 47' W, elevation 9.5 m (Figure 2.16). It is the only first-order station on the Arctic Coastal Plain. The data records are complete from 1921 - present. Barrow is 300 kilometers from the study areas (Figure 2.17).

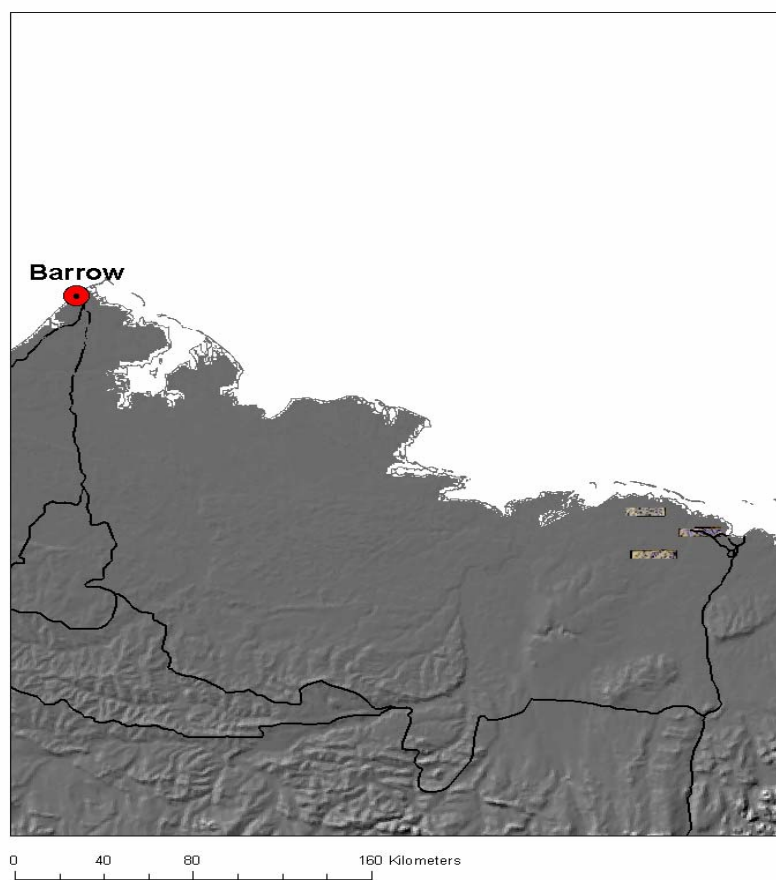


Figure 2.17 Barrow Weather Station in relation to the Prudhoe Bay/Arctic Coastal Plain study region.

3 Methods

3.1 INTRODUCTION

3.1.1 Introduction

To estimate surface water changes, I used remotely sensed images from the 1950s to the 2001. Except for the Prudhoe Bay/Arctic Coastal Plains Regions, the study regions were primarily representative of discontinuous permafrost (Figure 3.1). To establish a trend, a minimum of three image periods were needed for each region. These images would ideally be separated by 10-15 years. For each region I used the following images: black and white aerial photographs from the 1950s, color infrared aerial photographs from 1978-1982, and a Landsat Enhanced Thematic Mapper+ (ETM+) Image from 1999-2002. Landsat Thematic Mapper (TM) images from 1985-1995 provided extra observation periods to strengthen interpretation of any trends. In Alaska, however, it is often hard to obtain cloud/smoke free Landsat Satellite images during the summer months. I used smaller scale topographic maps of Alaska to select nine study regions that appeared to have a large number of closed-basin water bodies. I then searched for available aerial photography and satellite imagery covering each region. The final border for each region was ultimately determined by the availability of these early aerial photographs. A tenth candidate region near Arctic Village was dropped because of a lack of images from the 1950s.

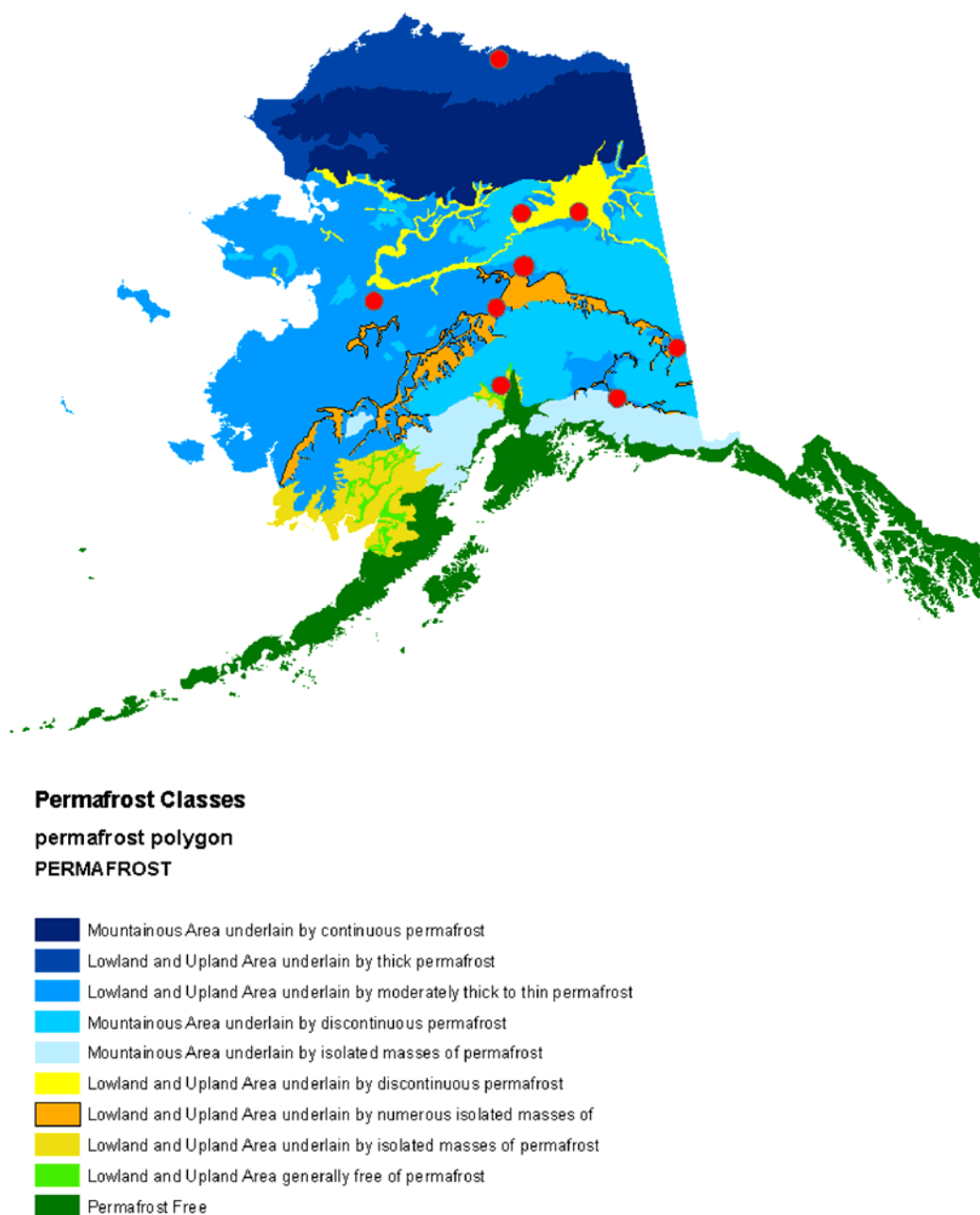


Figure 3.1 Permafrost map of Alaska (Ferrians, O. 1998).

3.1.2 Image Interpretation

Water absorbs radiation in the near- and mid-infrared spectral regions. Therefore, there is a strong contrast between water and land on infrared imagery (Figure 3.2), which allows for good delineation between water and other terrain features. Shadows from hillsides and clouds are also dark on images and could be confused with water in an automated spectral classification. To account for these possible problems, I acquired images that were cloud free and focused on study regions with minimal elevation change. Not relying on computer assisted classifications and hand digitizing the water bodies helped to minimize error associated with clouds and elevation.

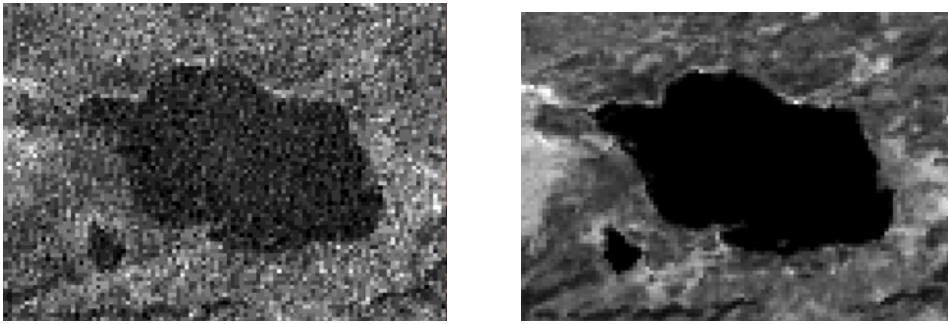


Figure 3.2 Water Body image in blue and Mid-Infrared spectral region in the Yukon Flats National Wildlife Refuge Landsat 7 ETM+ August 16, 2000.

3.1.3 Scanned Maps

I initially attempted to use digital images called digital raster graphics (DRGs) (Figure 3.3) for the 1950s period. DRGs are digital replications of the USGS Quadrangle maps. These USGS Quadrangle maps were typically created from black and white aerial photography made by the military during flights in the 1950s. After manipulating the DRGs into the GIS, and comparing them to several of the source aerial photographs, it became apparent that many of the DRGs had errors of over 30%. These were typically the result of misclassification of wetlands as water bodies, which would lead to overestimation of surface water area (Figure 3.4). This over representation of water bodies made it necessary to abandon the DRGs and use the original black and white aerial photographs.

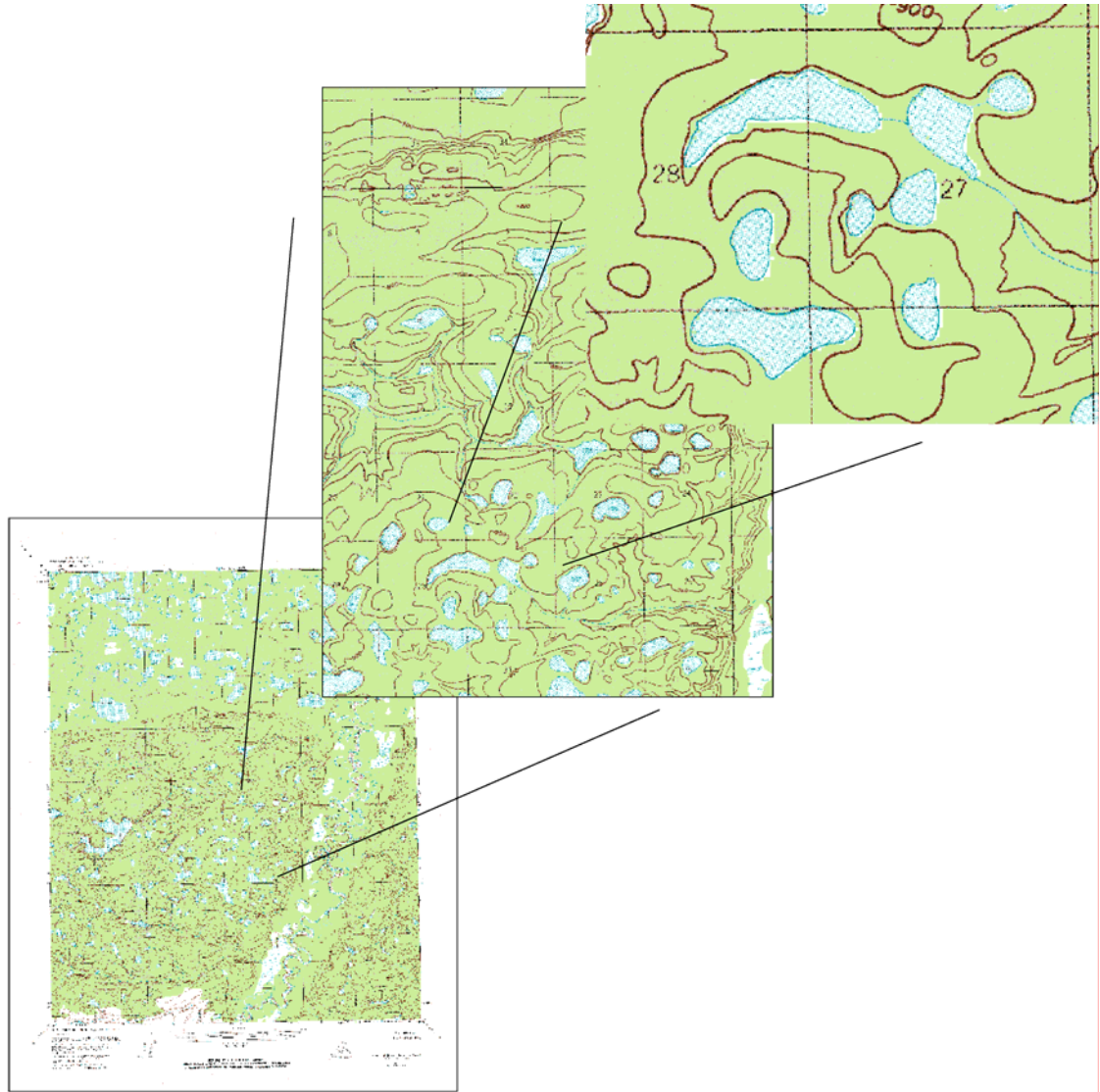


Figure 3.3 Digital Raster Graphic example from the Yukon Flats National Wildlife Refuge.

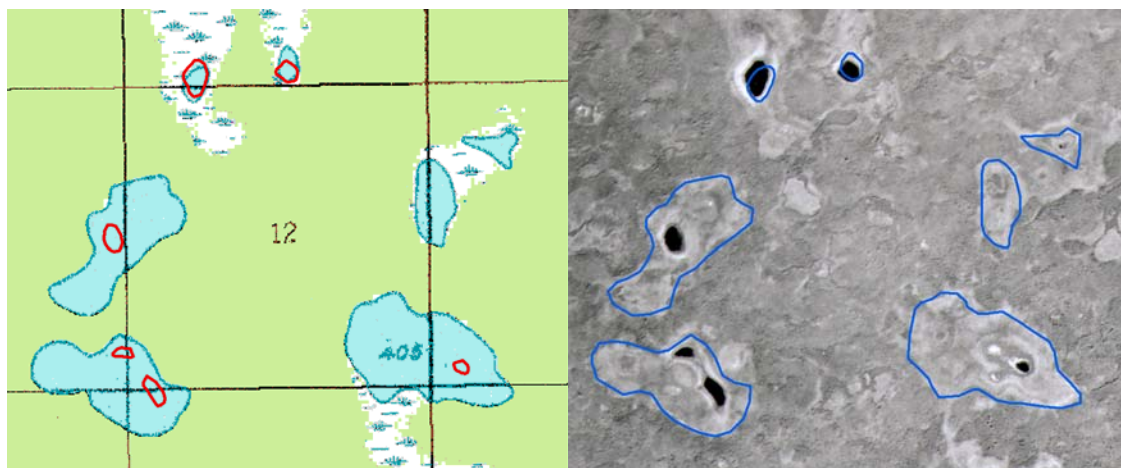


Figure 3.4 The left image shows the black and white aerial photography water body outlines in red superimposed over the digital raster graphics (DRG). The right image is the black and white aerial photograph with the DRG water body outlines in blue. The DRG images shows 100 ha of surface water area and 7 water bodies. The black and white image has 5.5 ha of surface water area and 6 water bodies.

3.1.4 1950s Aerial Photography

The black and white aerial photographs (see Figure 3.5 for an example) each covered a small area, and in several study regions over 40 photos were needed for complete coverage. This required a large amount of processing in order to make these images useful. In total, 230 black and white aerial photographs at a scale of 1:40,000 were ordered from the USGS map office in Anchorage. Arctic Village was a region that was dropped because of the unavailability of black and white aerial photographs for the 1950s. These photographs have been lost, never taken, or are still classified. This also occurred on the northern section of the Stevens Village region, where the flight lines stopped about halfway up the region.



Figure 3.5 Black and White Aerial photograph M616 0141 from the Yukon Flats National Wildlife Refuge at a scale of 1:40,000.

3.1.5 1978s – 1980s Aerial Photography

The Alaska High Altitude Aerial Photography (AHAP) program (see Figure 3.6 for an example) was flown between the years of 1978–1986, with over 70,000 frames. The program covers 95% of the state at a scale of 1:60,000 in color infrared (CIR). This is the most reliable source of images for the late 1970s and early 1980s. The Geodata center at the University of Alaska Fairbanks has a complete set of the AHAP series. This series is more complete and organized than the 1950s series. The 10x10 CIR transparencies were all scanned at 600 dpi in .tiff format. Tiff is a acronym for tagged image file format, and is one of the most widely supported file formats for storing bit-mapped images or in this case scanned images.

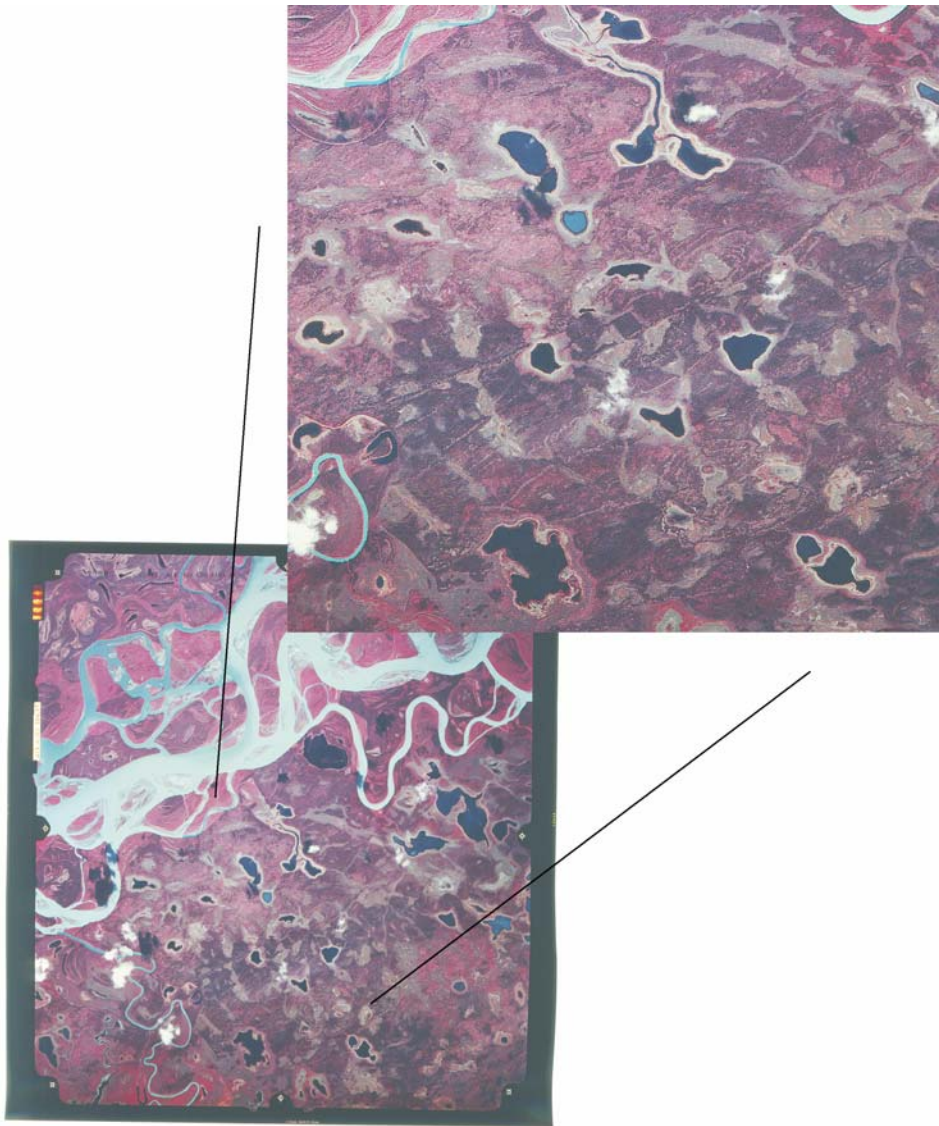


Figure 3.6 Color infrared aerial photograph Line 55 3298 from the Yukon Flats National Wildlife Refuge at a scale of 1:60,000.

A set of 1:120,000 black and white aerial photographs also were created during the AHAP program. The USGS used these photographs to produce Orthophotoquad maps of many areas in Alaska (see Figure 3.7 for an example). These areas correspond directly to the USGS 1:63,360 map series. These Orthophotoquad maps are a better format to work with than the original aerial photographs, because they are rectified to a planar map projection. However, the

images can be dark and their use requires a large format scanner. I used this format only in the Yukon Flats National Wildlife Refuge.

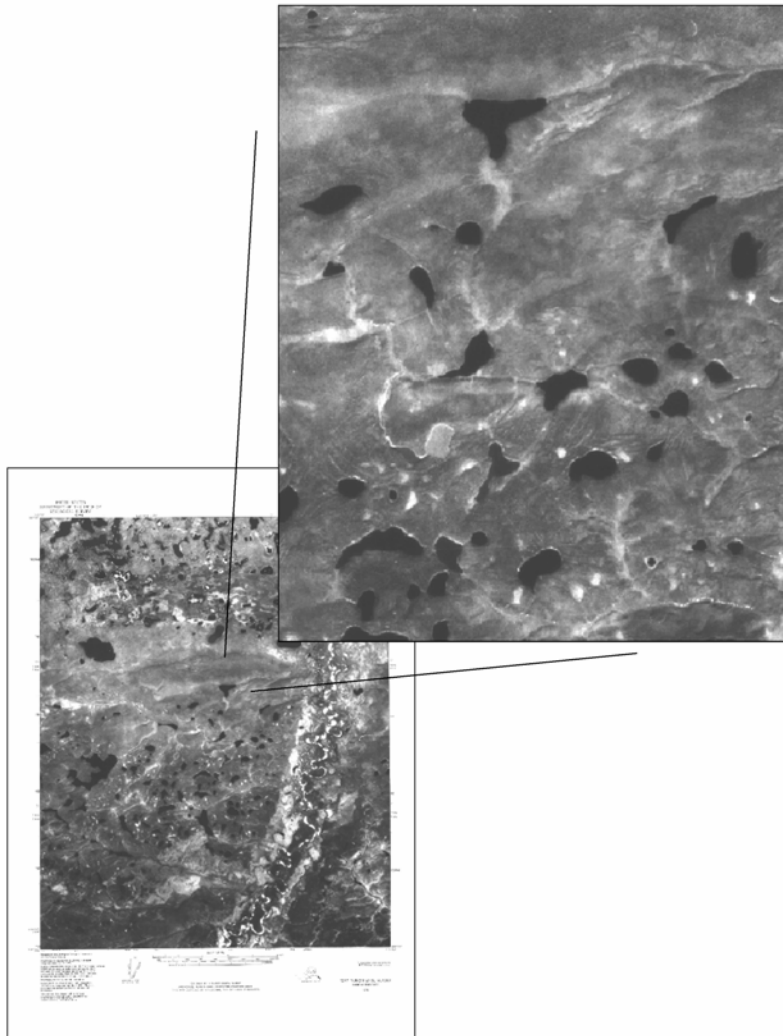


Figure 3.7 Orthophotoquad of Fort Yukon A-5 from the Yukon Flats National Wildlife Refuge at a scale of 1:120,000.

3.1.6 Satellite Imagery

Landsat Thematic Mapper (TM) images with a 30-meter cell size have been available since 1982. It was difficult to acquire useable Landsat TM and Landsat ETM+ imagery for nine areas across Alaska (Figure 2.1) because of smoke, clouds, and low solar angles. Yet, in order to detect and document change across time, it was necessary to have as many images as possible in a

time series to estimate a trend. After previewing browse images of Landsat scenes that could possibly contain a useable image, I identified and ordered as many as possible from the years of 1985-1995 that could be used for the study regions.

Landsat ETM+ images from 1999–2002 (see Figure 3.8 for an example) are the most current images in each region. The Landsat ETM+ images also have a better spatial resolution compared to the Landsat TM imagery. The Landsat ETM+ imagery has a 15-meter panchromatic band, that allows for better water body delineation.

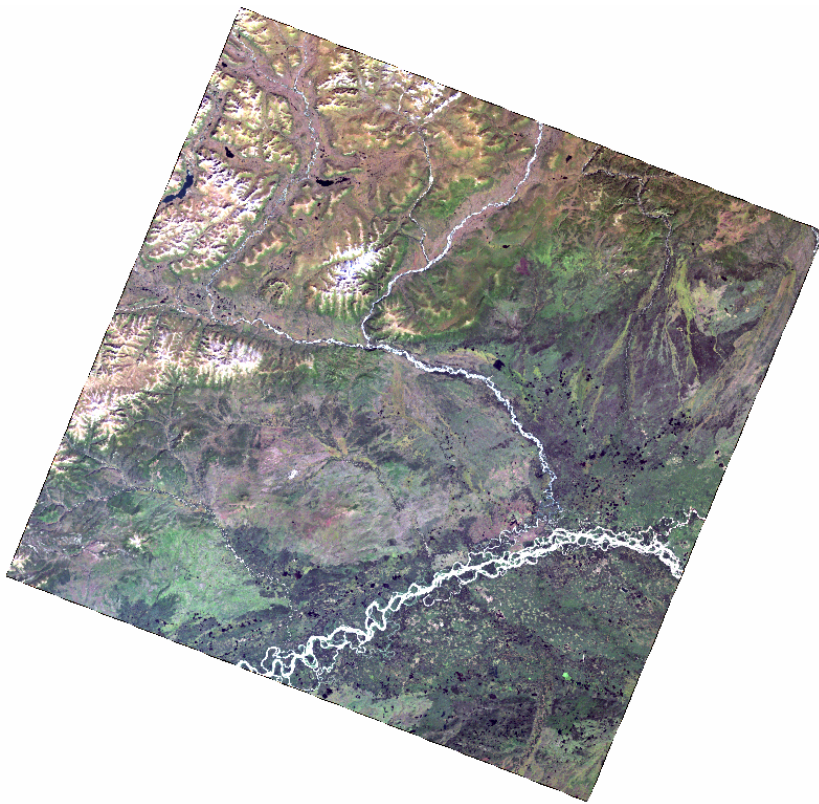


Figure 3.8 Landsat 7 ETM+ Satellite image of the Yukon Flats National Wildlife Refuge study region displayed in bands 3, 2, and 1 with a scale of 30 m. The image was taken August 26, 2000 Path 70 Row 13.

3.1.7 Image Rectification

Due to the different types of imagery available, I used different techniques and software to examine each region. At the end of the processing, each image was displayed in the Universal Transverse Mercator Projection (UTM) North America Datum (NAD) 27.

Each image of each region was georeferenced to the UTM projection, Nad27. Because the DRG topographic maps were available as a statewide source in the UTM Nad 27 projection, they were used as a source for rectifying photographs. Major roads and other stable locations were used as control locations for georectifying the other images.

Each image was rectified to a DRG topographic map using a second-order polynomial model. At least 25 control points were used to develop each rectification model. I maintained a Maximum Root Mean Squared Error (RMS) of less than 30 meters. I used those limits for all the black and white aerial photography, CIR, and Landsat images. After all of the images were rectified to the appropriate DRG, a time series was able to be produced for each region (Figure 3.9).

Minto Flats State Game Refuge: Image Rectification

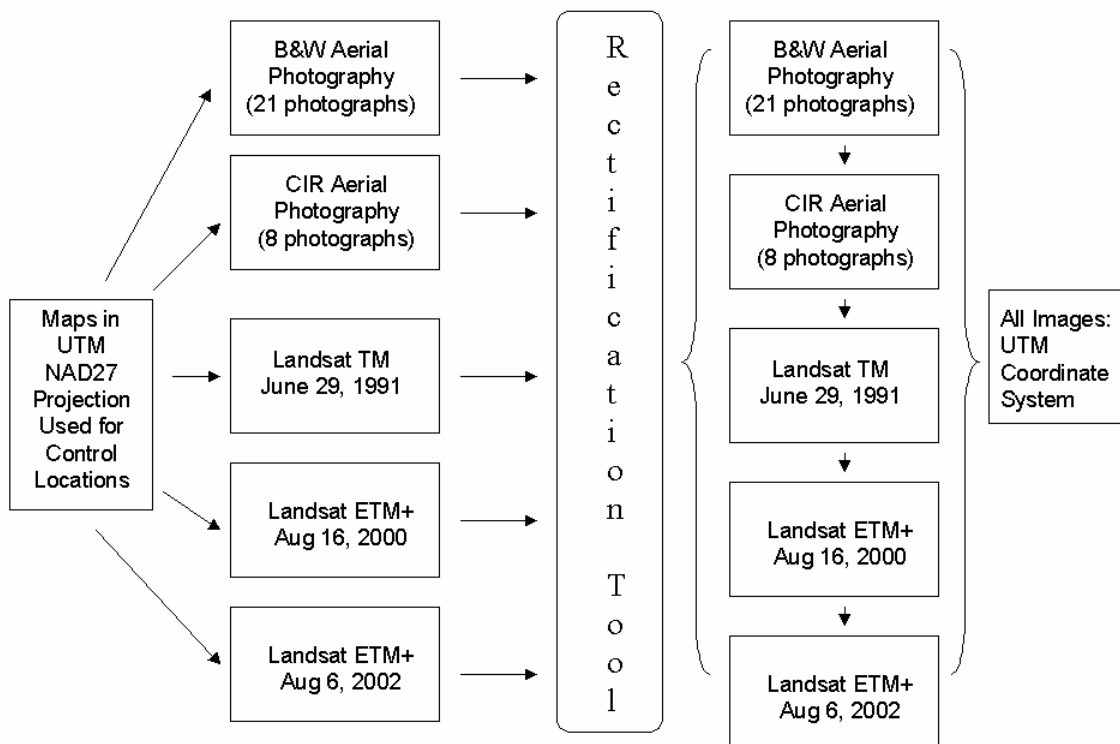


Figure 3.9 Image Rectification Example.

3.1.8 Water Body Creation

Digitizing creates a polygon that represents the water body on the aerial photograph by outlining each water body in a digital image using a mouse cursor. This new polygon can then be used to estimate surface water area and can be compared to all previous and subsequent images. The disadvantage to this is the time required to trace all of the pond shorelines in each region for each time frame. The advantage is an accurate representation of the water bodies in an image.

To minimize the amount of digitizing, I incorporated USGS Digital Line Graphics Hydrology (DLGs) (see Figure 3.10 for an example). DLGs are digital vector representations of hydrological features in a USGS map. These were created from the 1:63,360 USGS topographic quadrangle maps.

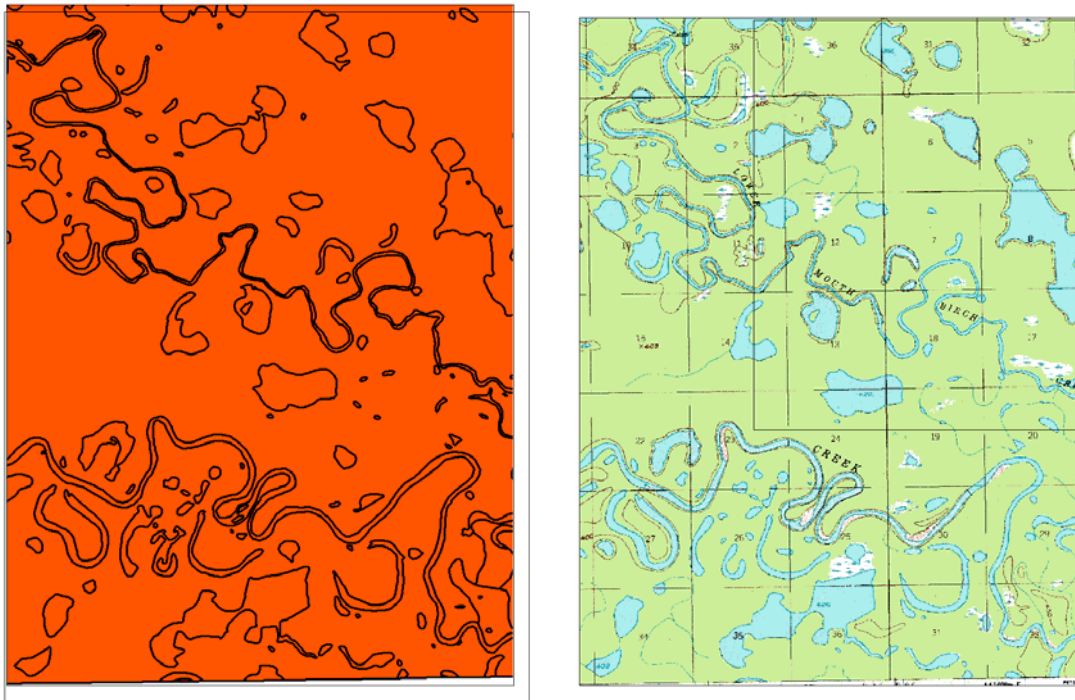


Figure 3.10 Portion of USGS Digital Line Graph and Digital Raster Graphic of the Yukon Flats National Wildlife Refuge.

To demonstrate how the DLG was used and how each water body theme is created, I will use Minto Flats State Game Refuge as an example (Figure 3.11). The DLG was created in 1986. After the DLG was draped over the DRG, any river, stream, open-basin water body, or erroneous water body was removed from the DLG. The polygons that remained represented all of the closed-basin water bodies for the DRG. These polygons were then superimposed upon the 1950s series of black and white photographs. The polygons were manipulated to represent the water body outline present on the black and white photographs. This process was repeated for each time frame available, five for Minto Flats State Game Refuge. Each water body was examined and changed on the corresponding polygon theme to reflect the water body conditions for the new image. After each year is complete, there is one DLG that corresponds to each year for which that an image is present. In the case of Minto Flats State Game Refuge there are five DLG shape files: 1954, 1978, 1991, 2000, 2002. Since the Landsat satellite imagery has a larger spatial resolution than the aerial photography I could not differentiate between land and water below the threshold of half an acre without some error. Therefore, any water body in the study that was less than half an acre was removed.

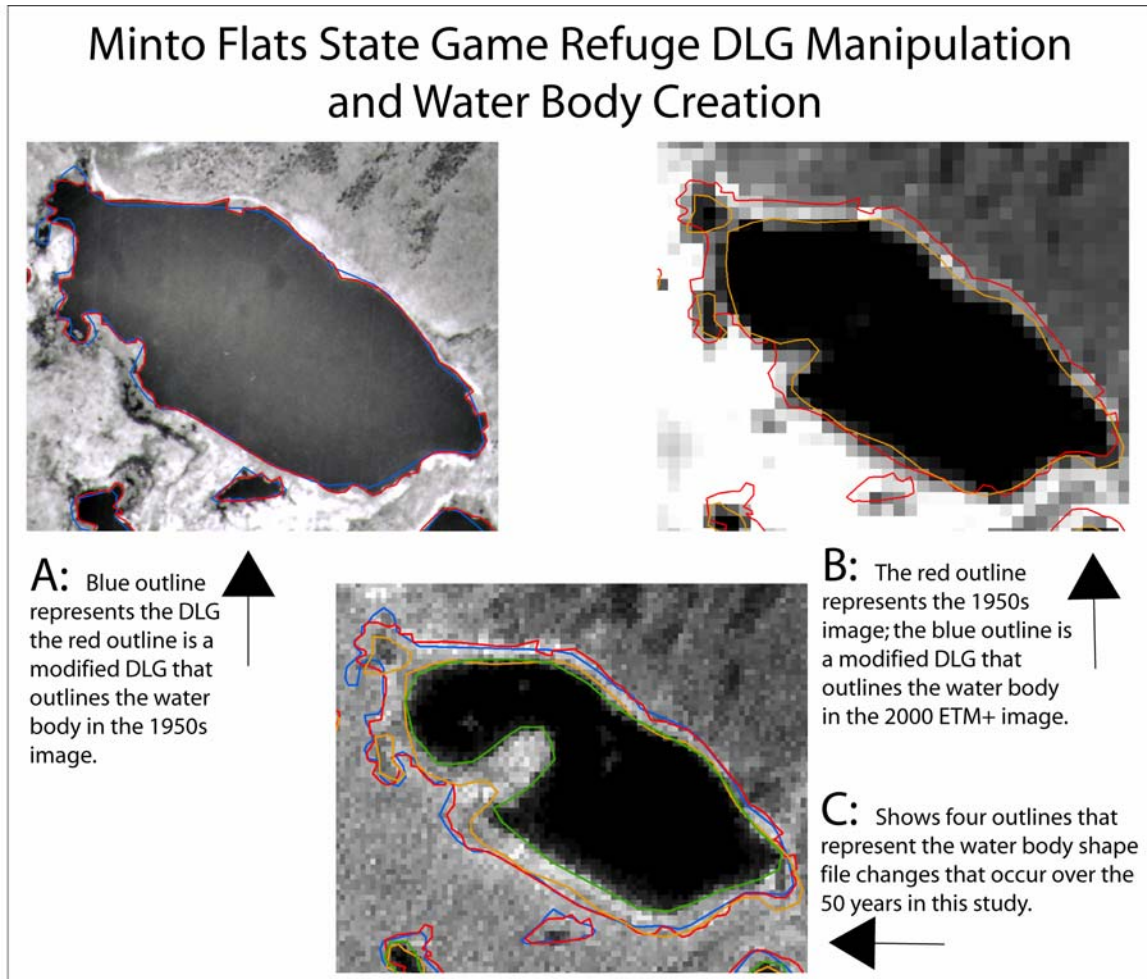


Figure 3.11 Three images from Minto Flats State Game Refuge show how the water body polygons are created and manipulated. **A:** Black and white aerial photography image with water bodies outlined in red and is 59 ha. **B:** Landsat ETM+ 2000 image water body is outlined in orange and is 49 ha. **C:** Landsat ETM+ 2002 water body outlined in green is 37 ha.

Each GIS polygon had an attribute table that included a column for hectares. For each time period I obtained the total number of water bodies and hectares present for each region, from the attribute table. This process was replicated for each one of the nine regions to create a GIS polygon theme that represented the water bodies for a specific region and time period (Figure 3.12).

Minto Flats State Game Refuge: Water Body Creation

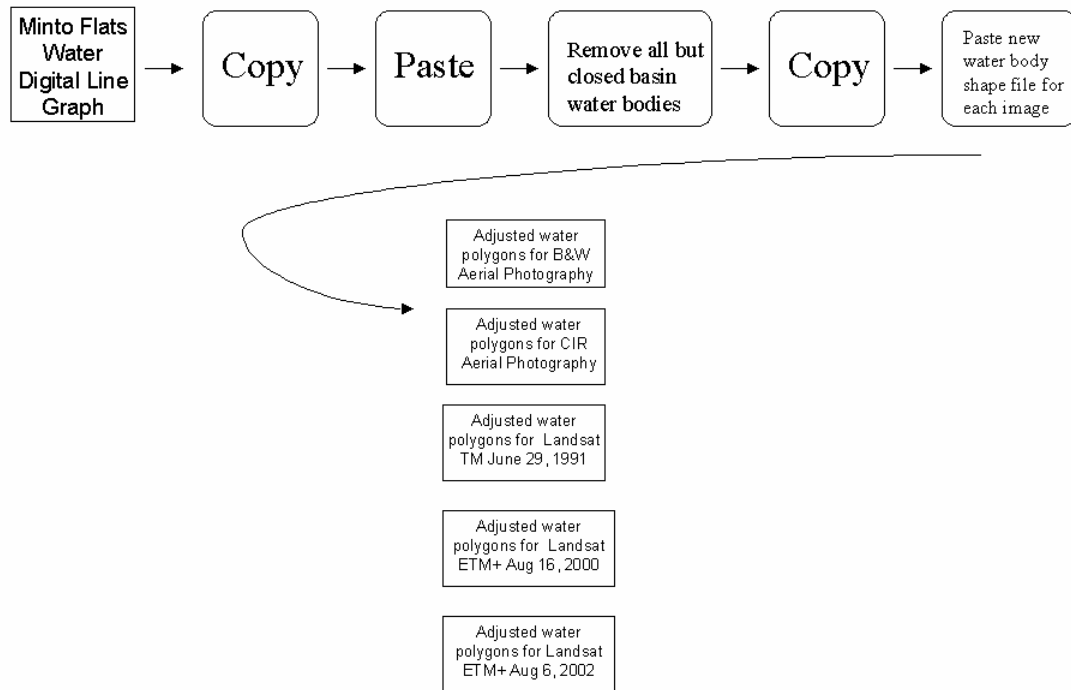


Figure 3.12 Example of creation of water body shape file. The rectified images from Figure 3.9 are use here as the five images that the DLGs we be modified too.

In this study I struggled with aerial photography and sun glint. Sun glint is the reflection of the sun off the surface of calm water that causes the water body to appear white instead of black (Figure 3.13). In Alaska, where the summer solar angles are relatively low, the sun glint can be more pronounced. To account for this problem, I used manual digitizing to create the water body themes for each time period. This technique made the delineation of closed-basin water bodies time consuming, but it provided me with the most accurate possible representation of water bodies in a region.

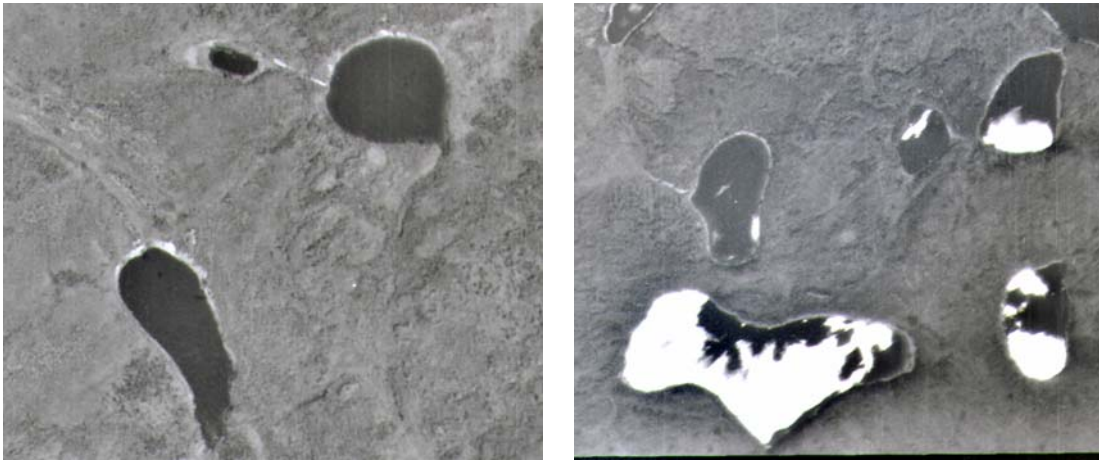


Figure 3.13 Example of water bodies with sun glint and without. When a water body has sun glint it appears white.

The study was restricted to closed-basin water bodies. Open-basin water bodies were only visually inspected while manipulating the closed-basin water body polygons for each time period. Visual inspection of the open-water bodies revealed changes in hydrology and surface area (see figure 3.14 for an example). These open-basin water bodies were not included in the study because reduction in surface water could be due to factors such as destruction of beaver dams. While the exact mechanism behind the disturbance of these open-water bodies is unknown, it is important to note that they can exhibit substantial reductions in surface water.

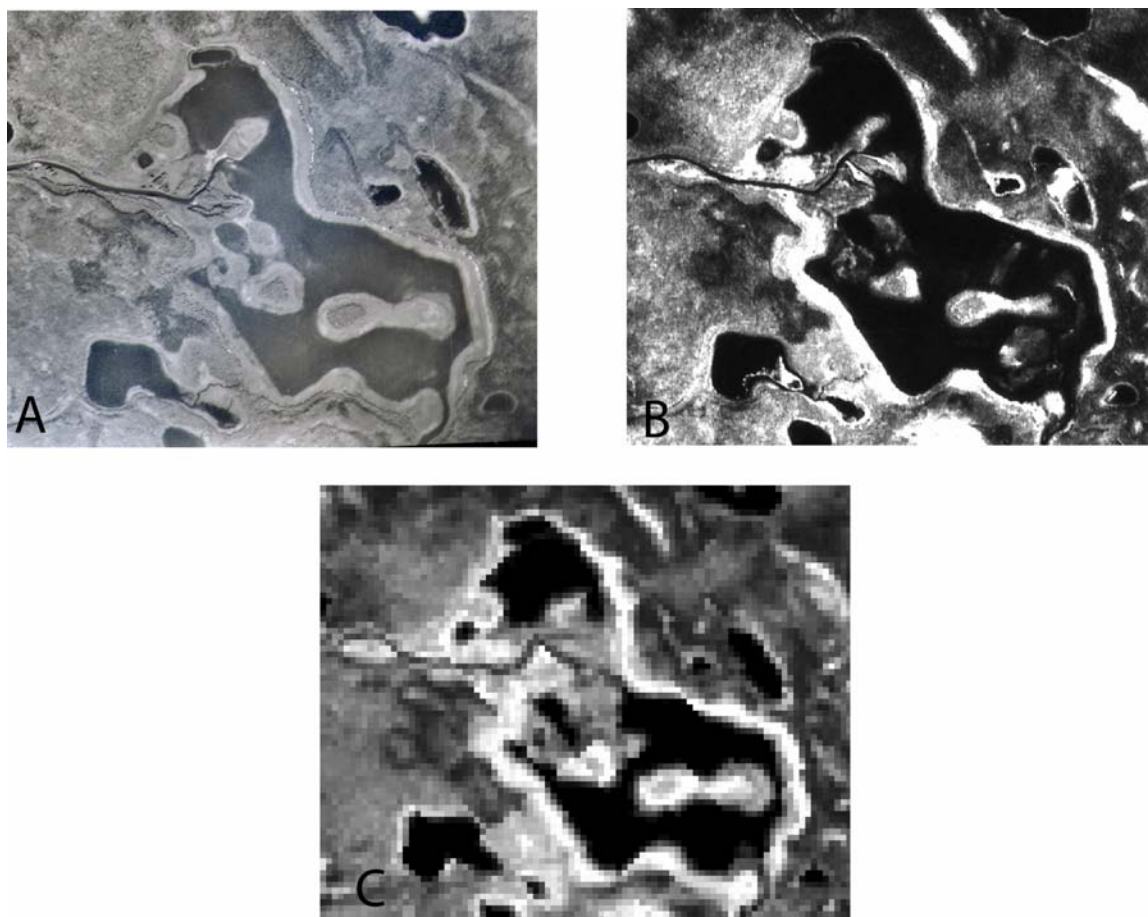


Figure 3.14 Example of an open-basin water body in the Yukon Flats National Wildlife Refuge. A: 1950 B: 1978 C: 2000. In this example B is clearly has more surface area of water then C. Also in example C, the northern section has split from the southern section. This was not the case in example A or B.

Floating vegetation, algal blooms, or emerging vegetation on top or closely surrounding a water body might lead to misclassification during the water body identification stage. To account for this, I often toggled the bands displayed from band 5 to color infrared , where vegetation becomes more apparent. By observing a water body in both band 5 and CIR, I was able to establish the water body borders.

3.1.9 Calculations Based on Weather Records

All weather records were obtained from the Summary of the Day dataset of the National Climate Data Center (NOAA) from climatologist Martha Shulski of the Alaska Climate Research

Center in Fairbanks, Alaska. I acquired three raw data formats: daily maximum temperature, daily minimum temperature, and daily total water equivalent precipitation (including snow) for each weather station. I defined a year as August to July to incorporate all weather prior to the date of the majority of the imagery used. In addition to this I obtained mean monthly temperature from the Remote Automated Weather Stations (RAWS) program. This data was used primarily to help show a correlation between the weather at the first order weather stations and weather located closer to the actual study regions.

To calculate Monthly Mean Maximum and Minimum temperature I used the two following equations:

Monthly Mean Maximum temperature

$$(\text{max temp day1} + \text{max temp day2} + \dots + \text{max temp day (n)}) / (n) \text{ days in month}$$

Monthly Mean Minimum temperature

$$(\text{min temp day1} + \text{min temp day2} + \dots + \text{min temp day (n)}) / (n) \text{ days in month}$$

With these two equations I created an Average monthly temperature for each weather station using this equation:

Mean Monthly temperature

$$(\text{monthly mean maximum temperature} + \text{monthly mean minimum temperature}) / 2$$

Potential evapotranspiration (PET) was calculated using the Thornthwaite's method (Thornthwaite, C.J. 1948), which is dependent on the mean monthly temperature. Thornthwaite's method predicts PET over a 12-hour period using a 30 day month. Thornthwaite's equation does not take into account day length and months that are not 30 days. Precipitation minus PET was conducted for all precipitation and for precipitation between April – September (Table 4.3).

For each study region I have include four graphs that demonstrate weather trends over the last fifty-years and how they relate to the results of this study (Appendix B). To help identify any trends in weather records over the fifty years, I used a locally weighted scatterplot smoothing (Lowess Smoothing). This helps to extract trends from noisy data such as weather. This process is a locally weighted regression, where each point along the smooth curve is estimated from a regression of data points close to the curve point, with the closest points being more heavily weighted.

The amount of smoothing that can be applied in a Lowess Smoothing is an adjustment of the f -parameter. This parameter is the fraction of the total number of points that is used in each regression. The smoothing parameter f was chosen to be 0.3 in this study. This parameter provided a good trade-off between noisy undersmoothing and over-smoothing, which misses some of the peak-and-valley details in the data. This smoothing process extracts a trend line from the data that in this study helps to identify a relationship, or lack of a relationship, between weather data and surface water area loss. The estimates of the Lowess Smoothing algorithm were used in Figures 4.4 to 4.29.

As stated earlier, Alaska has few reliable weather stations that have weather records spanning more than 30-years. Because of this many of the weather stations used in the study are located up to 100k away from the actual study region. I compared data from remote automated weather stations and the first order weather stations used in this study (Table 3.2). The high correlation values in table 3.2 allows me to make general relationships concerning trends with temperature between the first order weather stations and the study regions where the first order weather stations were not located near the study region.

Table 3.2 Using a simple correlation coefficient equation I compared temperature values between Remote Automated Weather Stations (RAWS) and the first order weather stations used in the study. In addition I compared some intermittent second order weather stations with the first order weather stations.

Correlation Coefficient Values Between Weather Sites		
	<u>Temperature</u>	<u>Precipitation</u>
RAWS Beaver / Bettels AP	0.989	N/A
RAWS Lake Minchumina / Fairbanks AP	0.872	N/A
RAWS Chatnika / Fairbanks AP	0.964	N/A
RAWS Innoko / McGrath AP	0.633	N/A
Prudhoe Bay / Barrow AP	0.909	0.33
Fort Yukon / Bettles AP	0.917	0.479

4 Results & Discussion

4.1 CHANGES IN WATER BODIES

All study regions in subarctic Alaska lost surface water area from 1950 to 2002 (Table 4.1 Figure 4.1). The Arctic Coastal Plain region, which is underlain by deep, continuous permafrost (often in excess of 400 m), had negligible change (Table 4.1). From the table below there are three areas that have losses prior to 1977, three after 1977, and two that have losses before and after 1977 (Figure 4.1). Copper River Basin and Innoko Flats National Wildlife Refuge had the most substantial reduction in surface water area, and the majority of the loss was prior to 1977.

Table 4.1 Surface water area change and net loss in hectares by region and image.

Study Site	Black and White Aerial Photography 1949 - 1956	Color Infrared Aerial Photography 1978 - 1982	Landsat TM 1991	Landsat TM 1995	Landsat ETM+ 1999	Landsat ETM+ 2000	Landsat ETM+ 2001	Landsat ETM+ 2002	Total Percent Change 1950 - 2000
Innoko Flats National Wildlife Refuge	2126	1532	-	-	-	1463	-	-	-31
Copper River Basin	130	95	-	85	-	-	93	-	-28
Minto Flats State Game Refuge	4066	3763	3952	-	-	3319	-	3060	-25
Yukon Flats National Wildlife Refuge	7773	8097	-	-	-	6359	-	-	-18
Stevens Village	5132	5106	4768	-	-	4746	-	4398	-14
Talkeetna	1530	1479	-	-	-	1455	-	-	-5
Denali National Park	1758	1964	-	-	-	1681	-	-	-4
Tetlin National Wildlife Refuge	4811	4566	-	-	4597	-	-	-	-4
Prudhoe Bay, Arctic Coastal Plain	3162	3127	-	-	3208	-	-	-	1

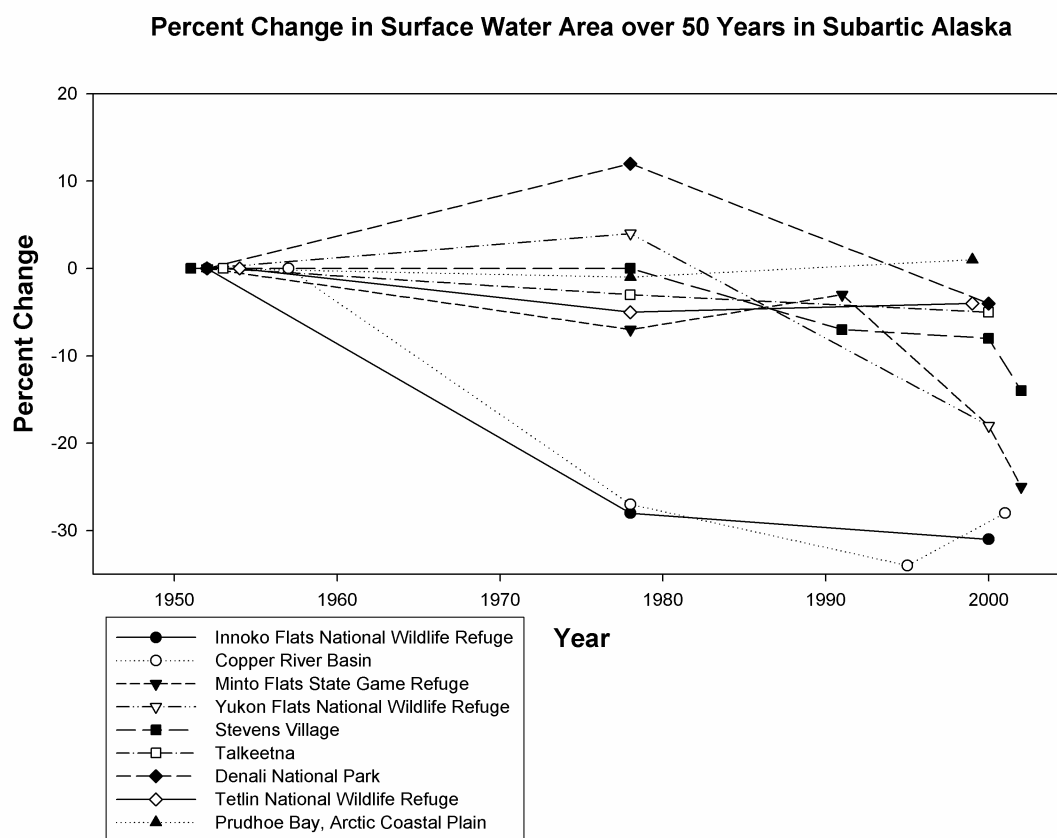


Figure 4.1 Linear trends for surface area loss for the nine-study regions show that many of the regions did not begin to show signs of degradation until after the post-1977 warming trend. All of the regions in the subarctic displayed a negative change over the fifty-year study period.

The number of water bodies in all the regions was reduced over the fifty-year study period (Table 4.2). Minto Flats State Game Refuge represented the largest loss (499 water bodies); Tetlin National Wildlife Refuge showed the second greatest loss of water bodies (427). The Denali National Park area had the smallest change, losing 42 water bodies. Most water body extinctions occurred after the warming trend of 1977 (Figure 4.3). The water body extinction pattern was similar to

Table 4.2 Total number of water bodies by region and time period.

Study Site	Black and White Aerial Photography 1949 - 1956	Color Infrared Aerial Photography 1978 - 1982	Landsat TM 1991	Landsat TM 1995	Landsat ETM+ 1999	Landsat ETM+ 2000	Landsat ETM+ 2001	Landsat ETM+ 2002	Total Number of Water Bodies lost 1950 -2000
Minto Flats State Game Refuge	1390	1203	829	-	-	934	-	891	-499
Tetlin National Wildlife Refuge	2152	2293	-	-	1725	-	-	-	-427
Innoko Flats National Wildlife Refuge	1205	1053	-	-	-	839	-	-	-366
Stevens Village	1141	1218	850	-	-	896	-	933	-208
Talkeetna	1052	1026	-	-	-	876	-	-	-176
Prudhoe Bay, Arctic Coastal Plain	1426	1448	-	-	1265	-	-	-	-161
Yukon Flats National Wildlife Refuge	1370	1267	-	-	-	1228	-	-	-142
Copper River Basin	101	53	-	37	-	-	46	-	-55
Denali National Park	876	964	-	-	-	834	-	-	-42

the surface area pattern except for Innoko Flats National Wildlife Refuge and Copper River Basin, which both showed substantial losses prior to 1977. As water bodies begin to lose surface area, they sometimes divide from one large water body into multiple water bodies (Figure 4.2), the estimated loss of water bodies may be a conservative measure of change (Table 4.2).

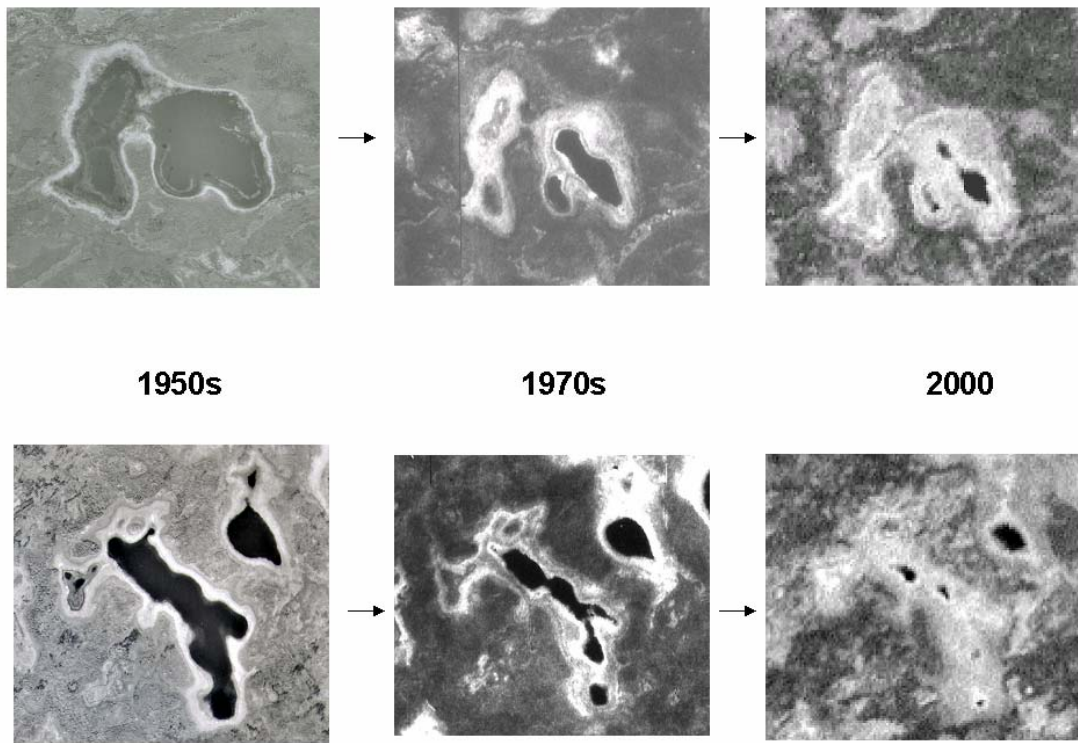


Figure 4.2 Time series of water bodies located in the Yukon Flats National Wildlife Refuge. This series is a typical example of the water loss patterns that appear across subarctic Alaska in response to a warming climate. The top series shows a 73 ha water body that is reduced to 11 ha by 1978 and is down to 4 ha by 2000. The bottom series shows two water bodies. The larger is 36 ha and the smaller is 23 ha. By 2000 they have drained to 1.5 ha and 3 ha, respectively.

Another likely explanation of the detected water body loss is the switch from aerial photography to satellite imagery, which could eliminate the smaller ponds in response to the change in spatial scales. To help compensate for the coarse resolution of the satellite imagery, I removed all the water bodies less than one-half acre from the study. In addition, it is important to note that these surface area changes reported are net changes for the entire study region. They include any gains or losses of water bodies over the fifty-years observed. This is important when looking at life cycles of water bodies because we would expect water bodies in a region to exhibit both growth and reduction over time.

Table 4.3 Results of digitizing closed-basin water bodies with different pixel sizes in two subsections of the Stevens Village study region. When using a larger pixel size (30 m) the results were often over estimating surface water area.

Pixel Size Water Area Comparison			
	3-meter pixels	30-meter pixels	Difference
Stevens Village Subset A	346 ha	356 ha	+10 ha
Stevens Village Subset B	361 ha	372 ha	+11 ha

To reduce the problem of different spatial resolutions from multiple forms of media in this study, would be to resample all of the imagery to a 30-meter pixel size. However, this would remove useful information therefore reducing the overall accuracy of the study. Instead I decided to retain all of the original spatial resolutions. In order to retain the original spatial resolutions for each image I need to demonstrate that the differences between the resolutions would not lead to artificial results. For example, the black and white aerial photography and the color infrared aerial photography have pixels sizes of approximately 1-meter. The Landsat TM imagery has pixels sizes of 30-meters. The concern is that the difference in pixel size might be the cause of a reduction in surface water area instead of climate. However, from Table 4.3 it becomes apparent that an increase in pixel size leads to an overestimate of surface water area. This is because the water body shorelines area not as well delineated with the 30-meter resolution. This would actually indicate that any loses observed might be greater than reported due to the over estimates by images that have higher spatial resolutions (ie. Landsat TM and ETM+ imagery).

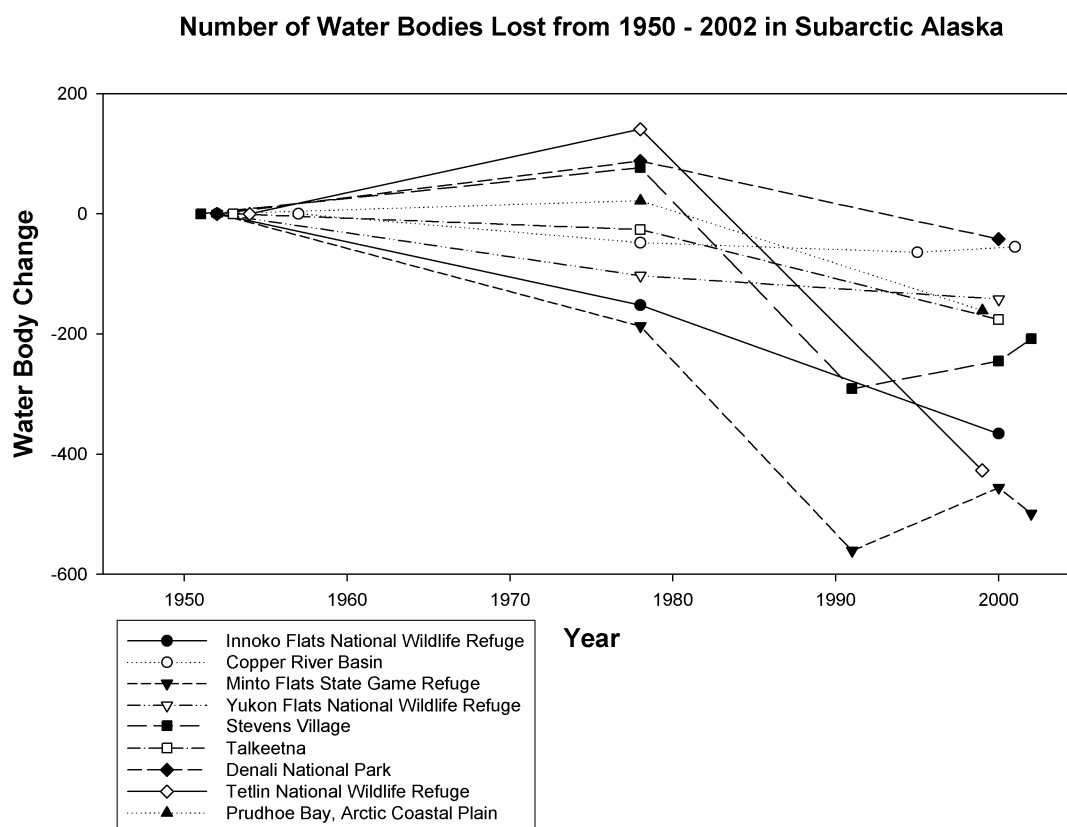


Figure 4.3 Linear trends for number of water bodies for the nine-study regions show that many of the regions did not begin to show substantial extinction of ponds until after the 1977 warming trend. All of the regions displayed a negative change over the fifty-year study time.

4.2 RELATIONSHIP TO CLIMATIC CHANGE

I used a simple linear regression to develop models that predict mean annual temperature, precipitation, PET, and P - PET as a linear function of time. From these regressions I obtained slope, R^2 , and P-values for the seven first order weather stations and two second order weather stations. Temperature records from the first order weather stations all have regression lines that have slopes that are significantly different from zero at the 0.05 level (Table 4.4).

PET values were significant at all first order weather stations. R^2 values were generally around .150, which is expected because of substantial year-to-year variation that is inherent with weather data. The statistical analysis for precipitation indicates that the regression lines were not significantly different from zero. Therefore, there were no statistically significant trends for precipitation. The lack of significance for the second order sites in regards to temperature is likely a response to a low sample size ($n = 12$ and $n = 26$).

Table 4.4 Temperature, Precipitation, and Potential-Evapotranspiration significance values as a function of years ranging from $n = 12$ - 63.

	Mean Annual Temperature			Annual Total Precipitation		
	Slope	R^2	P	Slope	R^2	P
Gulkana Airport $n = 61$	0.018	0.086	0.021	-0.278	0.005	0.599
Bettles Airport $n = 51$	0.046	0.259	0.000	1.192	0.035	0.188
Fairbanks Airport $n = 56$	0.038	0.231	0.000	0.063	0.000	0.916
Northway Airport $n = 53$	0.036	0.243	0.000	0.248	0.005	0.626
McGrath Airport $n = 63$	0.030	0.181	0.000	-0.042	0.000	0.953
Talkeetna Airport $n = 62$	0.027	0.145	0.002	-0.367	0.002	0.755
Barrow Airport $n = 61$	0.018	0.066	0.045	-0.322	0.024	0.237
Prudhoe Bay $n = 12$	0.197	0.219	0.125	2.490	0.079	0.377
Fort Yukon Airport $n = 26$	0.017	0.046	0.294	-0.033	0.000	0.957

Table 4.4 continued

	PET			P – PET (Yearly)		
	Slope	R ²	P	Slope	R ²	P
Gulkana Airport n = 61	0.406	0.111	0.009	-0.644	0.029	0.191
Bettles Airport n = 51	0.705	0.133	0.009	0.487	0.005	0.626
Fairbanks Airport n = 56	0.664	0.156	0.003	-0.600	0.014	0.389
Northway Airport n = 53	0.386	0.076	0.045	-0.138	0.001	0.806
McGrath Airport n = 63	0.536	0.189	0.000	-0.578	0.010	0.433
Talkeetna Airport n = 62	0.428	0.010	0.012	-0.794	0.007	0.509
Barrow Airport n = 61	0.712	0.095	0.016	-1.030	0.113	0.008
Prudhoe Bay n = 12	2.450	0.163	0.193	0.045	0.000	0.989
Fort Yukon Airport n = 26	0.552	0.134	0.066	-0.586	0.027	0.417

Table 4.4 continued

**P (Summer Only) -
PET**

	Slope	R²	P
Gulkana Airport n = 61	-0.480	0.020	0.271
Bettles Airport n = 51	0.560	0.010	0.490
Fairbanks Airport n = 56	-0.675	0.016	0.349
Northway Airport n = 53	0.094	0.001	0.867
McGrath Airport n = 63	-0.925	0.048	0.084
Talkeetna Airport n = 62	-0.392	0.004	0.631
Barrow Airport n = 61	-0.578	0.045	0.101
Prudhoe Bay n = 12	-1.200	0.022	0.648
Fort Yukon Airport n = 26	-0.470	0.026	0.428

With significant p-values for temperature and PET and linear values for precipitation I would expect that if I subtracted precipitation from PET that there would be a general increase in PET deficits as were reported by Oechel et al., 2000. However, the p-values in Table 4.4 show that this is not the case.

As surface water area and the number of water bodies decreased, all study regions in interior Alaska had an increase in mean annual temperature and PET (Figure 4.4 - 4.7, appendix B).

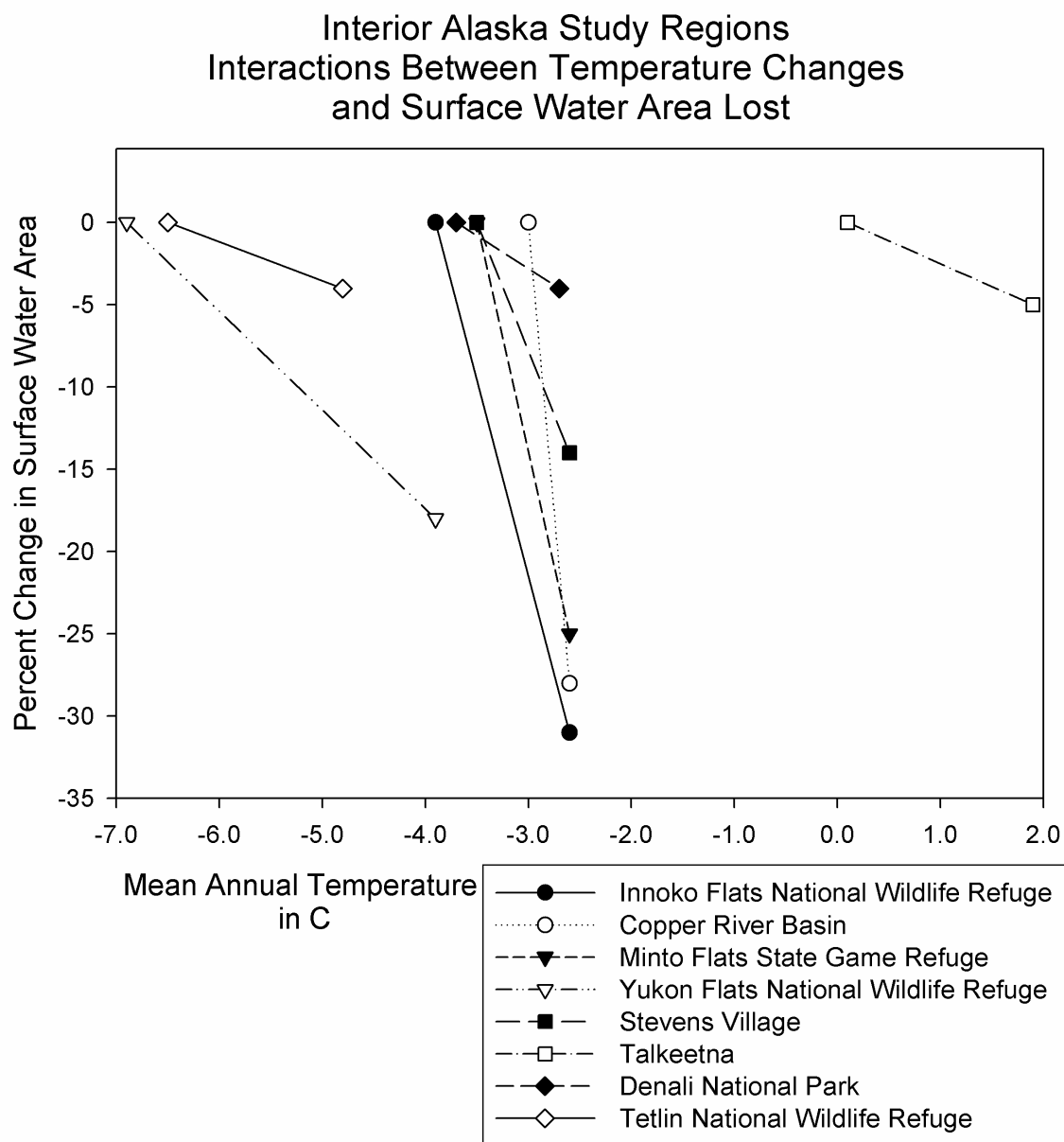


Figure 4.4 Interior Alaska temperature changes and surface water area changes between 1950 – 2002. All sites experienced a increase in temperature and decrease in surface water area.

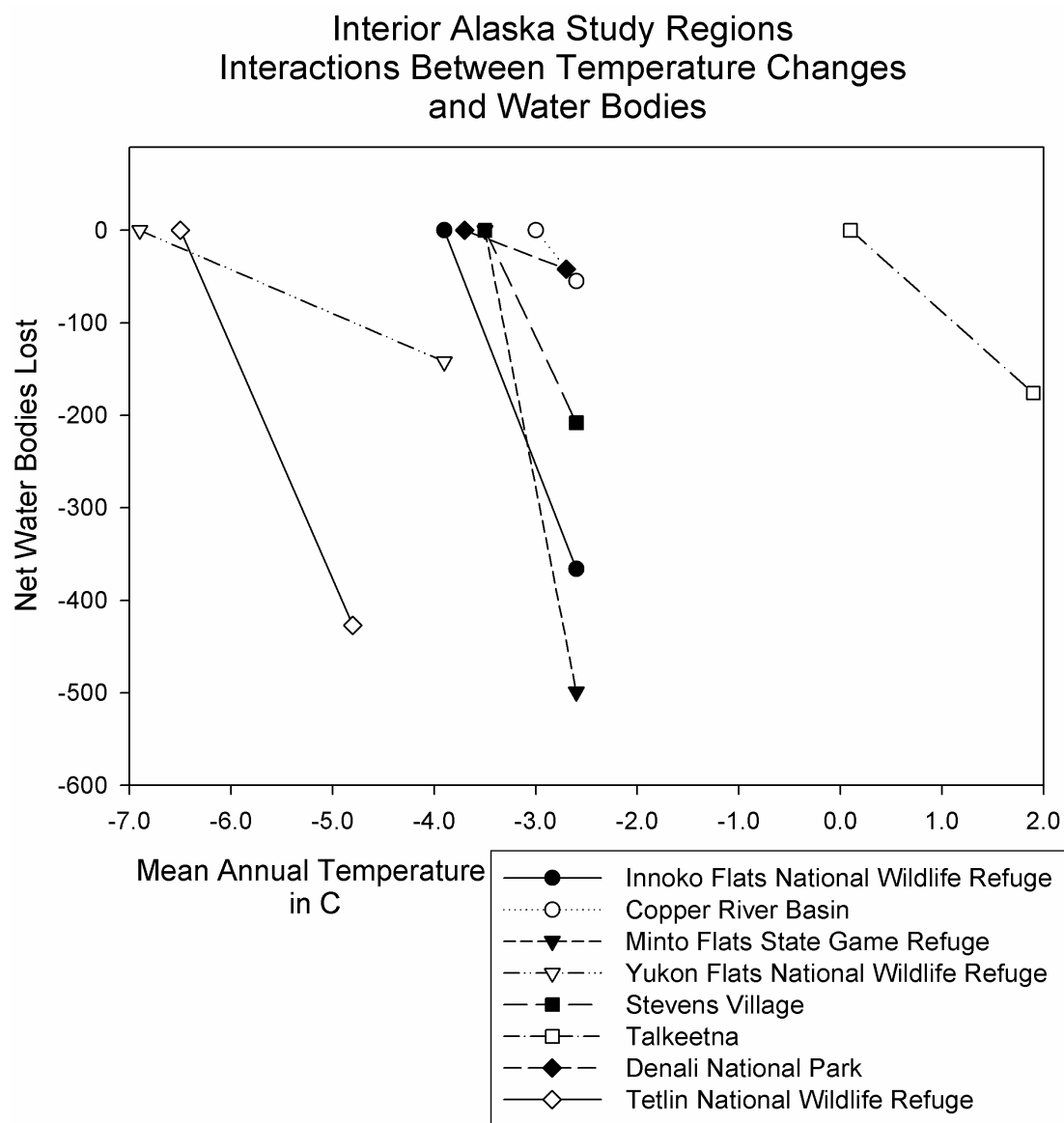


Figure 4.5 Interior Alaska temperature changes and net water body loss between 1950 – 2002. All sites experienced a increase in temperature and decrease in water bodies.

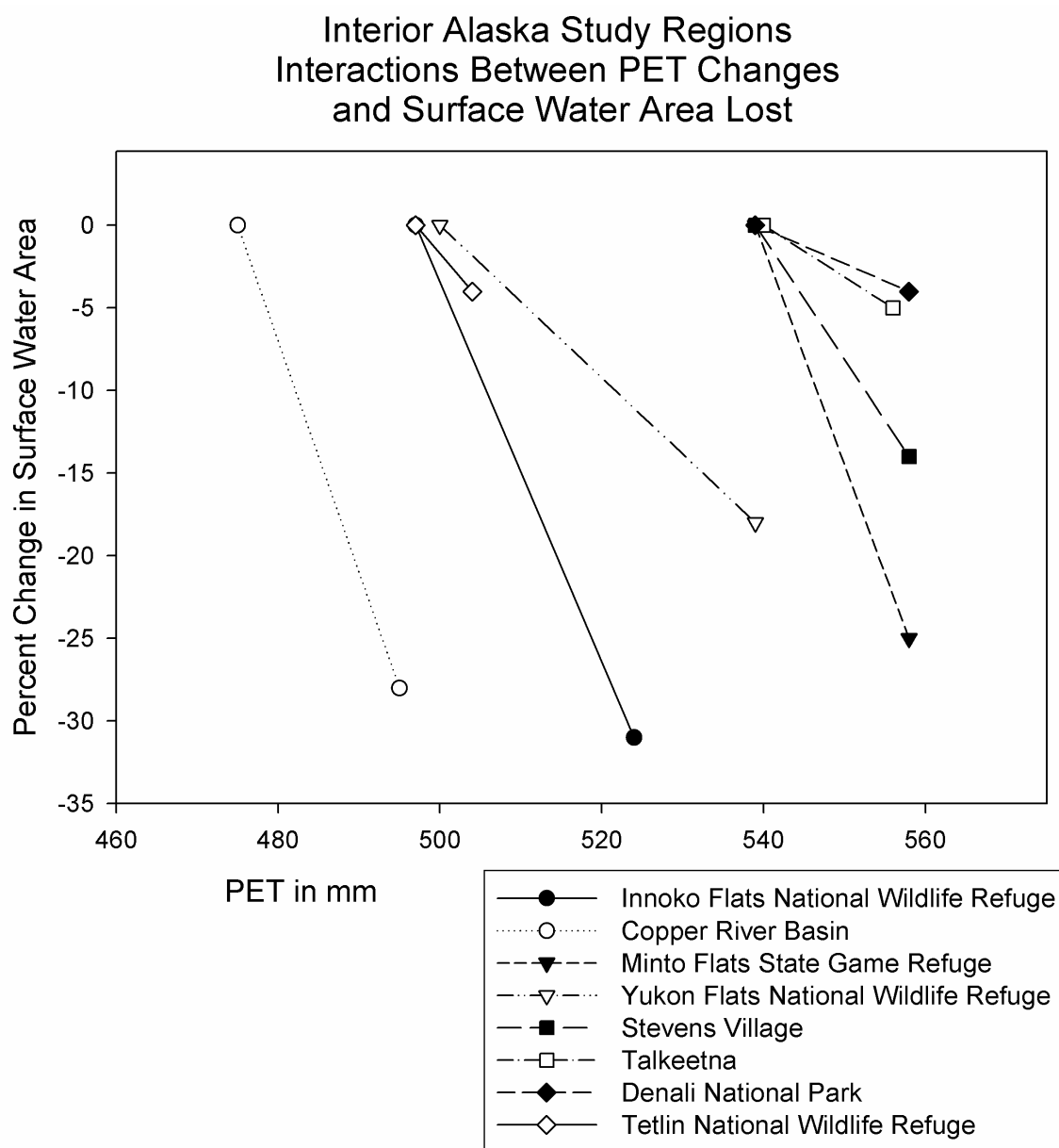


Figure 4.6 . Interior Alaska potential evapotranspiration (PET) changes and surface water area loss between 1950 – 2002. All sites experienced a increase in PET and decrease in surface water area.

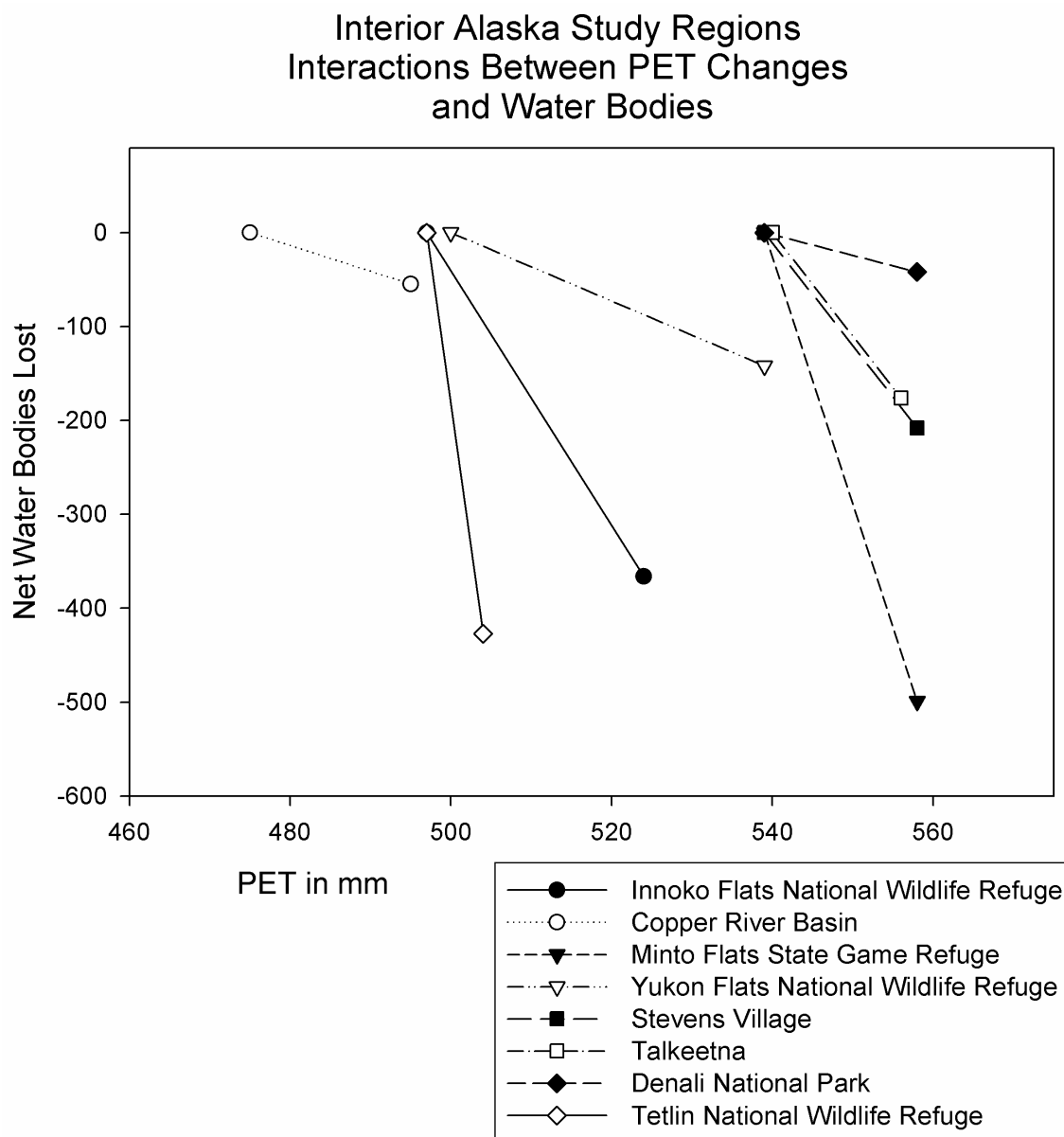


Figure 4.7 . Interior Alaska potential evapotranspiration (PET) changes and water body loss between 1950 – 2002. All sites experienced a increase in PET and decrease in water bodies.

As surface water area and the number of water bodies decreased, all study regions in interior Alaska with the exception Yukon Flats National Wildlife Refuge and Tetlin National Wildlife Refuge had an decrease P - PET (Figure 4.8, Figure 4.9, appendix B).

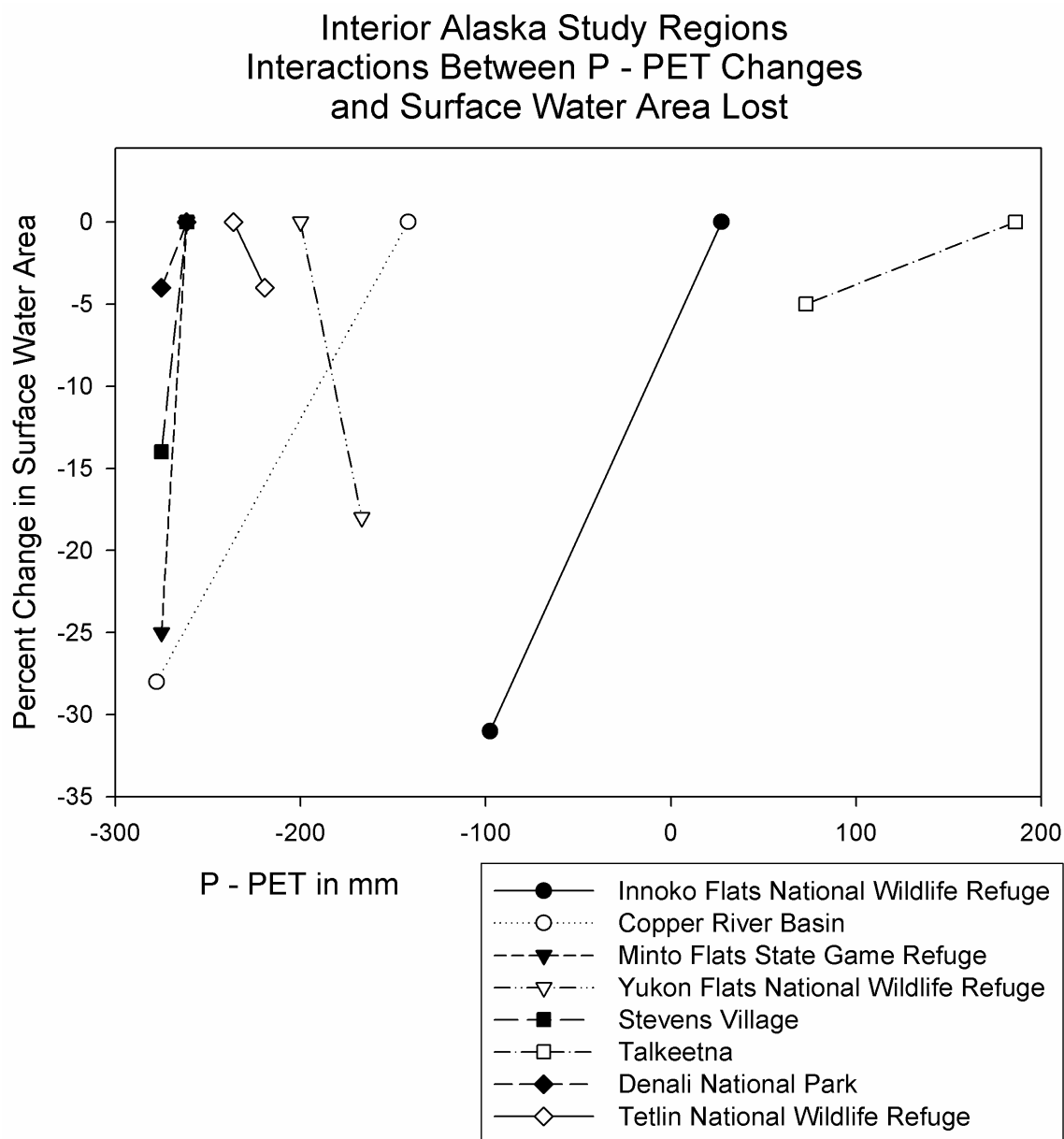


Figure 4.8 . Interior Alaska precipitation minus potential evapotranspiration (PET) changes and surface water area loss between 1950 – 2002. All sites, with the exception of Yukon Flats National Wildlife Refuge and Tetlin National Wildlife Refuge, experienced a decrease in P - PET and decrease in surface water area.

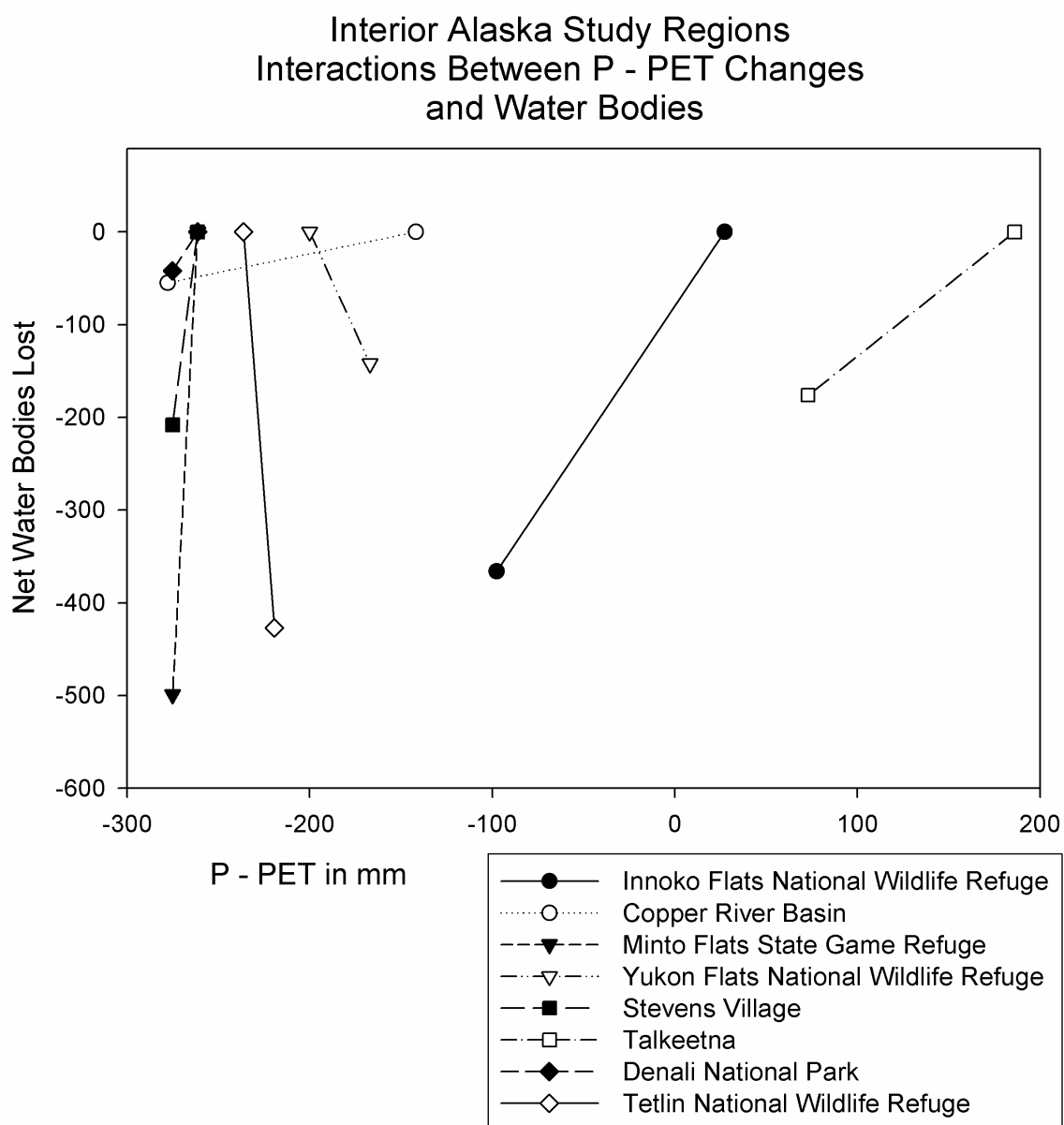


Figure 4.9 . Interior Alaska precipitation minus potential evapotranspiration (PET) changes and water body loss between 1950 – 2002. All sites, with the exception of Yukon Flats National Wildlife Refuge and Tetlin National Wildlife Refuge, experienced a decrease in P - PET and decrease in water bodies.

4.3 DISCUSSION

The study spans 1000 km from Copper River Basin to the Arctic Coastal Plain and 800 km, from Tetlin National Wildlife Refuge in the east to Innoko Flats National Wildlife Refuge in the west. Reduction in area of closed-basin water bodies and extinction of ponds has occurred in many regions of subarctic Alaska over the past fifty years. These changes are associated with warming air temperatures and increases in potential evapotranspiration.

4.3.1 Potential Mechanisms for Loss of Surface Water

The three most likely factors, based on the mechanisms presented in the Introduction, that would explain the surface area water loss reported in this study are increased evapotranspiration, increased active layer water holding capacity, and enlarged taliks (Figure 4.10). For all three mechanisms temperature is the driving factor, because both a growing active layer and enlarged taliks are responses to increased temperature and changing permafrost dynamics. Figure 4.6 also explores several cause and effect possibilities that may occur as a result of warming temperatures. These include increased subsurface drainage, changing plant communities, and drying soils.

Increased Mean Annual Temperatures as a Driving Variable Controlling Surface Water Area

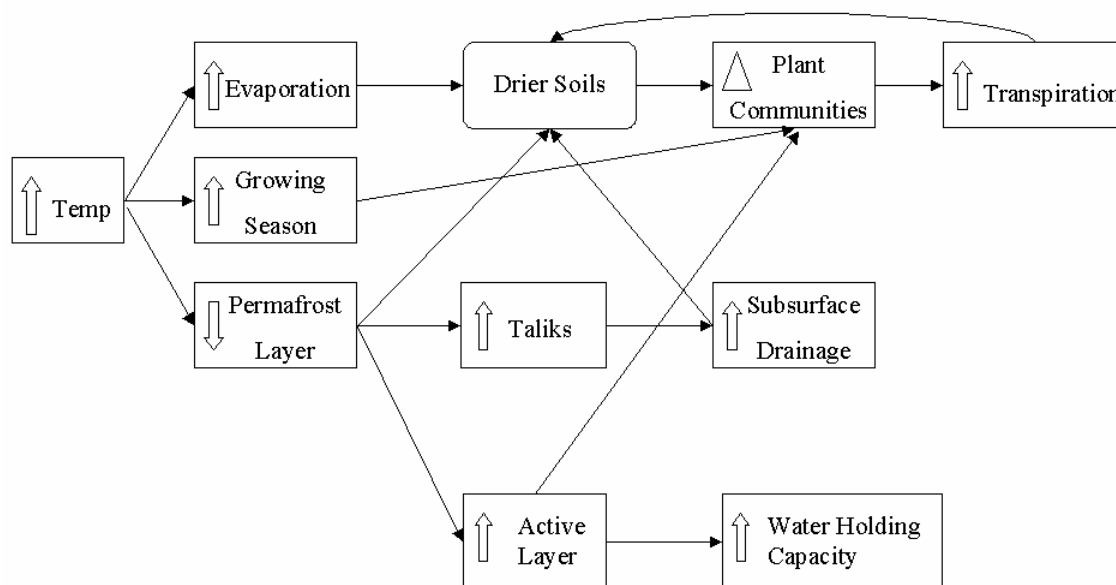


Figure 4.10 The effects of increasing mean temperatures on permafrost, hydrology, and vegetation

Fraver (2003) performed hydrologic studies on water bodies on the Seward Peninsula in Alaska. He concluded that wetlands maintain near maximum water holding capacity, even during years with large P - ET deficits. Using water balance equations, he also determined that PET and ET could not explain the observed water loss, and that it was likely that drainage through taliks was responsible. However, he was unable to quantify the loss through open taliks because he couldn't accurately quantify the lateral water fluxes between wetlands and ponds and the potential drainage of water bodies in the winter through taliks. Yoshikawa and Hinzman (2003) concluded that groundwater potential is the single most important component influencing shrinking water bodies, and drainage is likely through taliks. Changes in temperature and evaporation may lead to rapid invasion of plant communities (Thormann, 1998). As water level

recedes, competing vegetation, shrubs, and broadleaf species will take root in mineral-rich exposed soil.

One possible test of climate warming as a key contributor to water loss is to examine changes in a cooler landscape. The southern region of the Yukon Flats National Wildlife Refuge is 174 m above the rest of the study region and is on the north side of the southern foothills (Figure 4.11). I created polygons from the 1950 and 2002 water bodies that only included the water bodies in this elevated area. In this small subset, there were 67 water bodies covering 402 ha for the 1950 black and white aerial photography. The Landsat ETM+ subset had 68 water bodies covering 406 ha. Comparing these results show an increase of 4 ha in water surface area and one more water body from 1950 to 2000. The Yukon Flats National Wildlife Refuge as a whole showed an 18% loss. Because there was no loss in this subsection, I speculate that the higher elevation helped to maintain the permafrost integrity of this area, therefore maintaining relatively stable water body levels over the past fifty years.

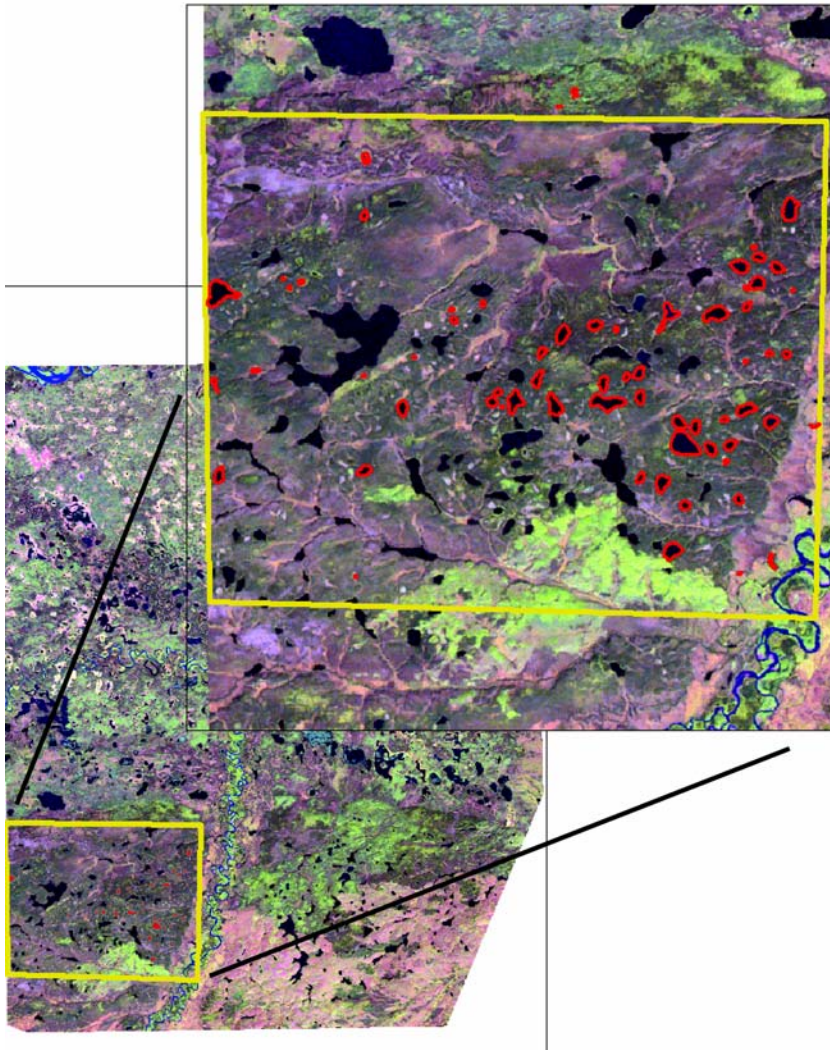


Figure 4.11 Yukon Flats National Wildlife Refuge high elevation subsection.

In the Yukon Flats National Wildlife Refuge there is a large group of small water bodies that have not changed over the fifty-year time frame (Figure 4.12). I at first expected that these water bodies would have disappeared over the fifty years, but, the images in figure 4.8 show that the water bodies remained intact. I speculate that these water bodies drained via taliks before 1950 and now have reached equilibrium with the Yukon River water table, allowing them to remain constant over time while other water bodies in the region have drained.

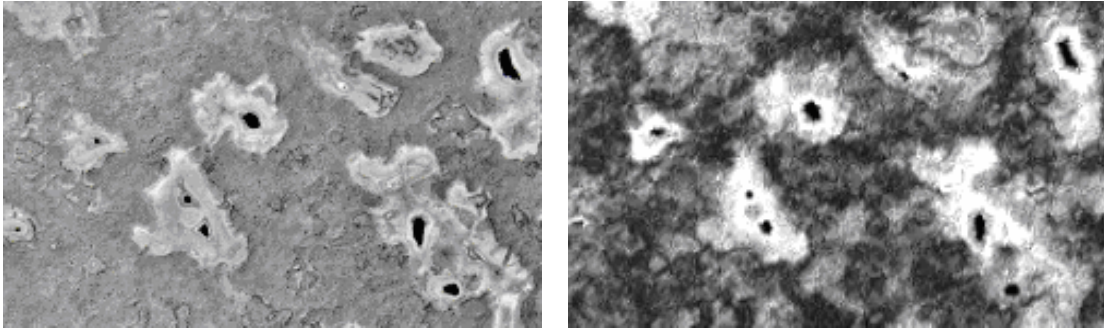


Figure 4.12 Group of stable water bodies in the Yukon Flats National Wildlife Refuge.

4.3.2 Inter-Annual Variability

Weather is a crucial but highly variable factor used to conduct this study. Weather patterns vary hourly, daily, monthly, yearly, etcetera. These variations could be a possible explanation for much of the reported surface water area loss. To help demonstrate that these losses are occurring in conjunction with inter-annual variability I conducted a study on a subsection in the Innoko Flats National Wildlife Refuge. I choose this site because it has the largest inter-year variability of the sites as well as the largest amount of reported surface water area loss.

The subsection is 37,644 ha and is located where the black and white aerial photography was from collected in mid-June. I obtained a Landsat ETM+ image from June 23, 2000 and compared the water bodies from this image to the water bodies from the black and white images from 1952. If inter-annual variability had a large influence on the results then I would have expected to see no change in water bodies between these two June images, only changes from June to August. However, from June 1953 to June 2000 there was a loss of 29% in surface water area and a loss of -117 water bodies (Table 4.5). These results are very similar to the results found in Table 4.1.

Table 4.5 This table explores the relationships between two mid-June images. These results suggest that inter-annual variability is not clouding the results of surface area loss or net water body loss.

Innoko Flats National Wildlife Refuge

	Surface Water Area	Water Bodies
June 24, 1953 aerial photography	972.2	490
Landsat ETM+ June 23, 2000	1376.7	607
Percent Change	-29%	-19%

The inter-annual variability of precipitation is another issue. In this study, if the original 1950 image was taken during a wet year and the 2000 image was taken during a dry year, the analysis would be biased as the two images reflect a decrease in water due to differences in annual precipitation rather than a longer trend. To minimize this effect, I used detailed weather records for fifty-years and selected imagery with similar observation dates and weather. All of the images, dates, and weather for those dates can be found in Figure 4.13, Figure 4.14, and Appendix A.

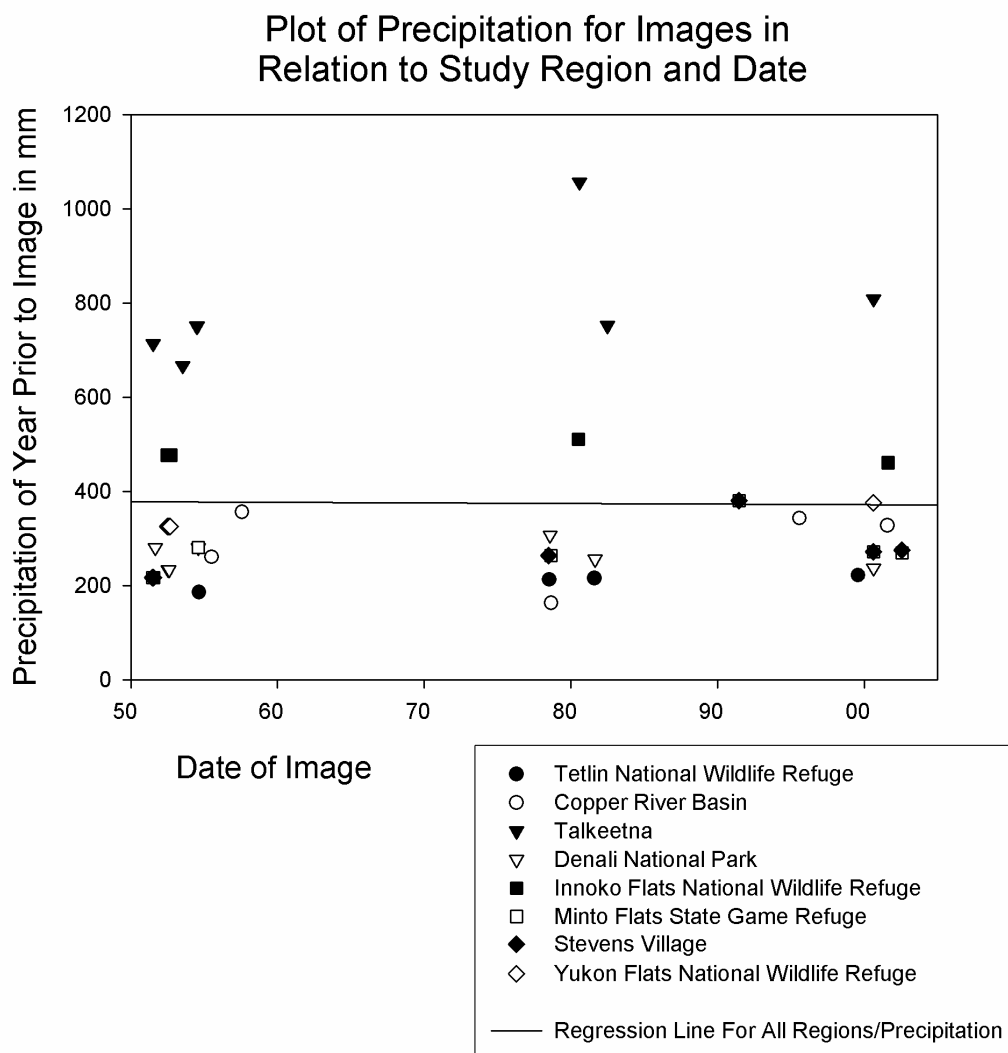


Figure 4.13 This scatter plot explores the variability in image dates and precipitation that occurred the year prior to the image. Note the general random array of points.

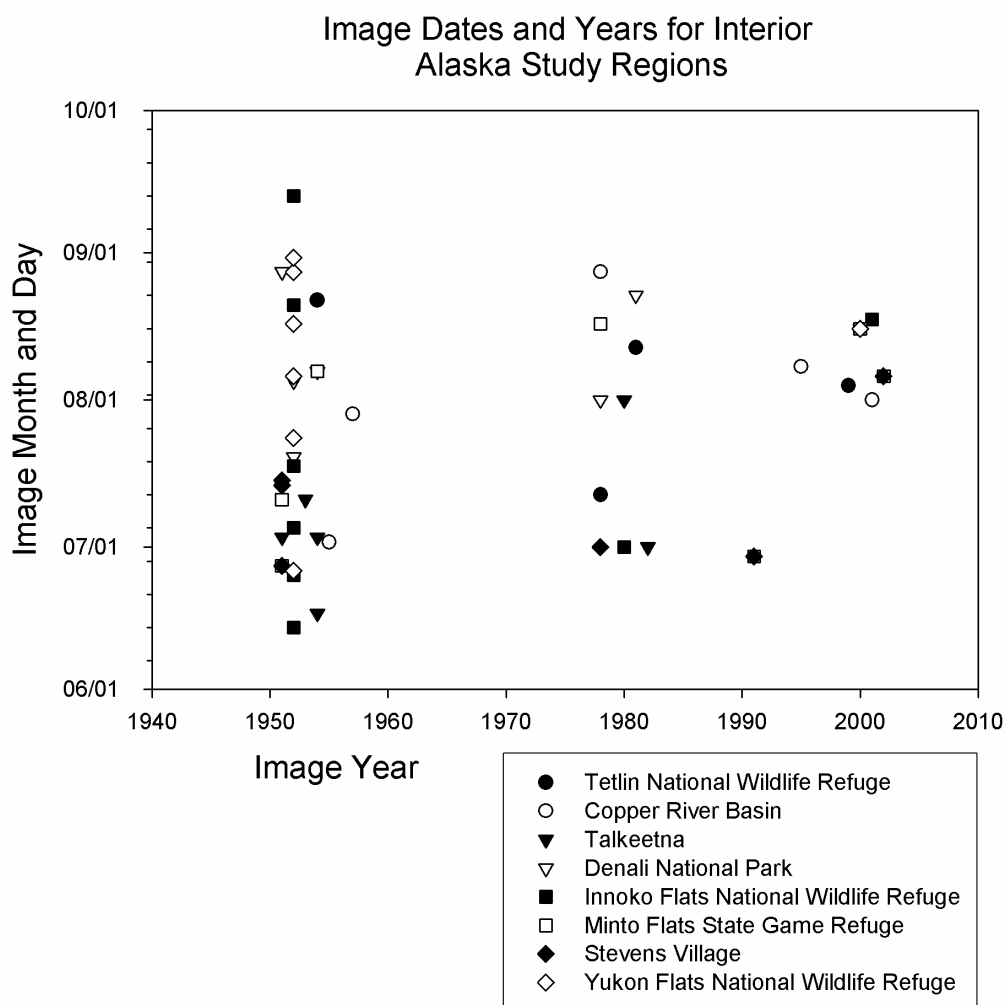


Figure 4.14 This scatter plot explores the variability in image dates with the image years. It is important to note the general random pattern.

Inter-annual variability is an issue with any study that looks over a time series. I do think that this study does have some effects from this variability. However, I have gone to great lengths to try to remove as much possible contamination that I can. The only way to fully remove inter-annual contamination would be to monitor these areas on a daily bases for a minimum of 10-years. This would allow the researcher to have recorded changes in the water bodies as effected by a variety of different weather patterns. The results presented in this study are generally valid in spite of inter-annual variability as shown in Table 4.1.

4.3.3 Other factors that might affect water loss

Wildfire is a common disturbance in the boreal forest. A large percent of interior Alaska has burned over the last fifty-years (Kasischke, 2000). Removal of the vegetative layer and the organic layer causes a substantial increase in the active layer during the first 10 years following the fire (Dryness, 1982; Viereck, 1982). Soil temperature warms following fire due to increased albedo of the surface, loss of transpiring vegetation, and removal of the insulating moss layer (Viereck, 1982). If climate is warming, the permafrost layer may not reestablish following a fire disturbance. The combination of increased fire frequency, increased fire severity, and a warming climate means that permafrost stability will continue to erode and permafrost reformation following a fire will be slowed or the permafrost may not reform. This in turn could lead to increased rates of water body drainage in regions recently effected by fire.

Many rivers in Alaska have stream flow gauges that are used by managers and scientists to examine stream flow dynamics. I used this data, in an attempt to detect increases in stream flow as a possible result of less water being retained in water bodies. However, the water bodies in subarctic and arctic regions are often shallow thaw ponds less than 3 meters deep. Although they may cover large areas, they do not necessarily contain large volumes of water (Black, 1969). Also, these losses occurred over the last thirty years, and the drainage rate probably did not undergo a rapid increase at any point during this time. If a given water body slowly drained over thirty years any annual increase in river flow would be too small to detect. Another possible problem with the river flow data is that during warmer years I would expect both increased evapotranspiration and increased glacial runoff. These issues confound analyses of stream runoff statistics.

Alaska is the most geologically active state in the United States. It experienced the largest recorded earthquake in North America and the second largest in the world on March 27, 1964, with a magnitude 9.2. On November 3, 2002, interior Alaska experienced a 7.9 earthquake. Native Alaskans have speculated that water body loss in their homelands began after the 1960s earthquake and has recently accelerated in response to the 2002 earthquake. It could be that these large earthquakes had enough power to generate cracks in the permafrost, allowing water to drain, but I doubt that these earthquakes have caused slow leaks that are leading to eventual drainage of many of these water bodies.

Thermokarst is the process by which thawing ice-rich permafrost leads to topographical depressions where water collects, which in turn further accelerates permafrost degradation (Yoshikawa and Hinzman, 2003). This cycle leads to the growth of the water body, as well as growth of the taliks that underlie the water body. Thermokarsting will cause an increase in surface water area. This process occurs over a longer time period, and is difficult to detect at 30-meter resolution. There has been a documented increase in upwelling around the Tanana flats (Jorgenson et al., 2001). These reported increases in upwelling and thermokarst could begin to help slow the loss of total surface water area as more water bodies are formed, in response to warming. While I did visually notice some new water bodies forming and any enlarging water bodies were included in the study, the overall loss of water bodies far exceeded the current growth of new ones.

4.4 CONCLUSIONS

From 1950 to 2002, there has been a substantial change in closed-basin water bodies in many areas of subarctic Alaska. While the exact mechanisms for surface water area loss are not completely understood, the water loss has occurred during a warming climate when precipitation levels have not changed significantly. Because the landscape level change has occurred in regions of discontinuous, warming permafrost, talik formation and growth appear to be an important mechanism for loss of surface water from closed-basin water bodies.

4.5 RECOMMENDATIONS

In order to fully grasp the degree of loss I have reported here, field-based studies are needed to investigate the cause of loss in each region. Due to the vast size of Alaska, this might be a difficult task, but it could be conducted over the next 5 – 10 years. I recommend that each study region have one ground-based study incorporated over the next five years. This will generate more detailed weather data, ground water hydrology data, and soil cores to evaluate historical fluctuations in water bodies.

To further close the gap on temporal variability as a confounding factor, a study that focuses on how seasonal variability and year-to-year variability would be valuable. This type of study could be conducted by using radar imagery. Radar has the ability to penetrate cloud and smoke cover, allowing weekly images for a study region. This study would ideally follow water body progression from May 15 to Sept 15 for a two-year period. Since the same imagery would be used for all the regions, classification and batch processing techniques could be used. Radar imagery may also be used to detect water body volume and ice depth during the winter months (Duguay and Lafleur, 2003).

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6 *Appendices*

Appendix A. Detailed Information on Images

Tetlin National Wildlife Image Summary				
Image Type	Image ID	Date of Image	Scale	Total Water Equivalent Summer to Summer in mm
B&W Aerial Photograph	AP M4H49 7	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 9	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 12	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 14	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 16	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 47	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 49	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 51	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 53	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 70	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 72	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 74	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 76	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 106	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 108	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 110	22-Aug-54	1:40,000	186
B&W Aerial Photograph	AP M4H49 112	22-Aug-54	1:40,000	186
Color Infrared Aerial Photograph	CIR 90_410	1-Jul-78	1:60,000	213
Color Infrared Aerial Photograph	CIR 90_411	1-Jul-78	1:60,000	213
Color Infrared Aerial Photograph	CIR 91_5488	1-Aug-81	1:60,000	216
Color Infrared Aerial Photograph	CIR 91_5490	1-Aug-81	1:60,000	216
Color Infrared Aerial Photograph	CIR 91_5492	1-Aug-81	1:60,000	216
Color Infrared Aerial Photograph	CIR 92_3962	1-Aug-81	1:60,000	216
Color Infrared Aerial Photograph	CIR 92_3964	1-Aug-81	1:60,000	216
Color Infrared Aerial Photograph	CIR 92_3966	1-Aug-81	1:60,000	216
Color Infrared Aerial Photograph	CIR 93_4097	1-Aug-81	1:60,000	216
Color Infrared Aerial Photograph	CIR 94_4117	1-Aug-81	1:60,000	216
Landsat 7 ETM+ Satellite Image	Landsat ETM+	4-Aug-99	15m	222

Copper River Basin Image Summary

Image Type	Image ID	Date of Image	Scale	Total Water Equivalent Summer to Summer in mm
B&W Aerial Photograph		29-Jul-57	1:40,000	356
B&W Aerial Photograph		29-Jul-57	1:40,000	356
B&W Aerial Photograph		29-Jul-57	1:40,000	356
B&W Aerial Photograph		29-Jul-57	1:40,000	356
B&W Aerial Photograph		2-Jul-55	1:40,000	261
B&W Aerial Photograph		2-Jul-55	1:40,000	261
B&W Aerial Photograph		2-Jul-55	1:40,000	261
Color Infrared Aerial Photograph		28-Aug-78	1:60,000	163
Color Infrared Aerial Photograph		28-Aug-78	1:60,000	163
Color Infrared Aerial Photograph		28-Aug-78	1:60,000	163
Color Infrared Aerial Photograph		28-Aug-78	1:60,000	163
Color Infrared Aerial Photograph		28-Aug-78	1:60,000	163
Color Infrared Aerial Photograph		28-Aug-78	1:60,000	163
Color Infrared Aerial Photograph		28-Aug-78	1:60,000	163
Landsat 5 TM Satellite Image		8-Aug-95	30m	343
Landsat 7 ETM+ Satellite Image		7-Aug-01	15m	328

Talkeetna Image Summary

Image Type	Image ID	Date of Image	Scale	Total Water Equivalent Summer to Summer in mm
B&W Aerial Photograph	AP M4F2 62	17-Jun-54	1:40,000	751
B&W Aerial Photograph	AP M4F2 64	17-Jun-54	1:40,000	751
B&W Aerial Photograph	AP M4F2 66	17-Jun-54	1:40,000	751
B&W Aerial Photograph	AP M4F2 68	17-Jun-54	1:40,000	751
B&W Aerial Photograph	AP M4F2 70	17-Jun-54	1:40,000	751
B&W Aerial Photograph	AP M4F2 72	17-Jun-54	1:40,000	751
B&W Aerial Photograph	AP M-128B 17	11-Jul-53	1:40,000	667
B&W Aerial Photograph	AP M-128B 19	11-Jul-53	1:40,000	667
B&W Aerial Photograph	AP M-128B 21	11-Jul-53	1:40,000	667
B&W Aerial Photograph	AP M-128B 23	11-Jul-53	1:40,000	667
B&W Aerial Photograph	AP M-128B 25	11-Jul-53	1:40,000	667
B&W Aerial Photograph	AP M-128B 26	11-Jul-53	1:40,000	667
B&W Aerial Photograph	AP M-128B 28	11-Jul-53	1:40,000	667
B&W Aerial Photograph	AP M-128B 30	11-Jul-53	1:40,000	667

B&W Aerial Photograph	AP M-128B 32	11-Jul-53	1:40,000	667
B&W Aerial Photograph	AP M-128B 34	11-Jul-53	1:40,000	667
B&W Aerial Photograph	AP M-128B 36	11-Jul-53	1:40,000	667
B&W Aerial Photograph	AP M4G12 17	3-Jul-54	1:40,000	751
B&W Aerial Photograph	AP M4G12 19	3-Jul-54	1:40,000	751
B&W Aerial Photograph	AP M4G12 21	3-Jul-54	1:40,000	751
B&W Aerial Photograph	AP M4G12 23	3-Jul-54	1:40,000	751
B&W Aerial Photograph	AP M4G12 25	3-Jul-54	1:40,000	751
B&W Aerial Photograph	AP M4G12 27	3-Jul-54	1:40,000	751
B&W Aerial Photograph	AP M-513 161	3-Jul-51	1:40,000	714
B&W Aerial Photograph	AP M-513 234	3-Jul-51	1:40,000	714
B&W Aerial Photograph	AP M-513 236	3-Jul-51	1:40,000	714
B&W Aerial Photograph	AP M-513 238	3-Jul-51	1:40,000	714
B&W Aerial Photograph	AP M-513 240	3-Jul-51	1:40,000	714
B&W Aerial Photograph	AP M-513 283	3-Jul-51	1:40,000	714
B&W Aerial Photograph	AP M-513 285	3-Jul-51	1:40,000	714
B&W Aerial Photograph	AP M-513 287	3-Jul-51	1:40,000	714
B&W Aerial Photograph	AP M-513 289	3-Jul-51	1:40,000	714
B&W Aerial Photograph	AP M-513 291	3-Jul-51	1:40,000	714
B&W Aerial Photograph	AP M-513 293	3-Jul-51	1:40,000	714
Color Infrared Aerial Photograph	CIR 96_0091	1-Aug-80	1:60,000	1057
Color Infrared Aerial Photograph	CIR 96_0089	1-Aug-80	1:60,000	1057
Color Infrared Aerial Photograph	CIR 97_0052	1-Aug-80	1:60,000	1057
Color Infrared Aerial Photograph	CIR 97_0050	1-Aug-80	1:60,000	1057
Color Infrared Aerial Photograph	CIR 98_163	1-Aug-80	1:60,000	1057
Color Infrared Aerial Photograph	CIR 98_161	1-Aug-80	1:60,000	1057
Color Infrared Aerial Photograph	CIR 98_159	1-Aug-80	1:60,000	1057
Color Infrared Aerial Photograph	CIR 98_157	1-Aug-80	1:60,000	1057
Color Infrared Aerial Photograph	CIR 99_9169	1-Jul-82	1:60,000	752
Color Infrared Aerial Photograph	CIR 99_9171	1-Jul-82	1:60,000	752
Color Infrared Aerial Photograph	CIR 99_9173	1-Jul-82	1:60,000	752
Color Infrared Aerial Photograph	CIR 99_9175	1-Jul-82	1:60,000	752
Landsat 7 ETM+ Satellite Image	Landsat ETM+	16-Aug-00	15m	809

Denali National Park Image Summary

Image Type	Image ID	Date of Image	Scale	Total Water Equivalent Summer to Summer in mm
B&W Aerial Photograph	AP M4H34 430	7-Aug-54	1:40,000	281
B&W Aerial Photograph	AP M4H34 432	7-Aug-54	1:40,000	281
B&W Aerial Photograph	AP M4H34 434	7-Aug-54	1:40,000	281
B&W Aerial Photograph	AP M4H34 511	7-Aug-54	1:40,000	281
B&W Aerial Photograph	AP M4H34 513	7-Aug-54	1:40,000	281
B&W Aerial Photograph	AP M626 658	20-Jul-52	1:40,000	281

B&W Aerial Photograph	AP M626 660	20-Jul-52	1:40,000	234
B&W Aerial Photograph	AP M626 663	20-Jul-52	1:40,000	234
B&W Aerial Photograph	AP M626 665	20-Jul-52	1:40,000	234
B&W Aerial Photograph	AP M626 667	20-Jul-52	1:40,000	234
B&W Aerial Photograph	AP M626 669	20-Jul-52	1:40,000	234
B&W Aerial Photograph	AP M626 722	20-Jul-52	1:40,000	234
B&W Aerial Photograph	AP M626 724	20-Jul-52	1:40,000	234
B&W Aerial Photograph	AP M626 726	20-Jul-52	1:40,000	234
B&W Aerial Photograph	AP M626 728	20-Jul-52	1:40,000	234
B&W Aerial Photograph	AP M632 141	MIA	1:40,000	
B&W Aerial Photograph	AP M632 143	5-Aug-52	1:40,000	234
B&W Aerial Photograph	AP M632 145	5-Aug-52	1:40,000	281
B&W Aerial Photograph	AP M530 174	28-Aug-51	1:40,000	281
B&W Aerial Photograph	AP M530 238	28-Aug-51	1:40,000	281
B&W Aerial Photograph	AP M530 236	28-Aug-51	1:40,000	281
B&W Aerial Photograph	AP M530 252	28-Aug-51	1:40,000	281
B&W Aerial Photograph	AP M530 254	28-Aug-51	1:40,000	281
Color Infrared Aerial Photograph	CIR L78 0093 406	Aug-79	1:60,000	307
Color Infrared Aerial Photograph	CIR L78 0095 406	Aug-79	1:60,000	307
Color Infrared Aerial Photograph	CIR L78 0097 406	Aug-79	1:60,000	307
Color Infrared Aerial Photograph	CIR L78 0099 406	Aug-79	1:60,000	307
Color Infrared Aerial Photograph	CIR L79 3693 03012	23-Aug-81	1:60,000	256
Color Infrared Aerial Photograph	CIR L79 3695 03012	23-Aug-81	1:60,000	256
Color Infrared Aerial Photograph	CIR L79 3697 03012	23-Aug-81	1:60,000	256
Color Infrared Aerial Photograph	CIR L80 3647 03012	23-Aug-81	1:60,000	256
Color Infrared Aerial Photograph	CIR L80 3649 03012	23-Aug-81	1:60,000	256
Color Infrared Aerial Photograph	CIR L80 3651 03012	23-Aug-81	1:60,000	256
Color Infrared Aerial Photograph	CIR L81 3716 03012	23-Aug-81	1:60,000	256
Color Infrared Aerial Photograph	CIR L81 3718 03012	23-Aug-81	1:60,000	256
Landsat 7 ETM+ Satellite Image	Landsat ETM+	16-Aug-00	15m	237

Innoko Flats National Wildlife Refuge Image Summary

Image Type	Image ID	Date of Image	Scale	Total Water Equivalent in mm
B&W Aerial Photograph	AP GAL33 12	21-Aug-52	1:40,000	477
B&W Aerial Photograph	AP GAL33 14	21-Aug-52	1:40,000	477
B&W Aerial Photograph	AP GAL33 16	21-Aug-52	1:40,000	477
B&W Aerial Photograph	AP GAL33 18	21-Aug-52	1:40,000	477
B&W Aerial Photograph	AP GAL37 2	13-Sep-52	1:40,000	477
B&W Aerial Photograph	AP GAL37 4	13-Sep-52	1:40,000	477
B&W Aerial Photograph	AP GAL37 6	13-Sep-52	1:40,000	477
B&W Aerial Photograph	AP GAL37 8	13-Sep-52	1:40,000	477
B&W Aerial Photograph	AP GAL03 15	14-Jun-52	1:40,000	477
B&W Aerial Photograph	AP GAL03 17	14-Jun-52	1:40,000	477

B&W Aerial Photograph	AP GAL03 19	14-Jun-52	1:40,000	477
B&W Aerial Photograph	AP GAL03 21	14-Jun-52	1:40,000	477
B&W Aerial Photograph	AP GAL03 23	14-Jun-52	1:40,000	477
B&W Aerial Photograph	AP GAL14 10	5-Jul-52	1:40,000	477
B&W Aerial Photograph	AP GAL14 12	5-Jul-52	1:40,000	477
B&W Aerial Photograph	AP GAL14 13	5-Jul-52	1:40,000	477
B&W Aerial Photograph	AP GAL14 14	5-Jul-52	1:40,000	477
B&W Aerial Photograph	AP GAL14 15	5-Jul-52	1:40,000	477
B&W Aerial Photograph	AP GAL14 17	5-Jul-52	1:40,000	477
B&W Aerial Photograph	AP GAL13 46	24-Jun-52	1:40,000	477
B&W Aerial Photograph	AP GAL13 48	24-Jun-52	1:40,000	477
B&W Aerial Photograph	AP GAL13 50	24-Jun-52	1:40,000	477
B&W Aerial Photograph	AP GAL13 52	24-Jun-52	1:40,000	477
B&W Aerial Photograph	AP GAL12 65	24-Jun-52	1:40,000	477
B&W Aerial Photograph	AP GAL12 67	24-Jun-52	1:40,000	477
B&W Aerial Photograph	AP GAL12 69	24-Jun-52	1:40,000	477
B&W Aerial Photograph	AP GAL23 21	18-Jul-52	1:40,000	477
B&W Aerial Photograph	AP GAL23 23	18-Jul-52	1:40,000	477
B&W Aerial Photograph	AP GAL16 34	5-Jul-52	1:40,000	477
Color Infrared Aerial Photograph	CIR L76 182 427	Jul-80	1:60,000	511
Color Infrared Aerial Photograph	CIR L76 184 427	Jul-80	1:60,000	511
Color Infrared Aerial Photograph	CIR L76 186 427	Jul-80	1:60,000	511
Color Infrared Aerial Photograph	CIR L76 188 427	Jul-80	1:60,000	511
Color Infrared Aerial Photograph	CIR L77 285 427	Jul-80	1:60,000	511
Color Infrared Aerial Photograph	CIR L77 287 427	Jul-80	1:60,000	511
Color Infrared Aerial Photograph	CIR L77 289 427	Jul-80	1:60,000	511
Landsat 7 ETM+ Satellite Image	Landsat ETM+	18-Aug-01	15m	461

Minto Flats State Game Refuge Image Summary

Image Type	Image ID	Date of Image	Scale	Total Water Equivalent in mm
B&W Aerial Photograph	AP M4H34 179	7-Aug-54	1:40,000	281
B&W Aerial Photograph	AP M4H34 181	7-Aug-54	1:40,000	281
B&W Aerial Photograph	AP M4H34 183	7-Aug-54	1:40,000	281
B&W Aerial Photograph	AP M4H34 390	7-Aug-54	1:40,000	281
B&W Aerial Photograph	AP M4H34 392	7-Aug-54	1:40,000	281
B&W Aerial Photograph	AP M4H34 394	7-Aug-54	1:40,000	281
B&W Aerial Photograph	AP M-517 83	11-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 85	11-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 87	11-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 89	11-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 96	11-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 98	11-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 100	11-Jul-51	1:40,000	217

B&W Aerial Photograph	AP M-517 148	11-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 150	11-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 152	11-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 154	11-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-512 287	27-Jun-51	1:40,000	217
B&W Aerial Photograph	AP M-512 289	27-Jun-51	1:40,000	217
B&W Aerial Photograph	AP M-512 290	27-Jun-51	1:40,000	217
B&W Aerial Photograph	AP M-512 292	27-Jun-51	1:40,000	217
Color Infrared Aerial Photograph	CIR L68 5585 02655	17-Aug-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L68 5587 02655	17-Aug-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L68 5589 02655	17-Aug-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L68 5591 02655	17-Aug-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L68 5585 02655	17-Aug-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L69 5521 02655	17-Aug-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L69 5519 02655	17-Aug-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L69 5517 02655	17-Aug-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L69 5515 02655	17-Aug-78	1:60,000	264
Landsat 5 TM+ Satellite Image	Landsat TM	29-Jun-91	30m	380
Landsat 7 ETM+ Satellite Image	Landsat ETM+	16-Aug-00	30m	272
Landsat 7 ETM+ Satellite Image	Landsat ETM+	6-Aug-02	15m	270

Stevens Village Image Summary

Image Type	Image ID	Date of Image	Scale	Total Water Equivalent in mm
B&W Aerial Photograph	AP M-518 419	14-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-518 421	14-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-518 423	14-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-518 543	14-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-518 545	14-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-518 547	14-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-518 549	14-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 54	15-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 56	15-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 59	15-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-517 61	15-Jul-51	1:40,000	217
B&W Aerial Photograph	AP M-512 178	27-Jun-51	1:40,000	217
B&W Aerial Photograph	AP M-512 180	27-Jun-51	1:40,000	217
B&W Aerial Photograph	AP M-512 183	27-Jun-51	1:40,000	217
B&W Aerial Photograph	AP M-512 185	27-Jun-51	1:40,000	217
B&W Aerial Photograph	AP M-512 258	27-Jun-51	1:40,000	217
B&W Aerial Photograph	AP M-512 260	27-Jun-51	1:40,000	217
B&W Aerial Photograph	AP M-512 262	27-Jun-51	1:40,000	217
B&W Aerial Photograph	AP M-512 329	27-Jun-51	1:40,000	217

B&W Aerial Photograph	AP M-512 331	27-Jun-51	1:40,000	217
B&W Aerial Photograph	AP M-512 333	27-Jun-51	1:40,000	217
Color Infrared Aerial Photograph	CIR L57_0049_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L57_0051_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L57_0053_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L57_0055_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L57_0057_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L57_0059_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L57_0061_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L58_0013_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L58_0015_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L58_0017_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L58_0019_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L58_0021_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L58_0023_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L58_0025_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L59_0202_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L59_0204_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L59_0206_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L59_0208_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L59_0210_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L59_0212_386	1-Jul-78	1:60,000	264
Color Infrared Aerial Photograph	CIR L59_0214_386	1-Jul-78	1:60,000	264
Landsat 5 TM+ Satellite Image	Landsat TM	29-Jun-91	30m	380
Landsat 7 ETM+ Satellite Image	Landsat ETM+	16-Aug-00	15m	272
Landsat 7 ETM+ Satellite Image	Landsat ETM+	6-Aug-02	15m	275

Yukon Flats National Wildlife Refuge Image Summary				
Image Type	Image ID	Date of Image	Scale	Total Water Equivalent in mm
B&W Aerial Photograph	AP M-634 101	6-Aug-52	1:40,000	326
B&W Aerial Photograph	7	24-Jul-53	1:40,000	326
B&W Aerial Photograph	AP M-616 129	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 131	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 133	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 135	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 137	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 139	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 141	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 161	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 163	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 165	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 167	26-Jun-52	1:40,000	326

B&W Aerial Photograph	AP M-616 169	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 171	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-616 173	26-Jun-52	1:40,000	326
B&W Aerial Photograph	AP M-643 31	17-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-643 33	17-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-643 35	17-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-643 37	17-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-643 39	17-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-643 41	17-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-643 43	17-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 92	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 95	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 97	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 99	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 101	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 103	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 111	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 113	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 115	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 117	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 119	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 121	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-651 123	28-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-652 12	31-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-652 14	31-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-652 16	31-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-652 18	31-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-652 20	31-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-652 22	31-Aug-52	1:40,000	326
B&W Aerial Photograph	AP M-652 24	31-Aug-52	1:40,000	326
Landsat 7 ETM+ Satellite Image	Landsat ETM+	16-Aug-00	15m	376

Appendix B. Detailed Temperature, PET, P-PET, and Precipitation Data for Each Region

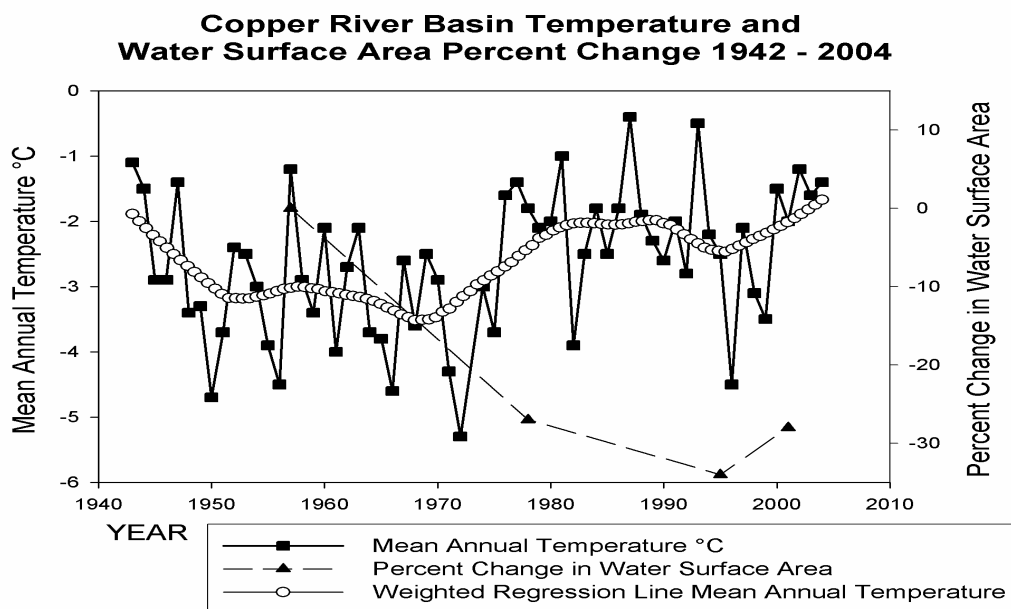


Figure 6.1 Copper River Basin temperature and surface water area results.

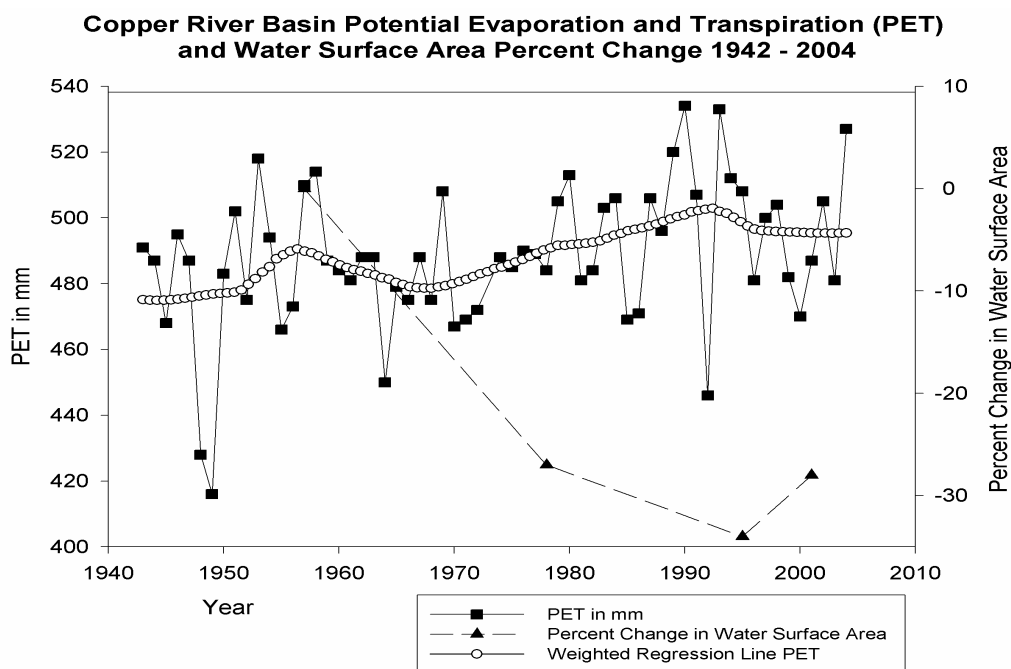


Figure 6.2 Copper River Basin PET and surface water area results.

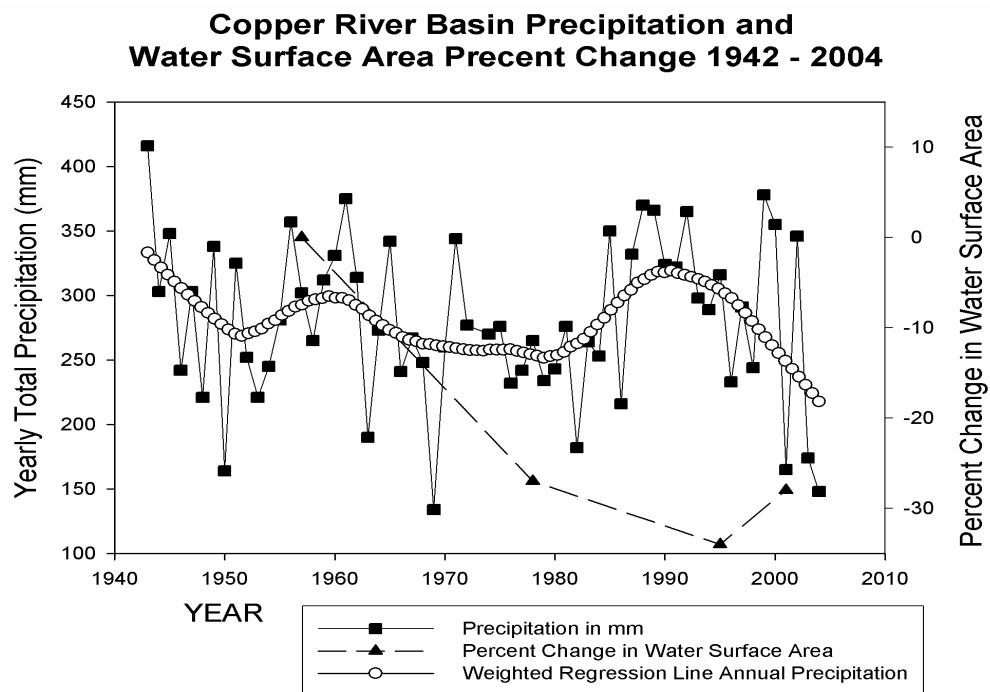


Figure 6.3 Copper River Basin precipitation and surface water area results.

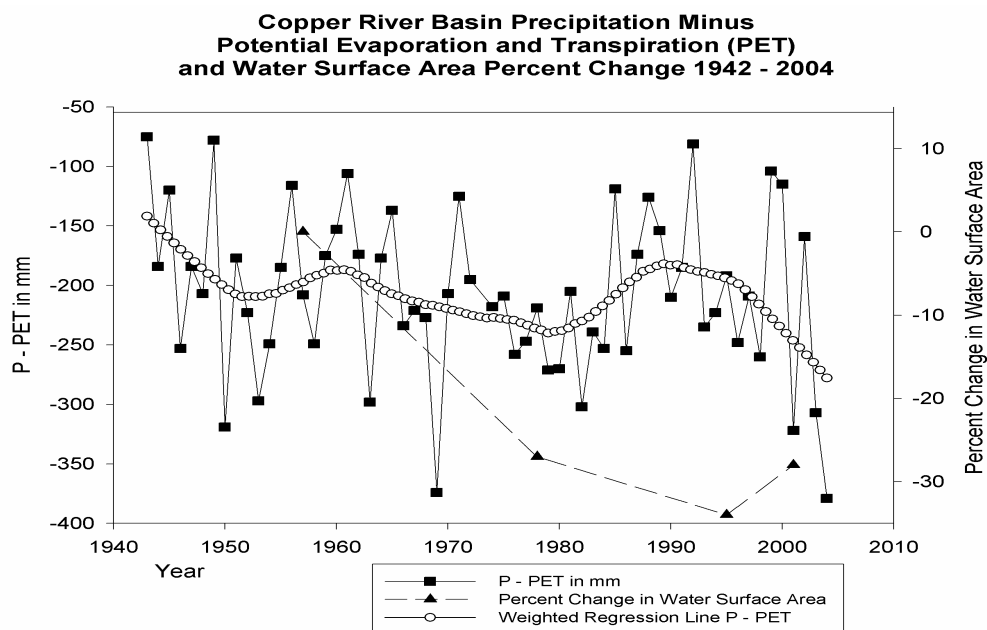


Figure 6.4 Copper River Basin P - PET and surface water area results.

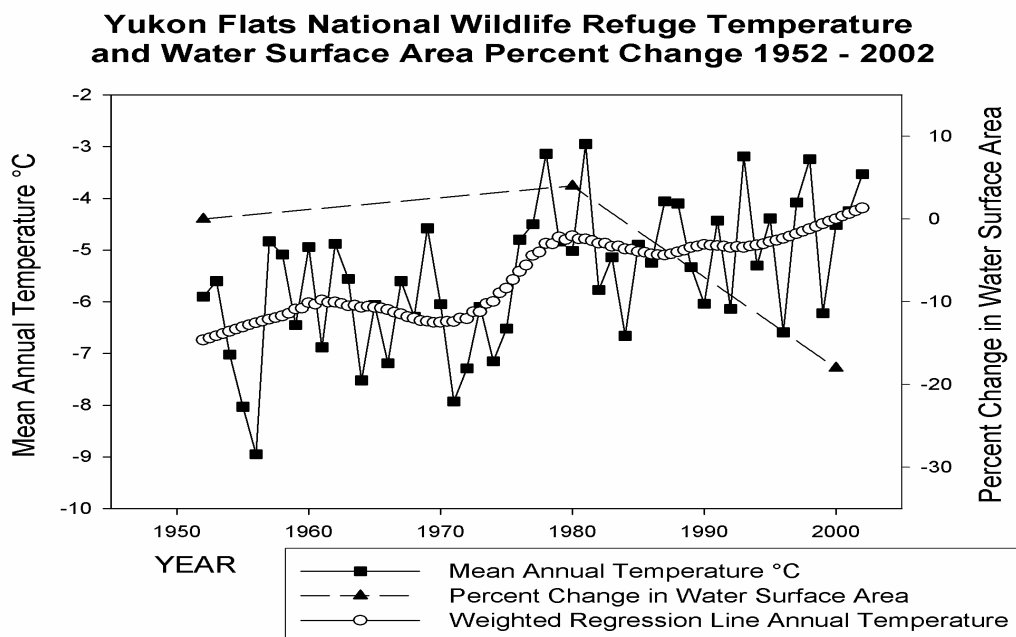


Figure 6.5 Yukon Flats National Wildlife Refuge temperature and surface water area results.

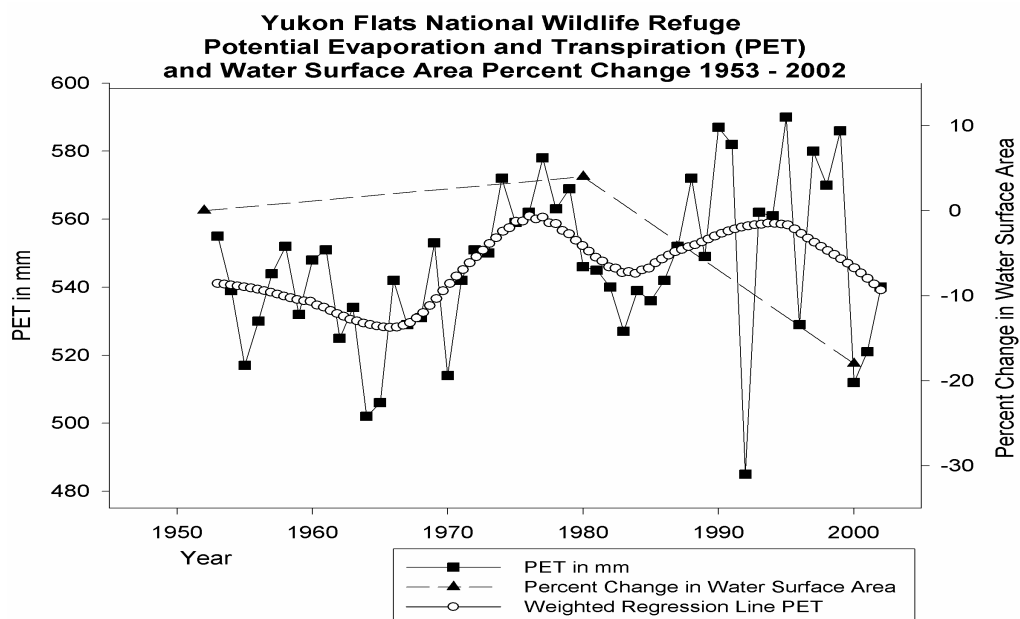


Figure 6.6 Yukon Flats National Wildlife Refuge PET and surface water area results.

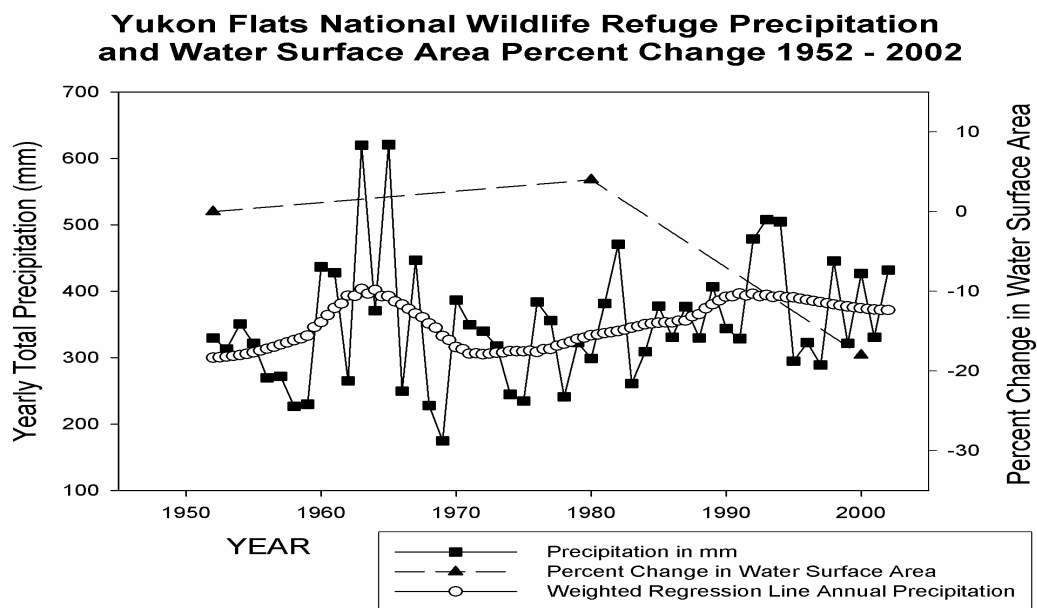


Figure 6.7 Yukon Flats National Wildlife Refuge precipitation and surface water area results.

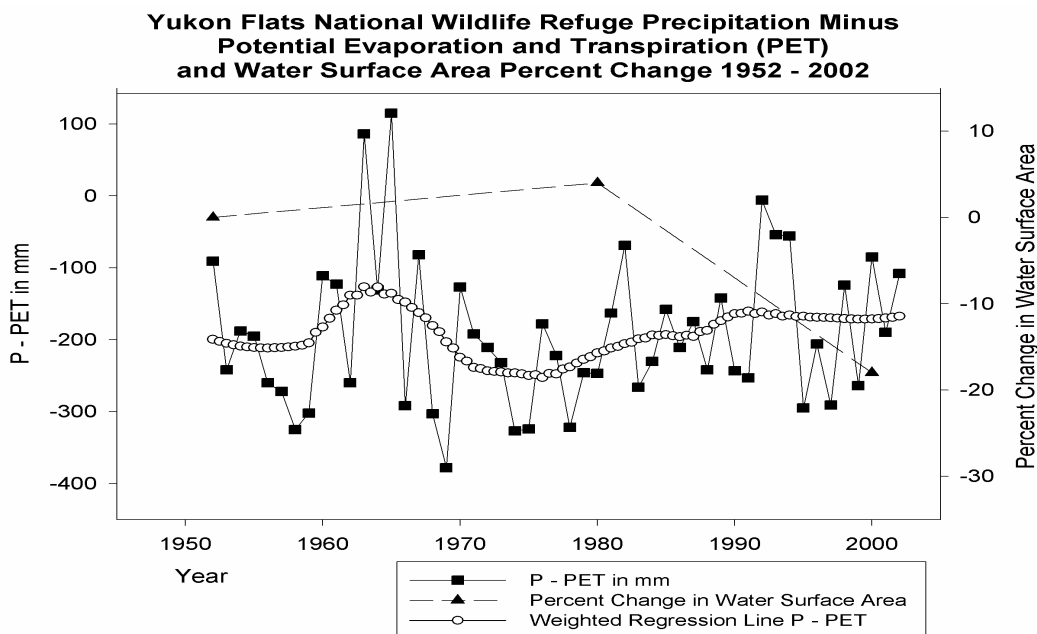


Figure 6.8 Yukon Flats National Wildlife Refuge P - PET and surface water area results.

Minto Flats State Game Refuge Temperature and Water Surface Area Percent Change 1949 - 2004

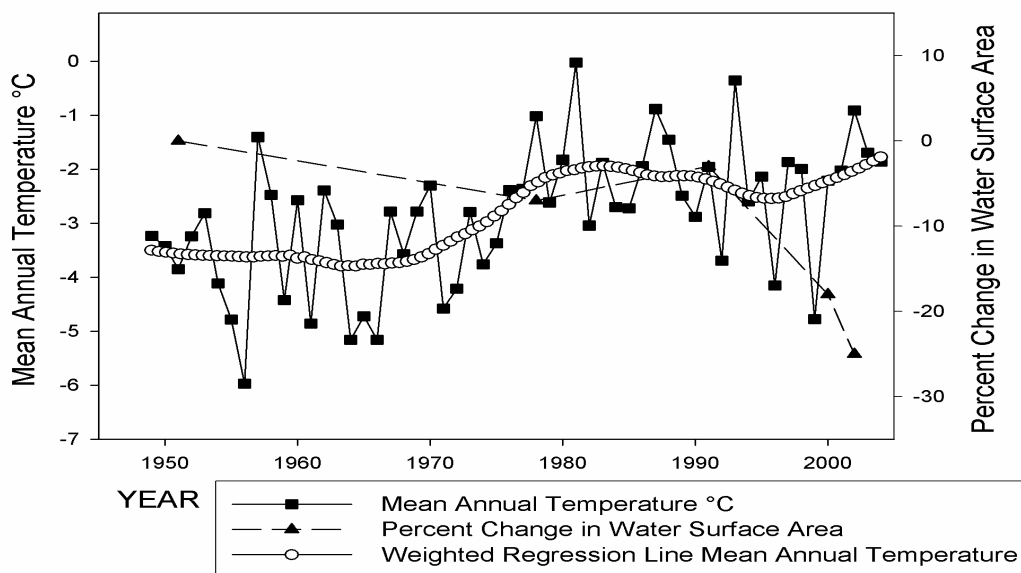


Figure 6.9 Minto Flats State Game Refuge temperature and surface water area results.

Minto Flats State Game Refuge Potential Evaporation and Transpiration (PET) and Water Surface Area Percent Change 1949 - 2004

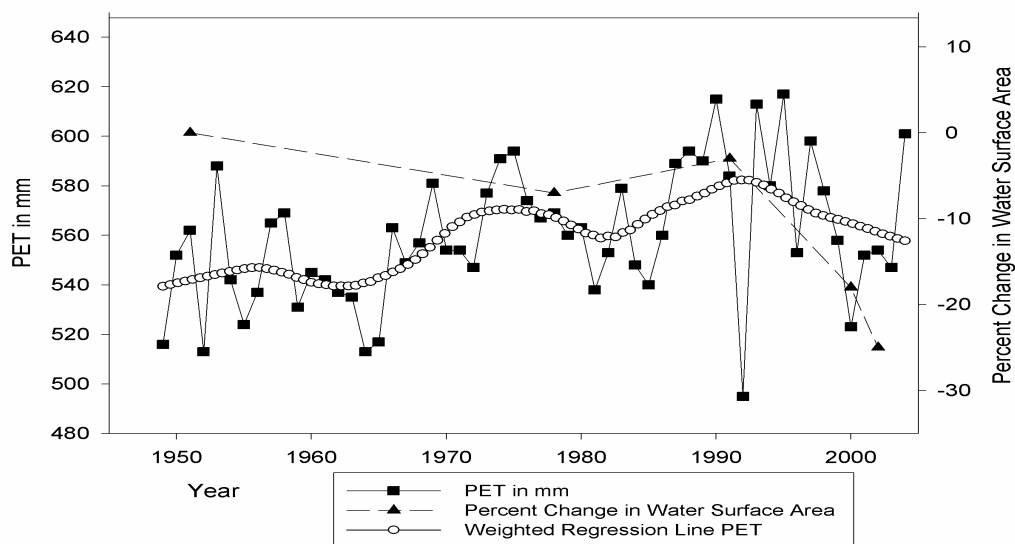


Figure 6.10 Minto Flats State Game Refuge fifty-year PET and surface water area results.

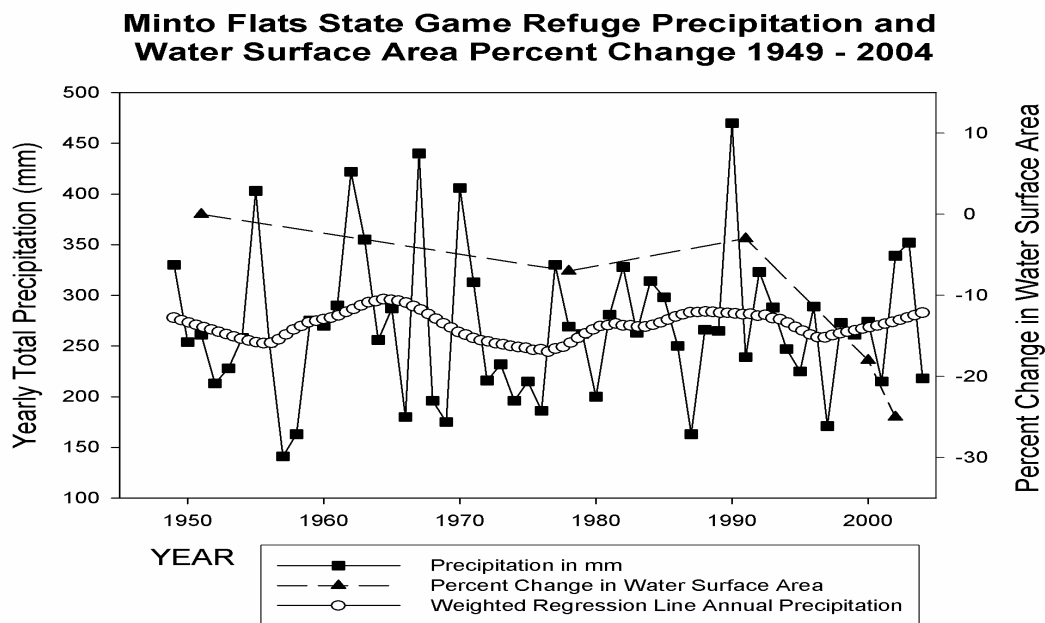


Figure 6.11 Minto Flats State Game Refuge fifty-year precipitation and surface water area results.

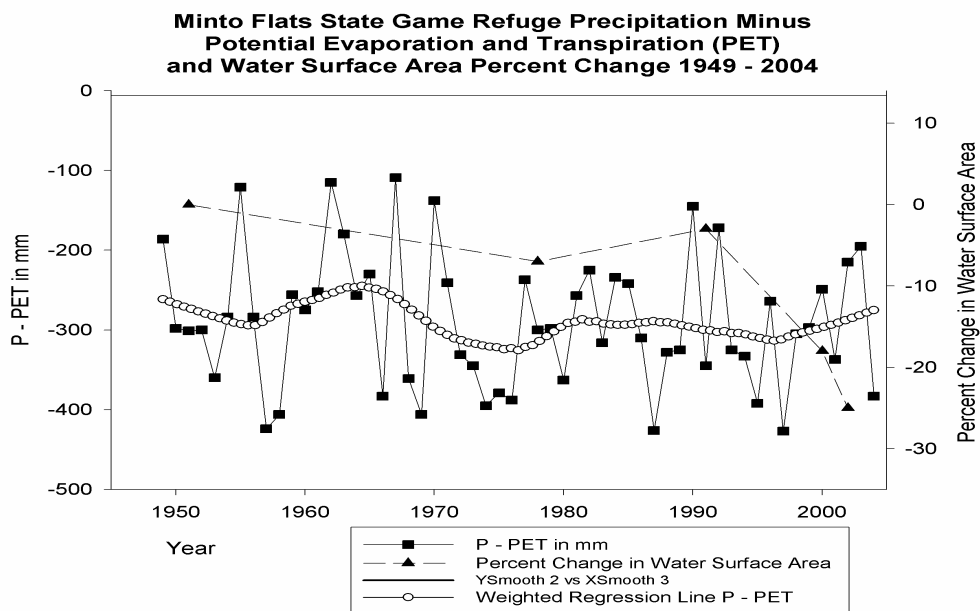


Figure 6.12 Minto Flats State Game Refuge fifty-year P - PET and surface water area results.

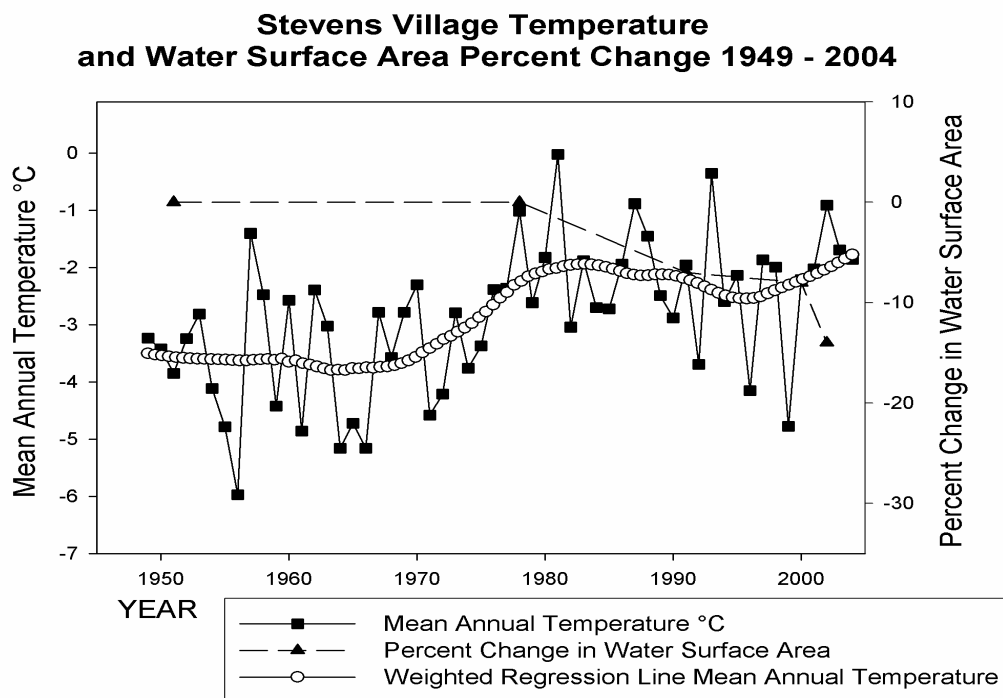


Figure 6.13 Stevens Village temperature and surface water area results.

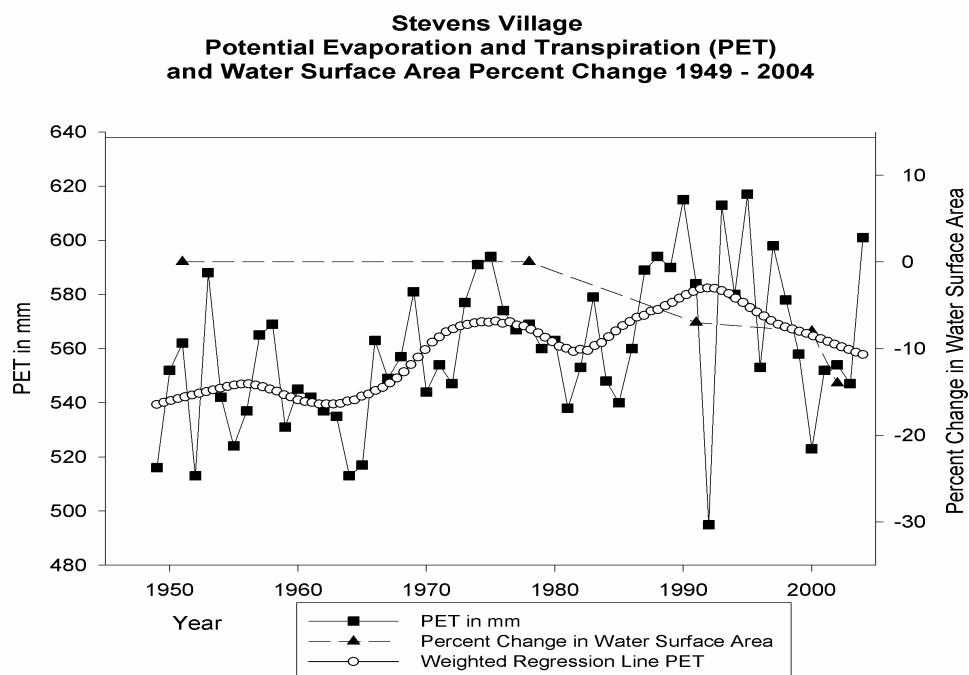


Figure 6.14 Stevens Village PET and surface water area results.

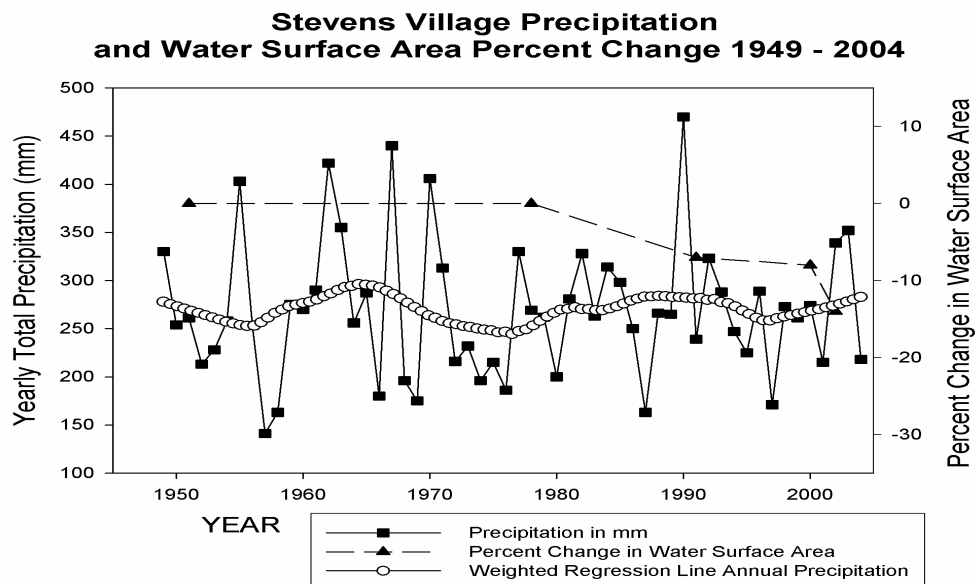


Figure 6.15 Stevens Village precipitation and surface water area results.

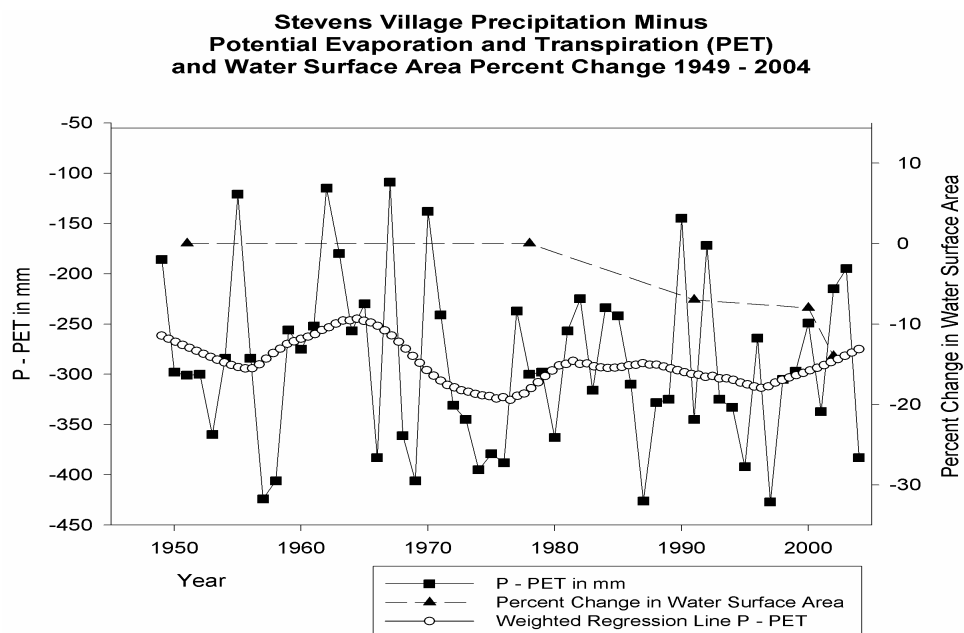


Figure 6.16 Stevens Village P - PET and surface water area results.

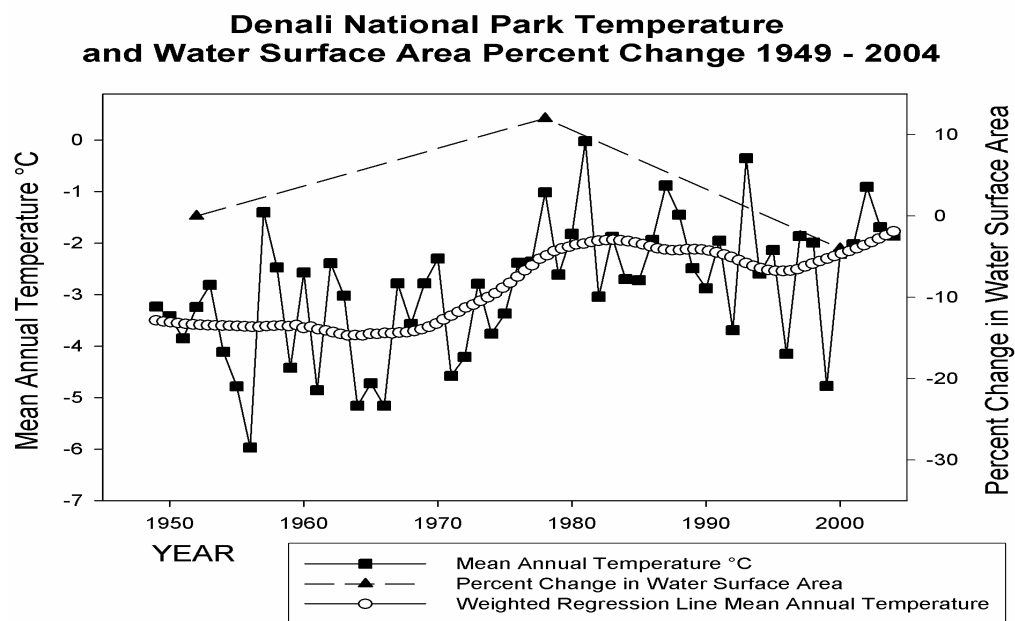


Figure 6.17 Denali National Park temperature and surface water area results.

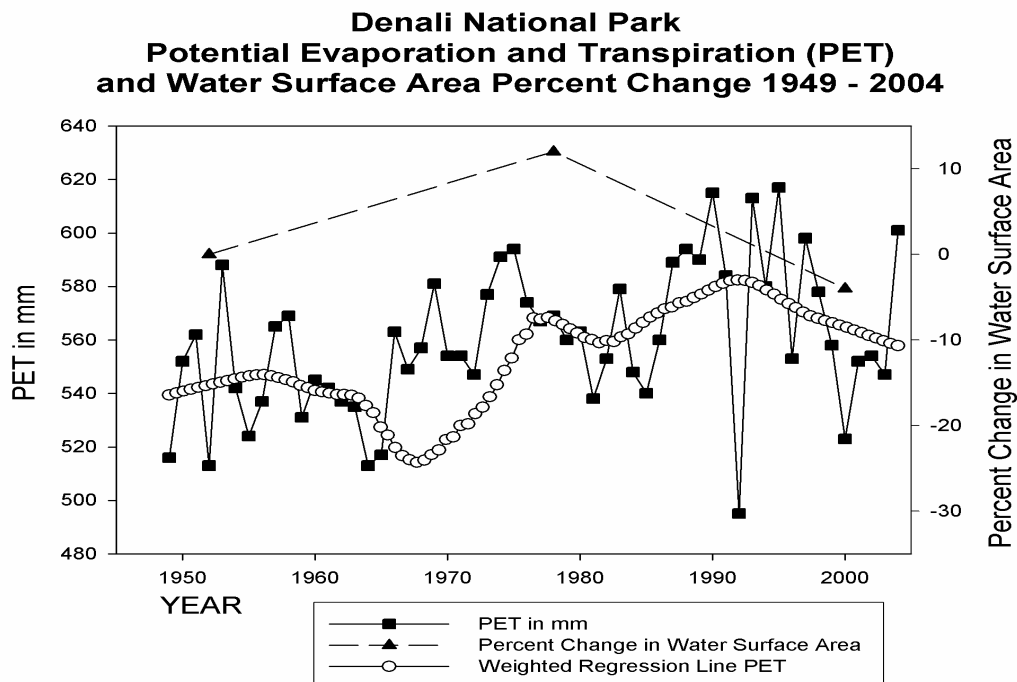


Figure 6.18 Denali National Park PET and surface water area results.

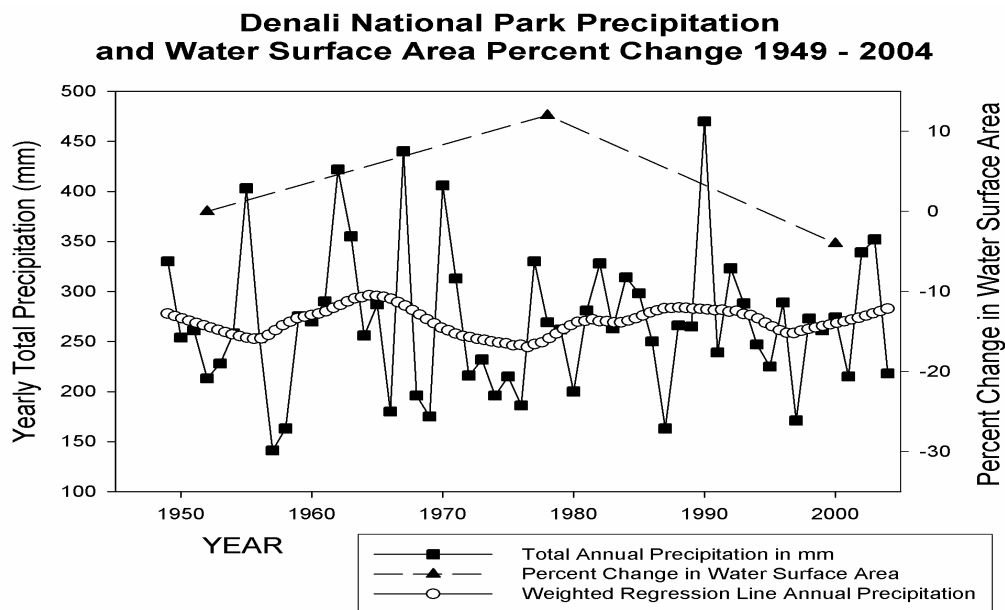


Figure 6.19 Denali National Park precipitation and surface water area results.

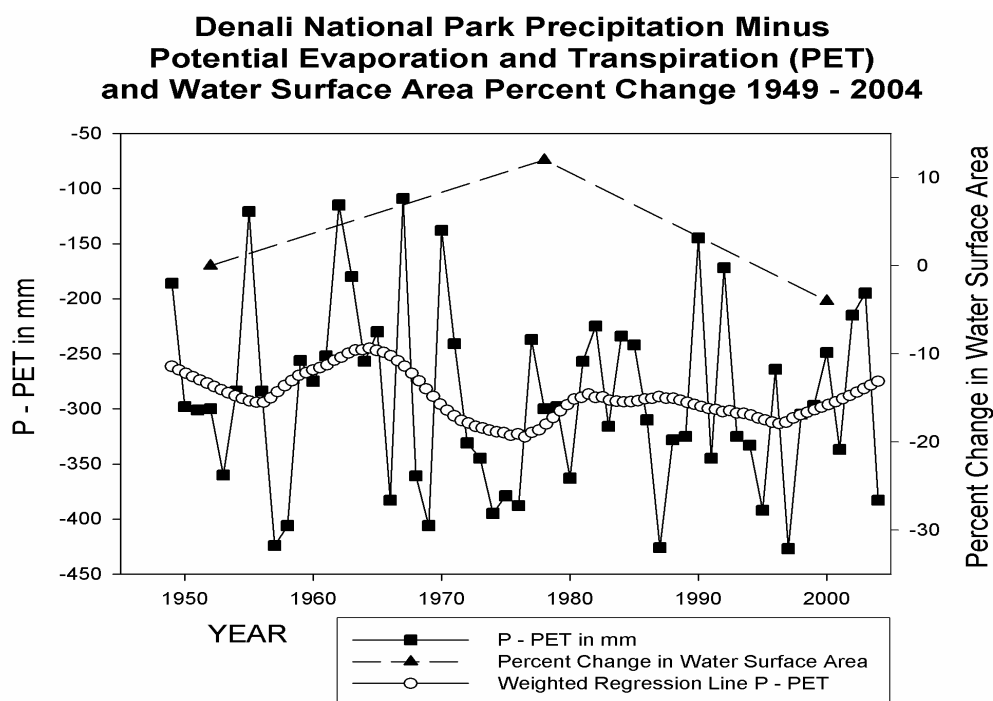


Figure 6.20 Denali National Park P - PET and surface water area results.

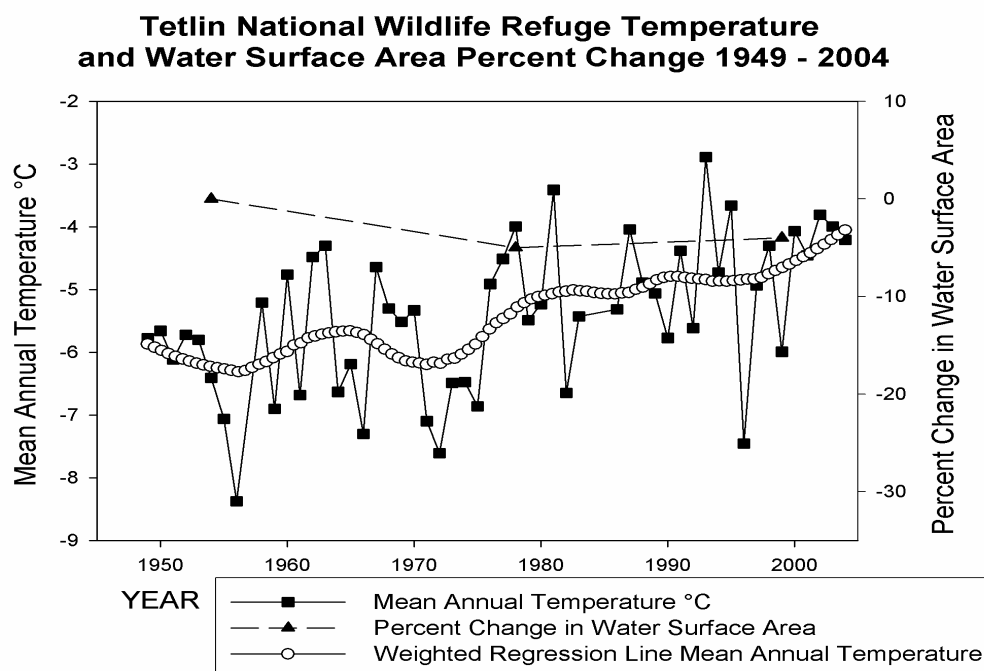


Figure 6.21 Tetlin National Wildlife Refuge temperature and surface water area results.

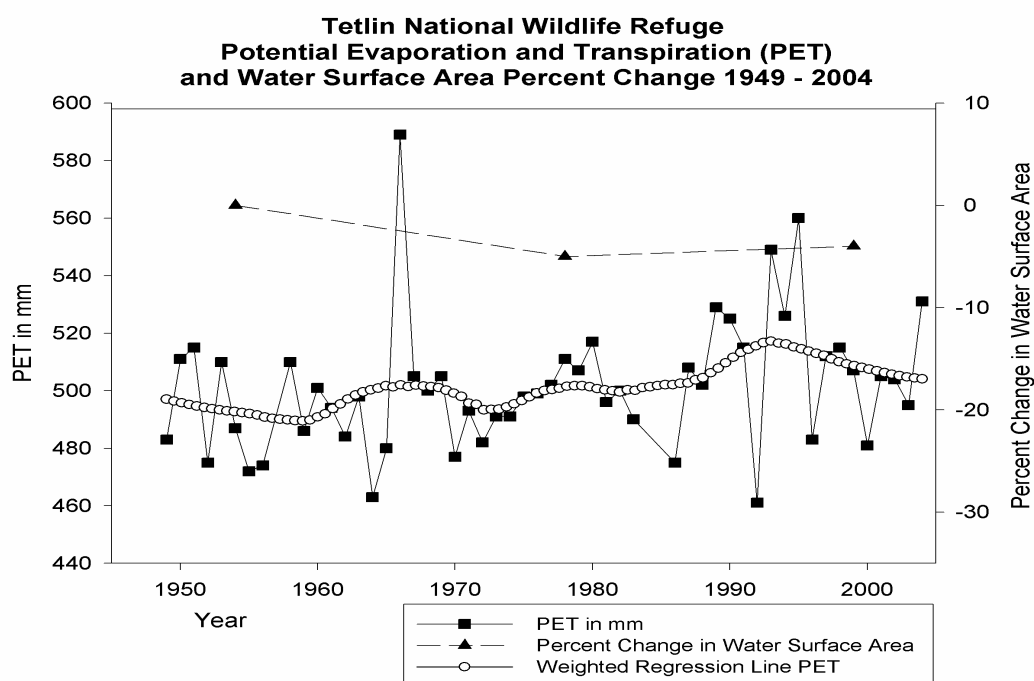


Figure 6.22 Tetlin National Wildlife Refuge PET and surface water area results.

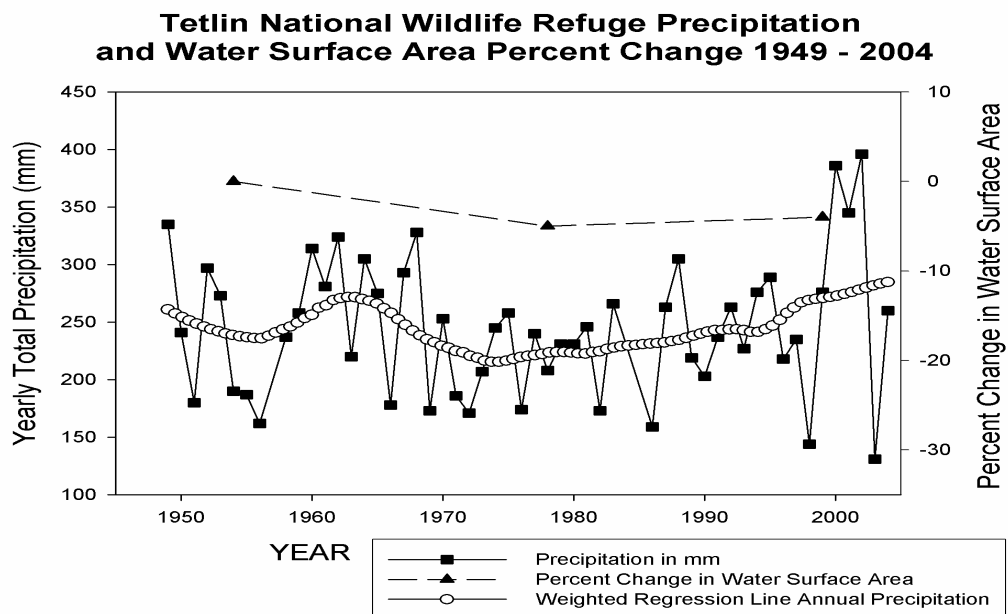


Figure 6.23 Tetlin National Wildlife Refuge precipitation and surface water area results.

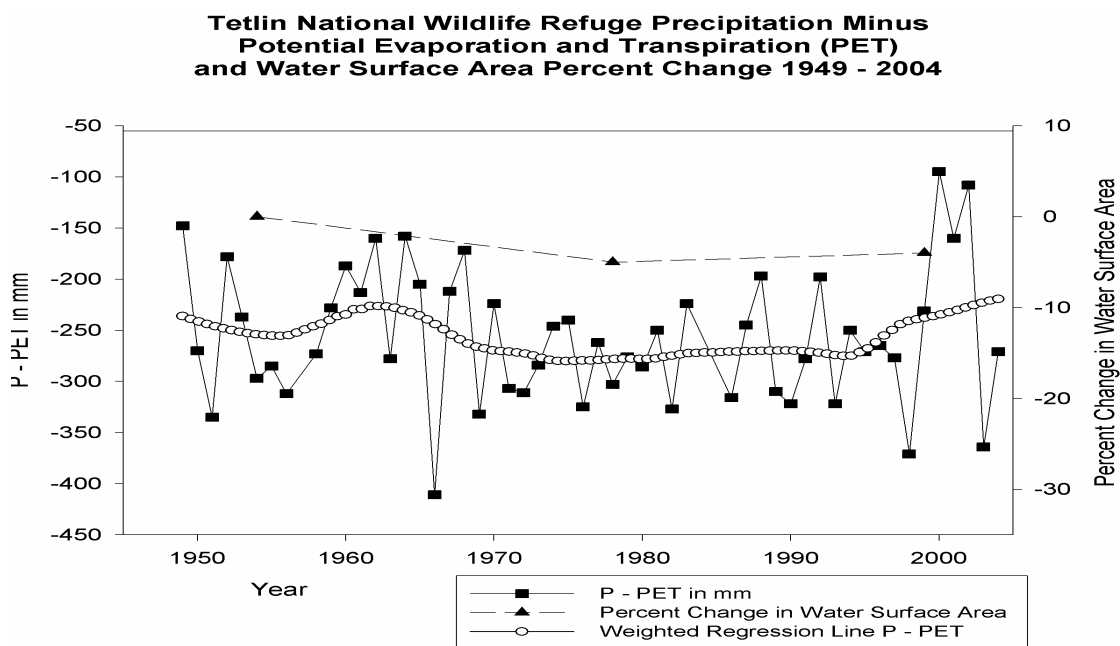


Figure 6.24 Tetlin National Wildlife Refuge P - PET and surface water area results.

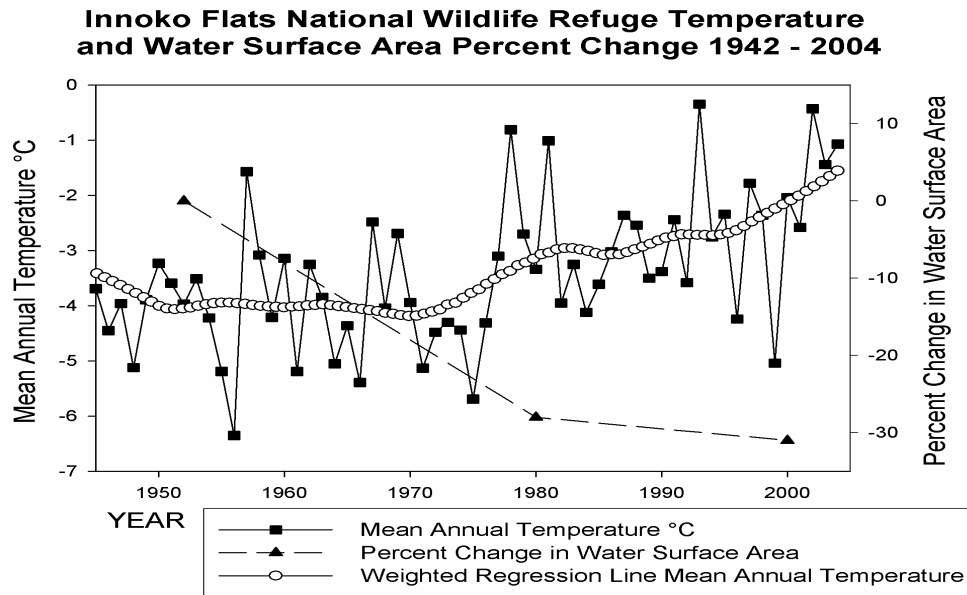


Figure 6.25 Innoko Flats National Wildlife Refuge temperature and surface water area results.

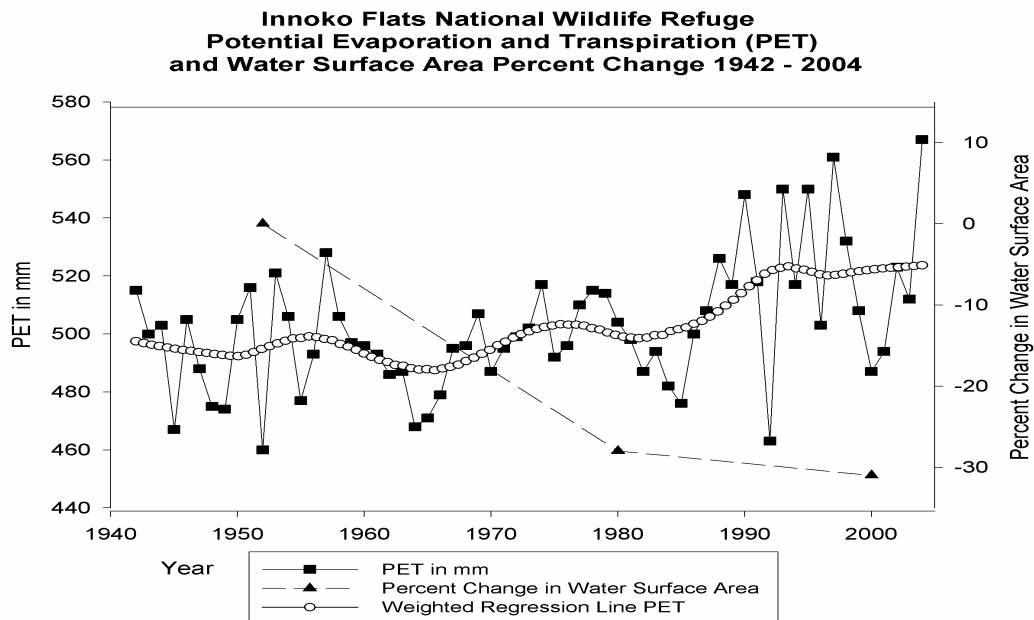


Figure 6.26 Innoko Flats National Wildlife Refuge PET and surface water area results.

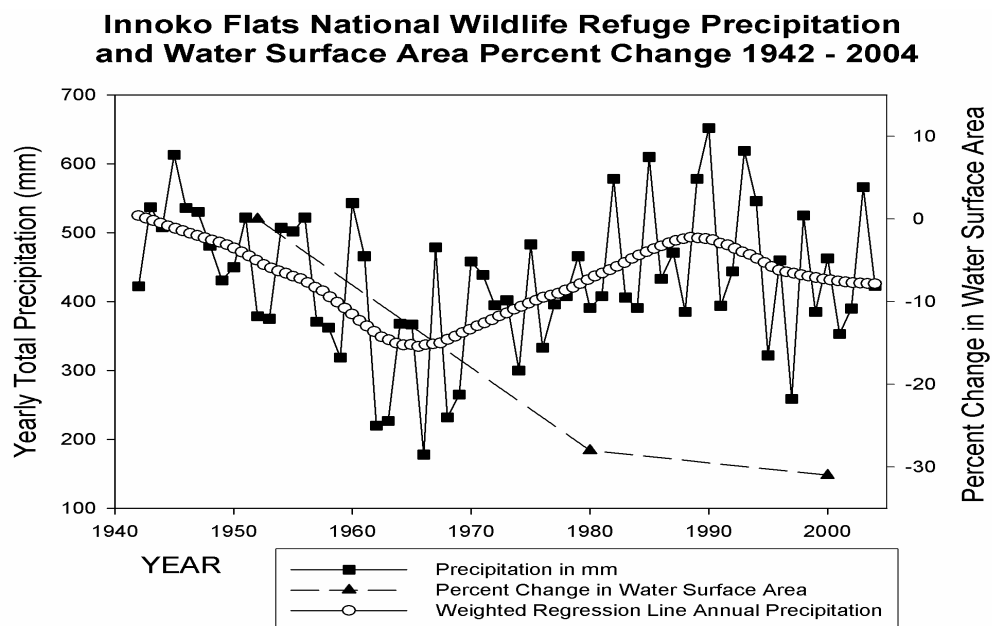


Figure 6.27 Innoko Flats National Wildlife Refuge precipitation and surface water area results.

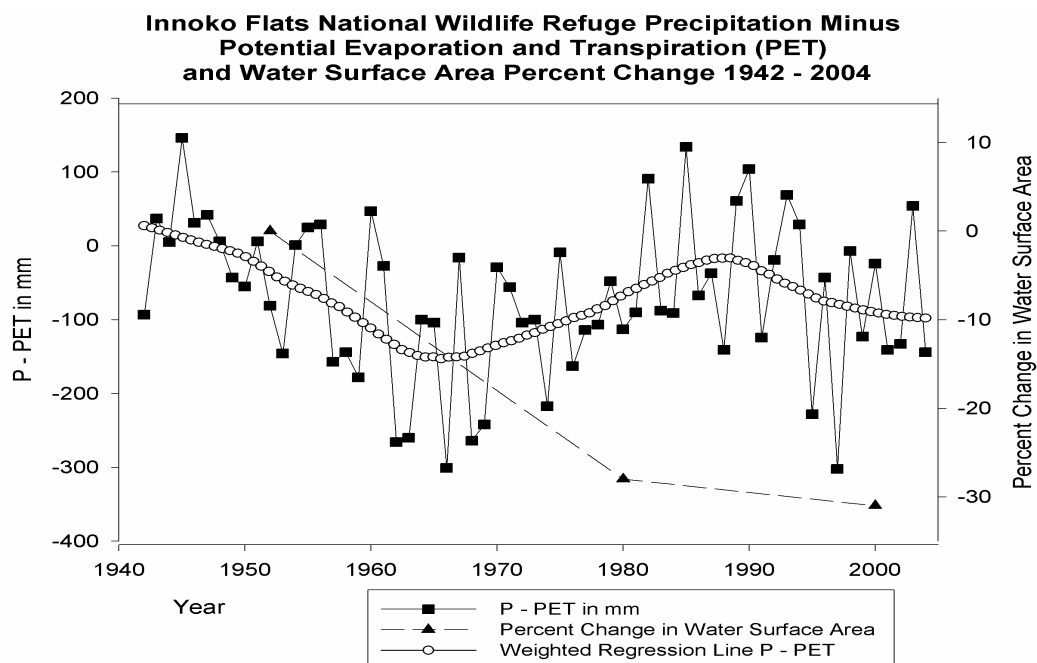


Figure 6.28 Innoko Flats National Wildlife Refuge P - PET and surface water area results.

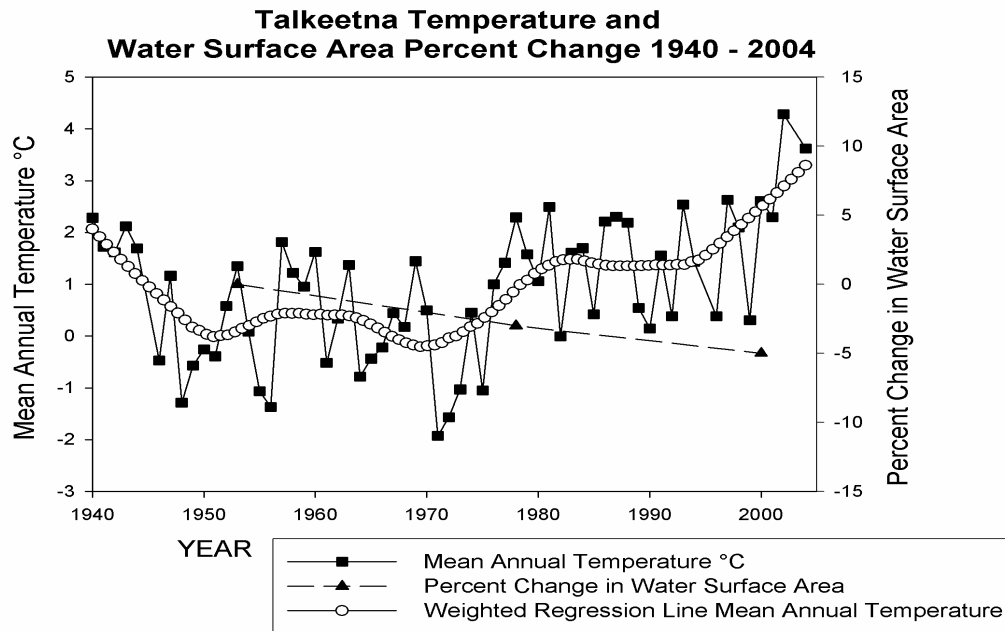


Figure 6.29 Talkeetna temperature and surface water area results.

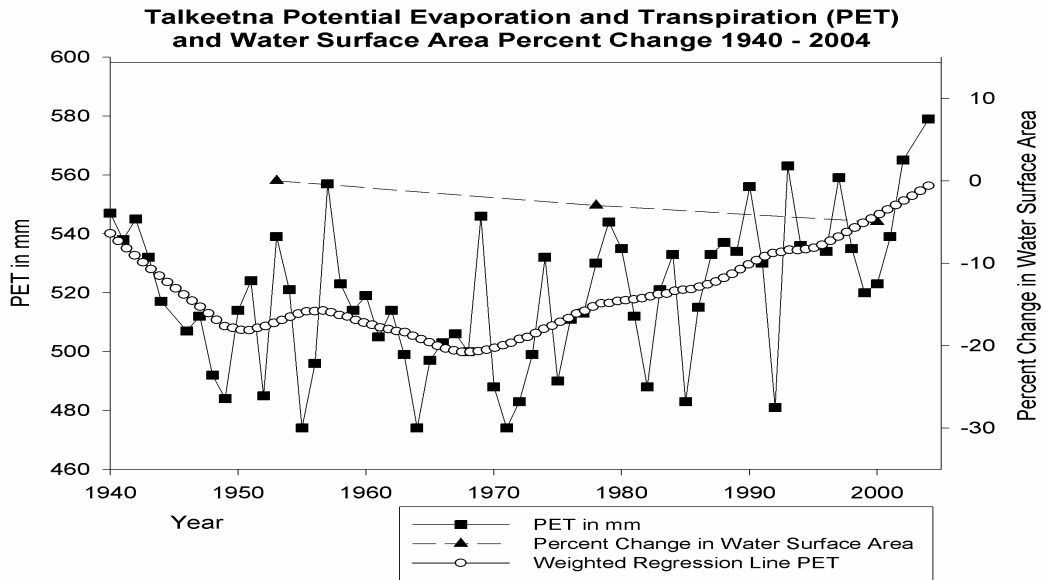


Figure 6.30 Talkeetna PET and surface water area results.

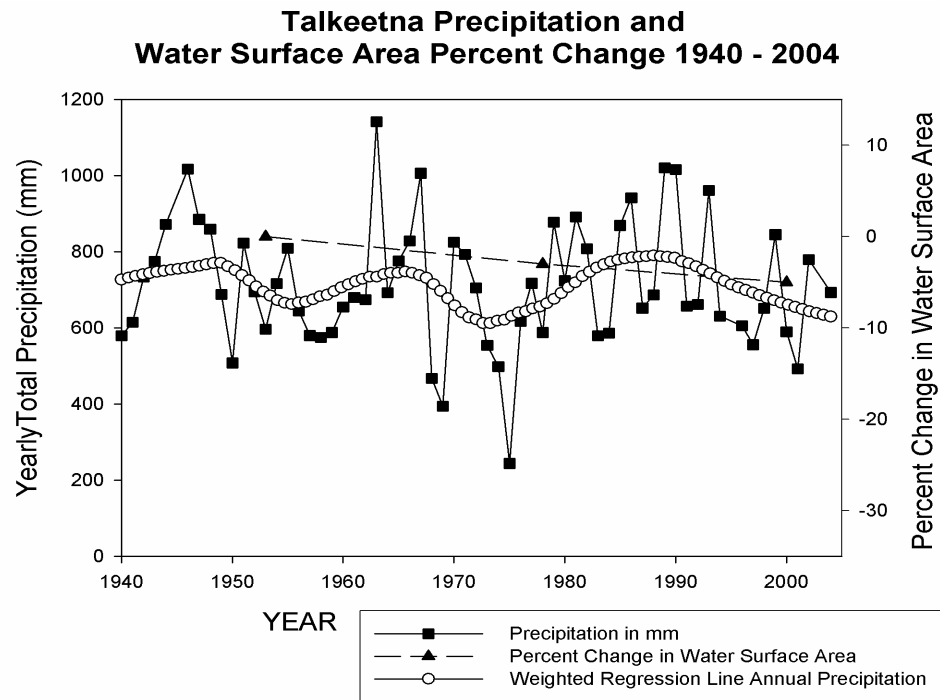


Figure 6.31 Talkeetna precipitation and surface water area results.

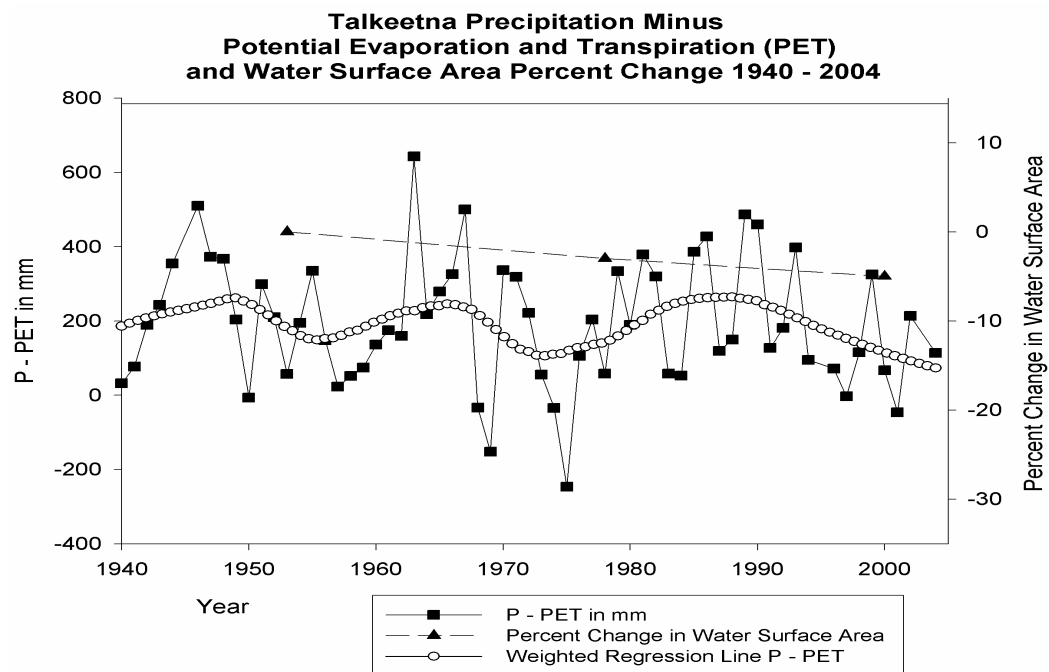


Figure 6.32 Talkeetna P - PET and surface water area results.

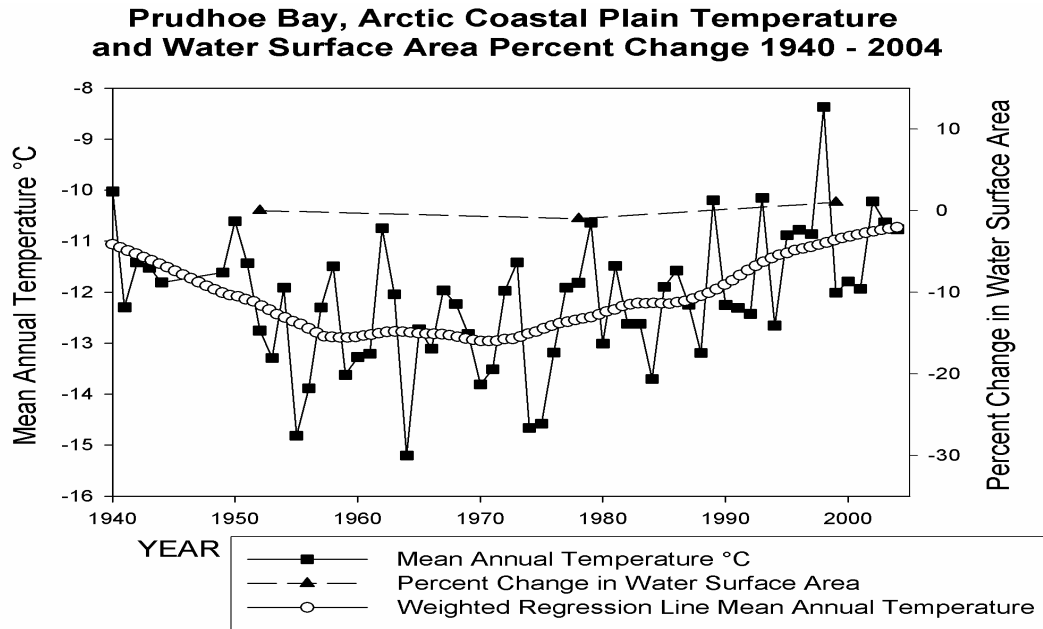


Figure 6.33 Prudhoe Bay, Arctic Coastal Plain temperature and surface water area results.

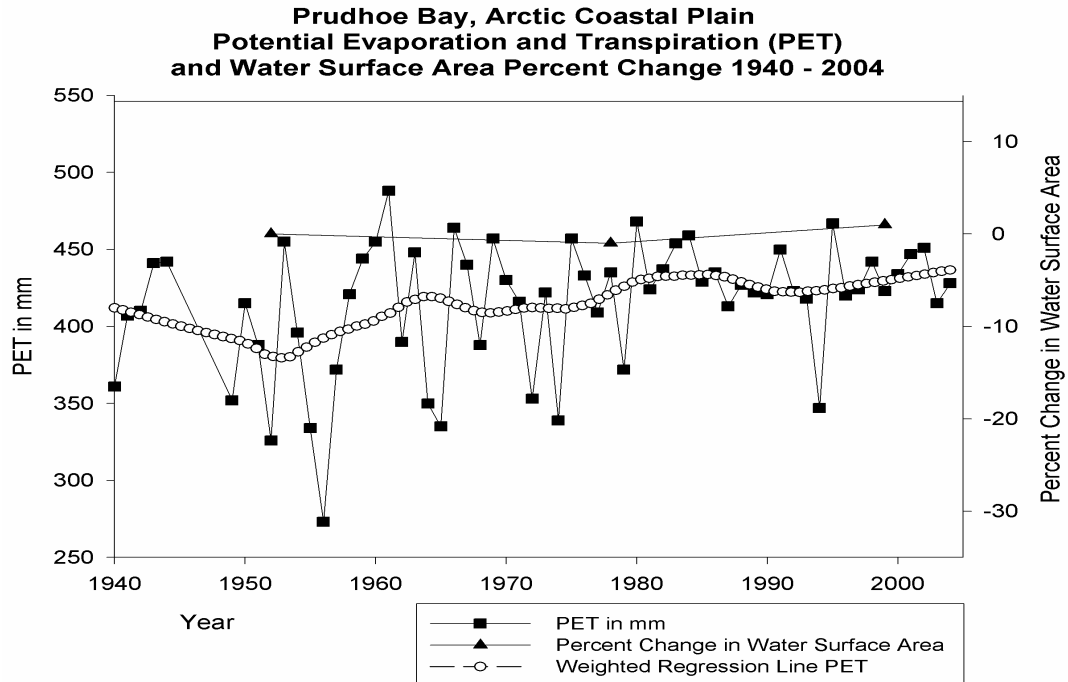


Figure 6.34 Prudhoe Bay, Arctic Coastal Plain PET and surface water area results.

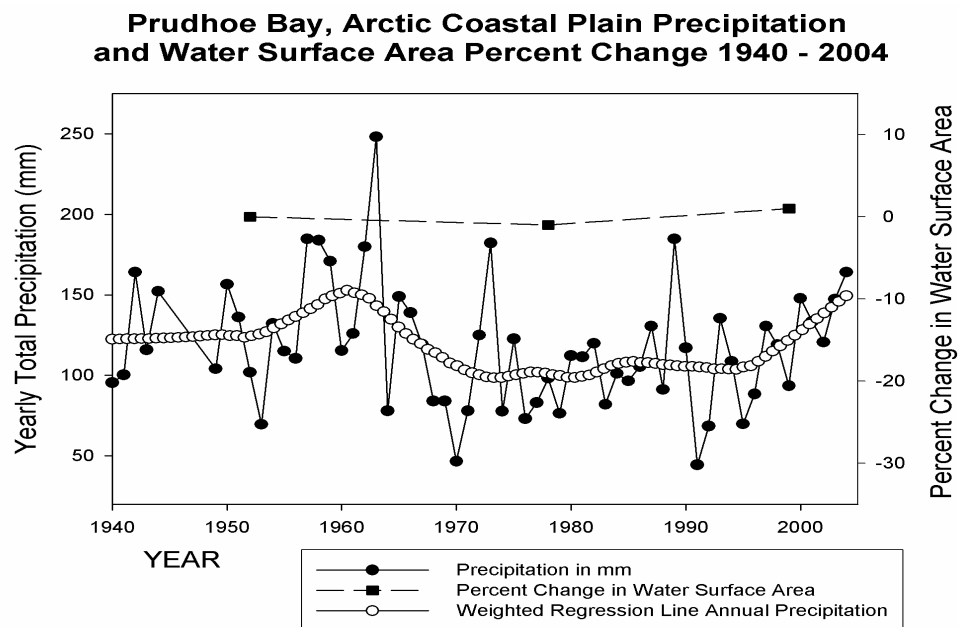


Figure 6.35 Prudhoe Bay, Arctic Coastal Plain precipitation and surface water area results.

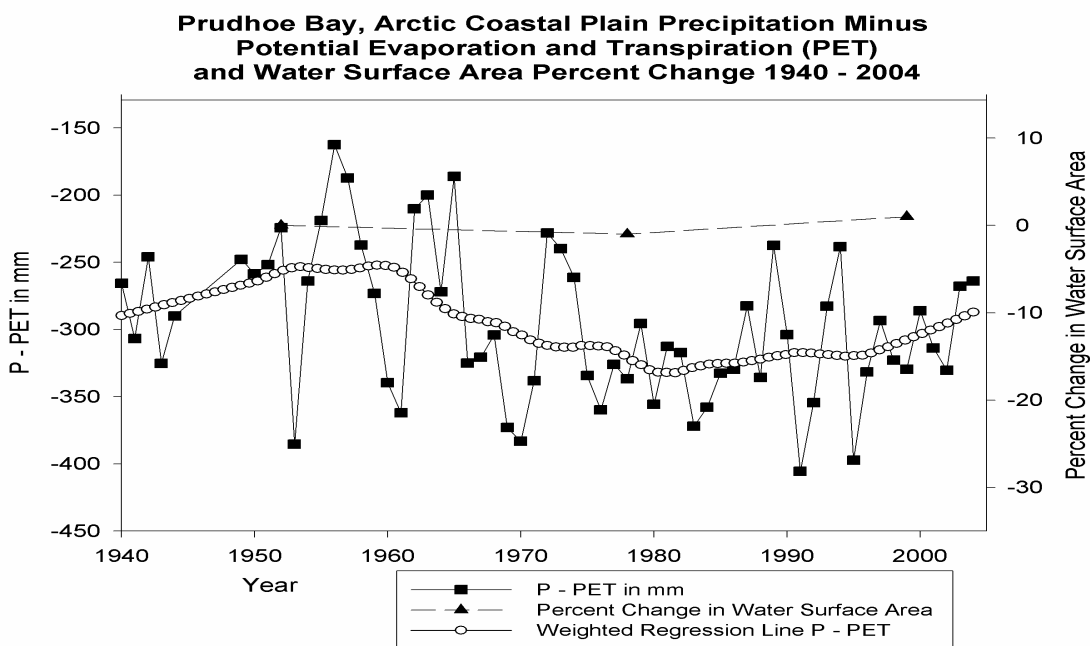


Figure 6.36 Prudhoe Bay, Arctic Coastal Plain P - PET and surface water area results.