AN ABSTRACT OF THE THESIS OF

Everett E. Spellman for the Master of Science in Physical Science Presented on April 30, 1993.

Title: Environmental Study of Devils Lake, North Dakota, using Landsat Multispectral Imagery.

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Landsat multispectral scanner (MSS) imagery was used to document environmental changes that have occurred in Devils Lake from 1973-1991. Devils Lake, a terminal lake located in northeast North Dakota, has glacial origins and is of special interest because of its fluctuating water level. The fluctuations are largely climatically controlled. Within recent years the water-level has risen to its highest elevation since the late 1800's, threatening to flood the city of Devils Lake and the surrounding area. Local citizens are interested in identifying a way to stabilize the water level so as to eliminate future flood threats.

A technique to estimate the surface-area of Devils Lake was developed and applied. The surface-area estimation technique involves the creation of an

infrared/red ratio to separate land and water surfaces within the images. This step is followed by reclassification and grouping of the surface areas of detectable water bodies. Finally the surface area is estimated by counting the number of pixels. For Devils Lake, comparison of the estimation results shows a good correlation with historical water elevation records taken at the lake.

Other tasks undertaken were the detection of environmental changes within the lake and the surrounding area. Environmental changes observed include not only water-level fluctuations but also water quality changes in the bays of the lake. Strong winds were correlated with images illustrating the ability of the wind to stir into suspension the lake bottom sediments of shallow water areas. Standard as well as special image-enhancement techniques were used to note these changes. Standard false-color composite images were viewed chronologically to note changes on land as well.

ENVIRONMENTAL STUDY OF DEVILS LAKE, NORTH DAKOTA, USING LANDSAT MULTISPECTRAL IMAGERY

A Thesis

Presented to

the Physical Science Department

Emporia State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

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April 30, 1993

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ACKNOWLEDGEMENTS

Many individuals and organizations were involved in the completion of this work. My deepest appreciation and gratitude is extended to each for their important role.

I thank the North Dakota Geological Survey and the North Dakota State Department of Health and Consolidated Laboratories for financially supporting the study. Without their assistance, the study would not have been possible.

As a participant in the National Atmospheric and Space Administration's Joint Venture (NASA-JOVE) program, I wish to applaud NASA's efforts to include universities in their research.

I would like to express my deepest gratitude to each of my committee members. To Dr. James Aber, I extend great thanks for serving as my advisor and committee chair. His continual insight and assistance have been an invaluable resource. Thanks is also extended to Dr. David Schroeder and Dr. Loren Tompkins for their time and cooperation.

I would like to recognize Scott Randolph for his role of downloading the Landsat computer-compatible tapes. In connection, thanks goes to the Emporia State University Data Center for the use of the mainframe computer.

Thanks also goes to the helpful, friendly, and hardworking members of the Interlibrary Loan Department at William Allen White Library.

Finally, I wish to thank my loving wife and caring family for their continual encouragement and support.

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CHAPTER 1

INTRODUCTION TO STUDY

Devils Lake Setting

Devils Lake, a large natural lake located in northeastern North Dakota, is of special interest because of its fluctuating water level. The Devils Lake drainage basin lies within the Red River of the North drainage basin (Fig. 1). The basin is unusual in that it is a terminal drainage basin; it has no outlet. In prehistoric times the water level ranged from the spillway elevation of about 442 m (1,453 feet) above sea level (asl) to periods of complete dryness. Historical records show that the lake has risen from a low of 427.0 m (1,400.9 feet) asl in 1940 (Wiche 1986) to the century high of 435.5 m (1,428.8 feet) asl in 1987 (Harkness et al. 1987).

Local citizens were especially concerned as the water level rose in the early 1980's to an elevation which threatened to flood the city of Devils Lake, a national guard camp, roads, fields, lagoons, and local sewage treatment plants (Wiche 1984). In 1987, the lake stood at an elevation of 435.5 m (1,428.8 feet) asl. Above 436 m (1,430 feet), substantial damage to developed areas could occur (Ludden et al. 1983). Although the water level of Devils Lake has since receded, the concern of future flood threats has not. Citizens are interested in developing a

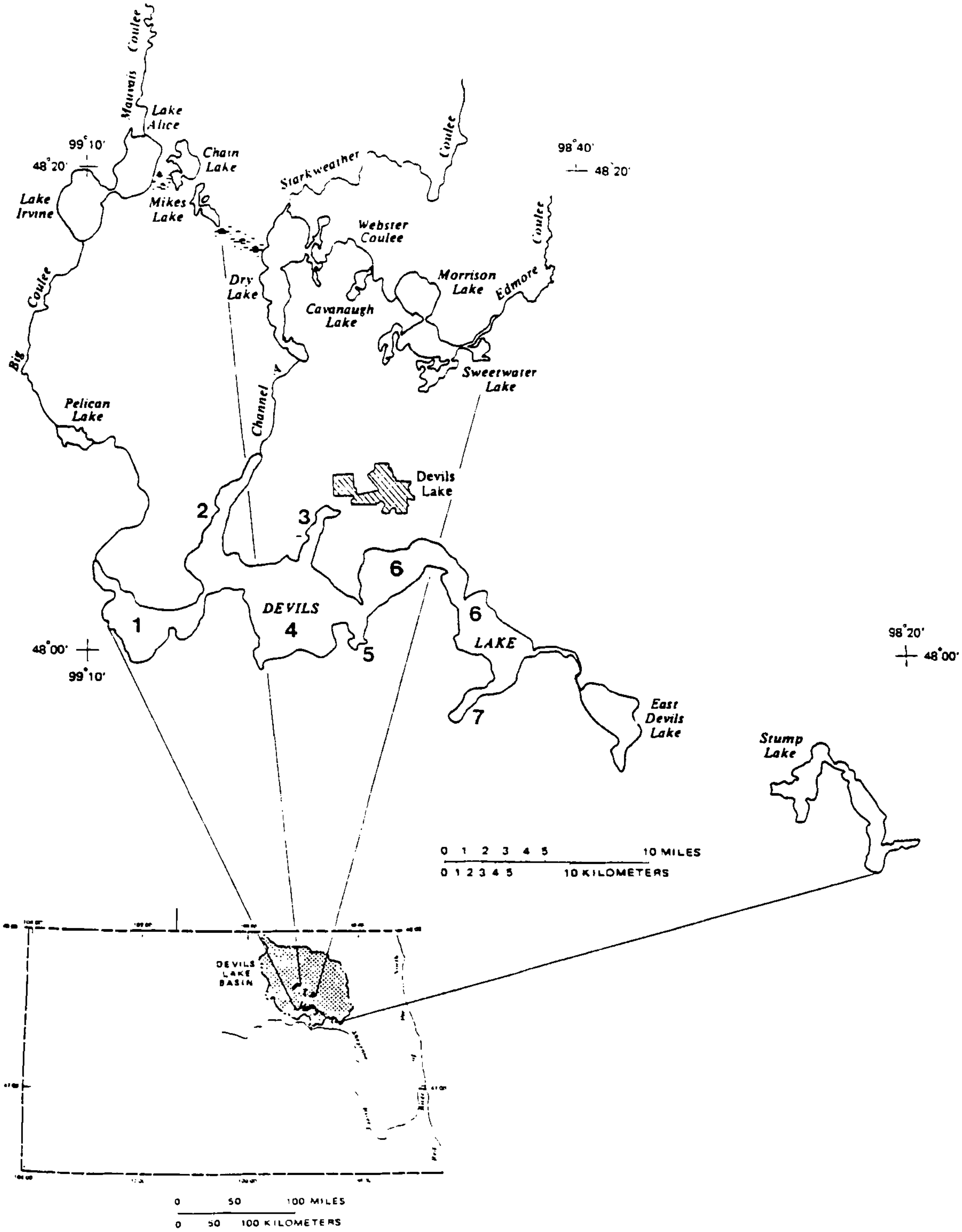


Figure 1. The location of the Devils Lake drainage basin and its associated Chain of Lakes. The bays of Devils Lake are: (1) West Bay, (2) Six Mile Bay, (3) Creel Bay, (4) Main Bay, (5) Mission Bay, (6) East Bay, and (7) Black Tiger Bay (modified from Ryan and Wiche 1988).

basin-wide water management plan so as to stabilize the lake's water elevation and prevent future flood threats.

Other problems, which need to be addressed by the new water resource management plan, include poor drainage resulting in farmland flooding, controversial wetland drainage, improvement in the water quality in Devils Lake, control of nitrogen- and phosphorus-rich agricultural runoff, control of soil erosion, and legal rights to the dry lakebeds within the basin. The implementation of such a plan will not only help provide solutions to these current problems, but will also help restore Devils Lake's reputation as a premier fishing and recreational facility. In addition, because the lake is a major regional fishing and recreational facility, improving the water quality could have important economic implications on the Devils Lake community.

Purpose

To successfully apply and maintain a water management program, a complete understanding of the past lake conditions must be attained. Many studies have been conducted in the past by conventional means. These investigations include lake sediment studies, hydrological studies, water quality studies, biological studies and landuse/landcover studies. The focus of this investigation is on the use of Landsat multispectral scanner (MSS) satellite data to document the surface-area changes and water-level fluctuations of Devils Lake from 1972, the year the first Landsat satellite was launched, to 1991. Additionally, changes in the environmental conditions within the Devils Lake region were monitored.

Early History of the Devils Lake Region

Devils Lake received its name from the translation of the Indian name "Mini-wakan," which in English means "the Enchanted Water" (Jackson and Spence 1970). Later, "Mini-wakan" was changed by white man to the current name of "Devils Lake." The earliest survey of the Devils Lake area was completed by Fremont in 1839. He was part of an expedition team that had the responsibility of surveying the lake. They recorded a water surface elevation of 449.9 m (1,476 feet) asl. They described the lake as "a beautiful sheet of water" with an irregular shoreline and commented on its brackish waters. They also noted the lack of an outlet and correctly placed it within the Red River of the North drainage basin. Like Fremont, Upham (1895) also conducted a survey of the area under the direction of the United States Army. From this time on, the lake was to be the focus of much interest.

The first pioneers to the Devils Lake area were most likely French and British fur traders (Babcock 1952). Between 1817 and 1827, Duncan Graham established a trading post on the portion of land that is now called Graham's Island. Fort Totten, established on July 17, 1867, was the first permanent white settlement. The fort served to protect future settlers of the area, to protect the overland route from southern Minnesota to western Montana, and to monitor Indian activity (Babcock 1952).

The construction of what is now known as the Great Northern Railroad brought the first large influx of settlers in 1882-83 (Babcock 1952). These settlers established many small communities within the Devils Lake area. The most prominent of these settlements was Creelsburgh, named after its surveyor, Herber M. Creel. It was established near what is now called Creel Bay and in 1883 was renamed Devils Lake.

Today the city of Devils Lake is the largest city in the Devils Lake drainage basin and has a population of nearly 7,800. It serves as the county seat of Ramsey County. The major industries of the surrounding Devils Lake area are agriculture and recreation. Some of the major crops that are grown in the area are spring and durum wheat, sunflowers, barley, flax, and hay. Major recreational activities include summer and winter (ice) fishing, hunting and camping. Naturally, Devils Lake continues to play a central role in the lives of the local residents.

Previous Works

Because Devils Lake is the only major water body in the region, it became the center of attraction which drew many settlers to the area. As a result, the lake has also been the focus of many scientific studies. Early studies include regional surveys conducted by Fremont in 1839 and Upham in 1895, and general geological surveys by Willard (1907) and Horton et al. (1910). Swenson and Colby (1955) studied the water quality of the lake from November 1948 to December 1952. Mitten et al. (1968) continued the water quality work of Swenson and Colby for the period of 1952 to 1960. They described in detail some of the factors affecting the chemical quality of the surface-waters in Devils Lake and its basin. Many biological quality studies have also been conducted. These include studies by Young (1924), Anderson (1969), Shubert (1976), and Verch and Blinn (1972). Young (1924) discussed the studies that were conducted at the Devils Lake biological station from 1911 to 1923. Anderson (1969) conducted a study on the factors affecting the phytoplankton development and photosynthetic potential in Devils Lake from June 1965 to August 1968 while Shubert (1976) studied the factors affecting the algal growth potential in 1974 to 1975. Likewise, Verch and Blinn (1972) studied the seasonal variations in algae concentrations of the lake.

More recently, studies have been conducted not only on Devils Lake but on the drainage basin as well. Many of these studies were developed to protect the natural and economic productivity of the basin. One such study was that of the Devils Lake Advisory Committee. In their 1976 report, they cited "sheet flooding" as a major problem within the basin. This condition is caused by poor drainage patterns and results in the destruction of many crops. In addition, they also produced landuse/landcover estimations of the Devils Lake basin and developed recommendations for basin-wide monitoring policies.

* * *

CHAPTER 2

DEVILS LAKE DRAINAGE BASIN

Physiography and Drainage

The Devils Lake drainage basin, which covers a surface area of 9,868 sq km (3,810 sq miles), is divided into nine sub-basins and one smaller terminal drainage basin, the Stump Lake drainage basin (Wiche 1986). The individual sub-basins are the Edmore Coulee sub-basin, the Starkweather Coulee sub-basin, the Calio Coulee sub-basin, the Mauvais Coulee sub-basin, the Little Coulee sub-basin, the Comstock sub-basin, the Devils Lake (North slope) sub-basin, and the Devils Lake (South slope) sub-basin (Fig. 2). These sub-basins drain into Devils Lake except parts of the Edmore Coulee, Starkweather Coulee, Mauvalis Coulee, Little Coulee, and the Stump Lake drainage basin; these drain into either East Devils Lake or Stump Lake. Therefore, the total basin area that drains into Devils Lake is potentially about 8,599 sq km (3,320 sq miles) (Wiche 1986).

The surface topography of the Devils Lake drainage basin was formed during the late Wisconsin glaciation, approximately 20,000 to 11,000 radiocarbon years before present (Fenton et al. 1983), and has since experienced little postglacial surface modification. It slopes gently inward toward Devils Lake which is situated along the southern border. Due to this gently sloping topography,

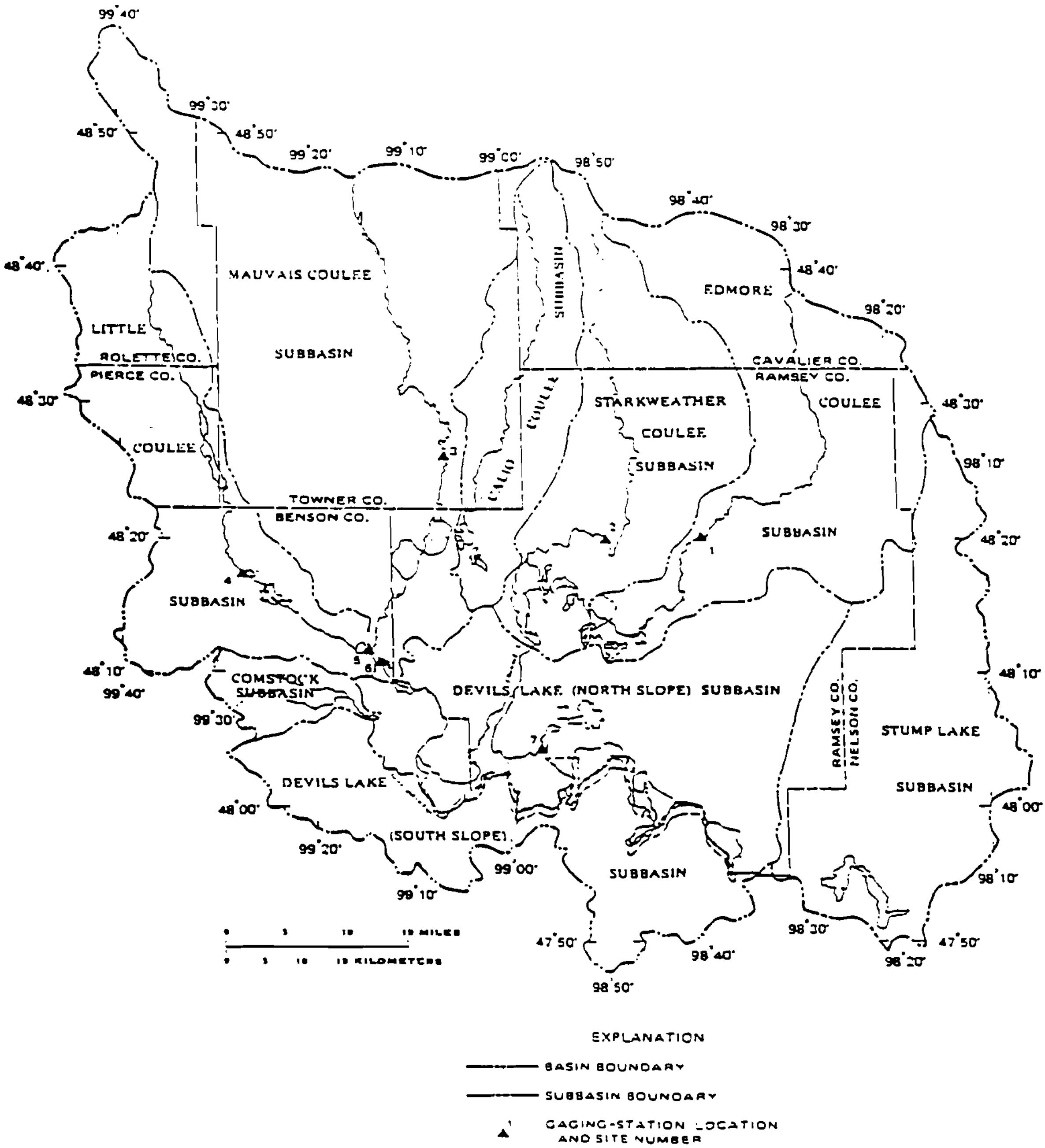


Figure 2. Individual sub-basins within the Devils Lake drainage basin (Wiche 1986).

the northern, eastern, and western boundaries of the basin are poorly defined. Only the southern boundary, which consists of a series of ice-thrust hills, is well defined.

Landforms within the drainage basin range from a generally flat topography, to shallow depressions and potholes, to large basins and large ice-thrust hills. The shallow depression and pothole areas were formed as glacial debris slid off the sides of large stagnant melting blocks of ice. The rock and soil debris piled up leaving rings of sediment that later filled with water forming vast wetlands. The hilly ice-thrust region, which forms the southern boundary, is identified by the presence of enormous blocks of displaced bedrock. These hills were formed by the plucking action of two advancing ice-lobes, one from the north, the other from the northeast. As the two ice-lobes converged, they pulled or pushed entire blocks of bedrock from beneath the glacier and piled them a short distance to the south and east (Aber et al. 1993). Such conditions often create large basins located directly to the north of the ice-thrust structures. Such glaciotectonic landforms have been termed a "hill-hole pair" (Aber et al. 1989).

Because the slope of the landscape is minimal beyond the ice-pushed hills, few well-developed drainage channels have formed within the Devils Lake basin. As a result, the northern portion of the drainage basin flows into a series of basins referred to as "the Devils Lake chain of lakes"

(Fig. 1). These lakes are connected by a poorly defined "C-shaped" drainage channel. Prior to 1979 this chain of lakes began at Sweetwater Lake located to the north of the city of Devils Lake. From there the overflow discharge ran consecutively into Morrison Lake, Cavanaugh Lake, Dry Lake, Chain Lake, Lake Alice, Lake Irvine, and then into Big Coulee. Big Coulee completed the chain by flowing through Pelican Lake and finally into the West Bay of Devils Lake. After 1979 the natural flow was interrupted by the construction of channel "A". This channel was built from Dry Lake to Six Mile Bay of Devils Lake to shorten the flow path.

Provided that the water level was to reach its late Wisconsin elevation of 442.9 m (1,453 feet) asl, the discharge from Devils Lake would continue by flowing into East Devils Lake, Stump Lake, and eventually into the Sheyenne River. Although this poorly defined drainage system does exist, water in the system rarely has the opportunity to flow due to the fact that the lakes are below their thresholds most of the time.

Geological Setting

Quaternary History:

Devils Lake is located within the glaciated plains of the Central Lowland Province (Fig. 3). In most of the drainage basin, Quaternary sediments are directly underlain by shale of the Cretaceous Pierre Formation and shale and

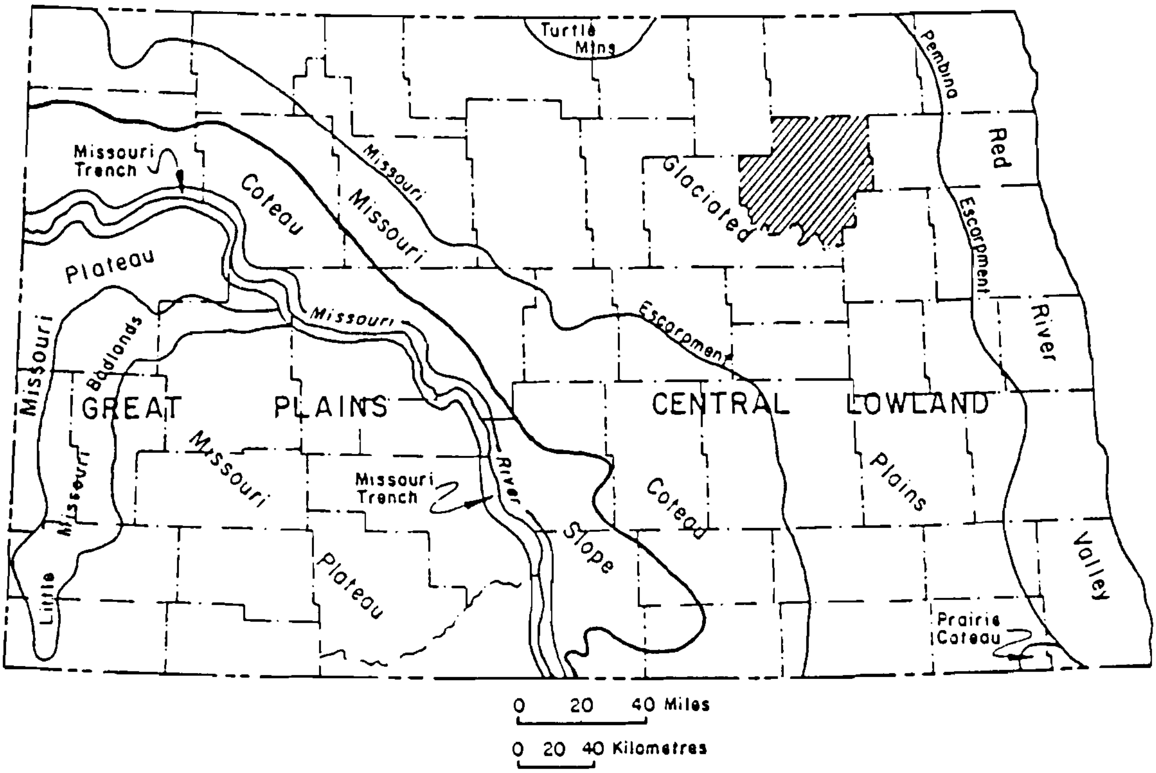


Figure 3. Location of Ramsey County including Devils Lake within the Glaciated Plains of North Dakota (taken from Hobbs and Bluemle 1987).

sandstone of the Fox Hills Formation (Devils Lake Basin Advisory Committee, 1976). Tertiary sediments are lacking in the basin due to uplift and erosion which took place in eastern North Dakota prior to the deposition of Quaternary sediments. During the Late Tertiary, most of western and central North Dakota, including the Devils Lake area, was drained by the Cannonball River which flowed northward (Fig. 4). At this time, the landscape of the region was formed predominately by shale of the Pierre Formation.

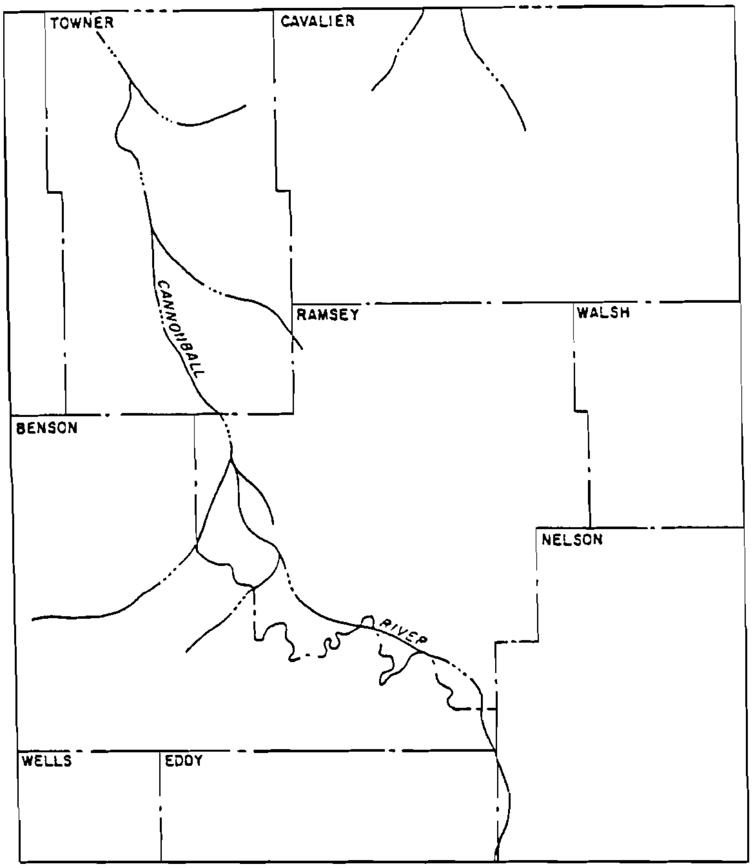


Figure 4. The flow of the preglacial Cannonball River through the Devils Lake area. Devils Lake is located on the southern boundary of Ramsey County (taken from Hobbs and Bluemle 1987).

During the Quaternary, the climate alternated between cold and warm events resulting in periods of glaciation separated by interglacial periods. As glaciers advanced into the area, they overrode the weathered Pierre Shale landscape. As a result, the surface is covered extensively with glacial till that is composed mainly of Pierre shale. Because each till layer was eroded to various degrees during interglacial periods, each is made up of varying amounts of shale; the older till layers contain more shale than do the younger ones (Hobbs and Bluemle 1987).

As the lobes of the ice sheet advanced into the region, the northward flowing Cannonball River was blocked creating a large proglacial lake. As the water of the lake rose, it overflowed creating the Starkweather Diversion Trench (Fig. 5). During later glaciations, this trench was filled with sediment and now forms the present day Starkweather Aquifer. During the late Wisconsin, glaciers again advanced into the Devils Lake region, this time forming the large Devils Lake basins and the associated

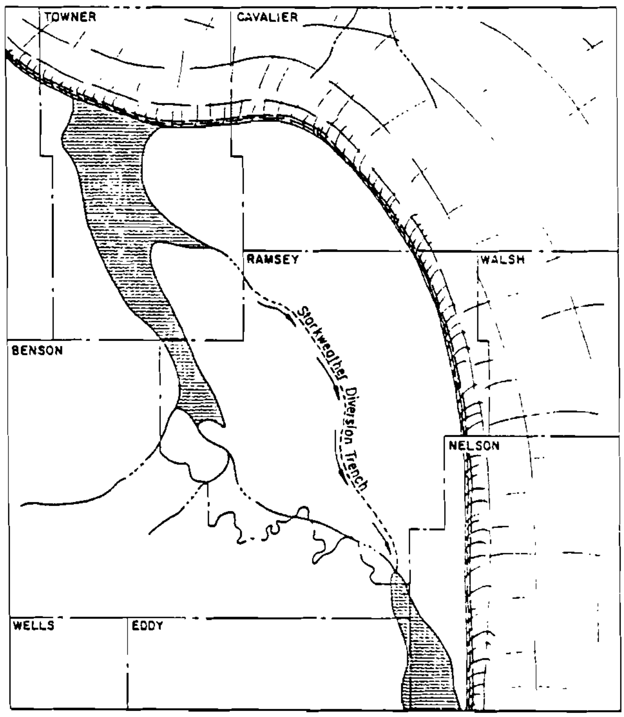


Figure 5. Advancing glaciers blocked the northward flowing Cannonball River creating a large proglacial lake. Overflow from the lake created the Starkweather Diversion Trench (adapted from Hobbs and Bluemle 1987).

ice-thrust hills to the south. The basins, which Devils Lake partially occupies, cover an area of about 1,300 km^2 (500 sq miles). The hills to the south cover an area of about 780 km^2 (300 sq miles). The relief from the bottom of the basin to the top of the hills is in excess of 200 m (650 feet) (Hobbs and Bluemle 1987).

After Devils Lake and the associated ice-shoved hills were formed, the glaciers receded and glacial Lake Minnewaukan formed along the margin of the ice (Fig. 6). The elevation of the lake stabilized at 443 m (1,453 feet) asl, which was the spillway elevation of the Big Stony spillway. This spillway is located on the southern shores of West Stump Lake and at one time carried meltwater from glacial Lake Minnewaukan to the Sheyenne River. Other temporary glacial spillway channels were cut at times when the lake level rose above 443 m (1,453 feet) asl. One of these channels was Big Coulee (also known as Seven Mile Coulee) southeast of Fort Totten. This coulee carried water away from what is now the southwestern corner of Main Bay of Devils Lake.

As the glacier continued to recede, Lake Minnewaukan grew toward the north and maintained an elevation of about 443 m (1,453 feet) asl. Eventually, the ice-water contact ceased allowing a second lake, Lake Cando, to form along the ice margin ahead of Lake Minnewaukan. Lake Cando stabilized at an elevation above that of Lake Minnewaukan and therefore overflowed into Lake Minnewaukan.

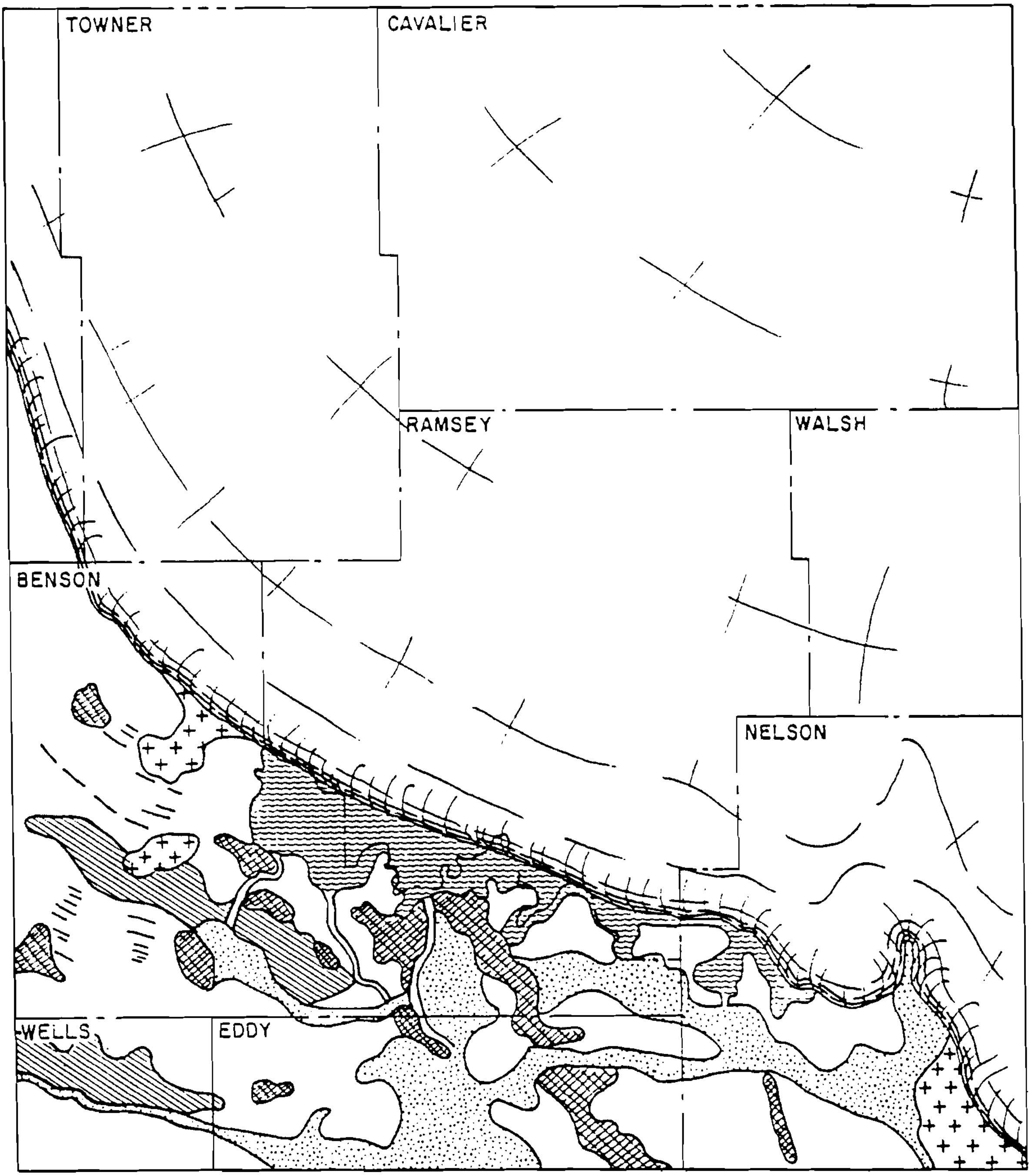


Figure 6. Glacial Lake Minnewaukan which formed as the late Wisconsin glaciers retreated. The patterns in the diagram are as follows: wavy lines = Lake Minnewaukan, cross-hatched = ice-thrust region, stippled = outwash plains, cross pattern = stagnant blocks of ice, unmarked = till plains, and diagonal lines = undefined (taken from Hobbs and Bluemle 1987).

Aquifers:

Several aquifers have formed as a result of past glacial events. These aquifers are developed in either buried preglacial valleys that were filled with glacial drift or in glacial outwash plains that formed below large spillway channels. The most prominent of the glacial drift aquifers is the Spiritwood aquifer. It follows the ancient Cannonball River channel and is overlain by Devils Lake and several other lakes in the "Chain-of-Lakes." Another important aquifer, the Warwick aquifer, is located about 30 km (20 miles) southeast of the city of Devils Lake. It was formed by the meltwaters that flowed out of East Devils Lake through the Warwick spillway channel. It covers an area of about 130 km^2 (50 sq miles) and is composed of glacial outwash sediment. This aquifer has an abundant supply of high-quality groundwater and is used as the municipal water supply for the city of Devils Lake as well as for irrigation. These aquifers are believed to have only minimal, if any, inflow into Devils Lake (Wiche 1988).

Other aquifers in the Devils Lake region are composed of local bedrock. The bedrock aquifers in the Devils Lake region are the Dakota aquifer and the Pierre aquifer. The Dakota aquifer is made up of a Cretaceous sandstone and underlies the entire Devils Lake basin. The top of this aquifer is at depths greater than 300 m (1,000 feet) below the surface and is believed to have no interaction with Devils Lake. The Pierre aquifer is located within the fractures of the upper 15 to 60 m (50 to 200 feet) of the Cretaceous Pierre Shale.

Climate

North Dakota is located in the geographical center of North America. As a result, it is influenced by three main air masses: air streams from the Gulf of Mexico, the Pacific Ocean and the continental north. These three air masses interact in various ways providing North Dakota with its relatively dry climate. Aside from this fact, the other major climatological factor that affects the water level of Devils Lake is the lack of physical barriers to control the wind (Joraanstad and Dando 1977). This is most noticeable during the summer months when large volumes of water, up to 75 cm (30 inches) per year (Ludden et al. 1983), are evaporated from the lake surface by the prevailing northwesterly winds.

According to U.S. Climatological Data, the mean annual precipitation at the Devils Lake KDLR first-order weather station for the years of 1948 to 1991 is about 43 cm (17 inches). Most precipitation falls between the months of May and September, with the heaviest rainfalls occurring in June (Fig. 7). Temperature extremes range from a high of 39^{o}C (103^{o}F) to a low of -38^{o}C (-37^{o}F). The mean monthly maximum temperatures show January as the coldest month, and July as the warmest (Fig. 7). As a result, the average annual evaporation of the region is much greater than the average annual precipitation. Runoff in the spring is predominately from the melting of the winter snows which plays an important role in the lake's water elevation.

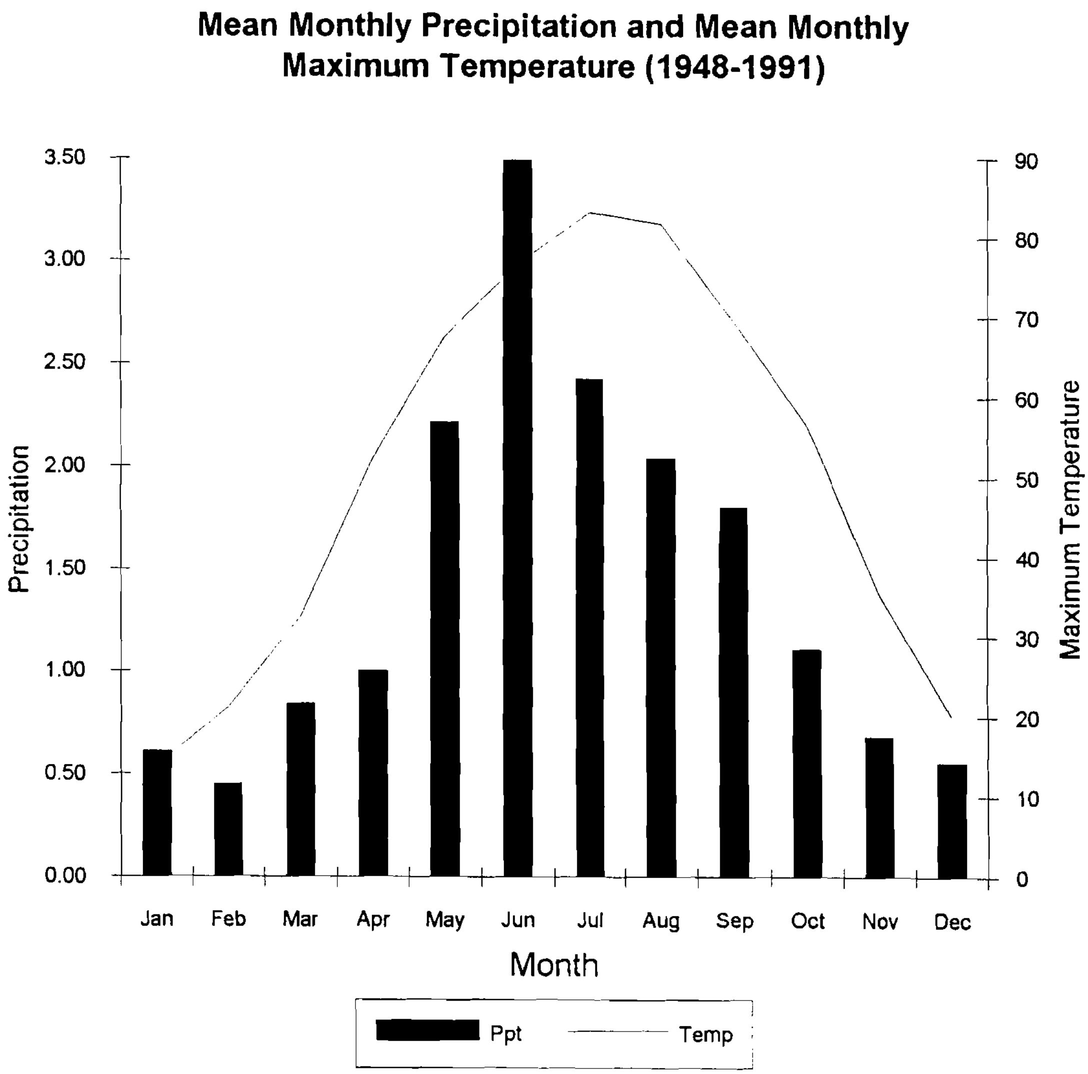


Figure 7. Graph showing mean monthly precipitation and mean monthly maximum temperature for the Devils Lake vicinity. Precipitation is reported in inches and temperature is reported in degrees Fahrenheit. The graph is based upon data recorded by the first order KDLR weather station in the city of Devils Lake from 1948 to 1991.

CHAPTER 3

HYDROLOGY OF DEVILS LAKE DRAINAGE BASIN

Description of Devils Lake

Devils Lake occupies the lowest elevations of the Devils Lake drainage basin and is located south of the city of Devils Lake. It forms a portion of the boundary between Ramsey and Benson Counties in the southern part of the Devils Lake basin. The lake is of irregular shape and consists not only of Main Bay but also, West Bay, Six Mile Bay, Creel Bay, East Bay, Black Tiger Bay, and Mission Bay (Fig. 1).

The hydrologic budget of the lake is unique. Like other terminal lakes, the water level is strongly affected by climatic conditions (Wiche 1986). The runoff and precipitation that enter the lake are offset by the demand of evaporation. Unlike other terminal lakes, the chain of lakes upstream of Devils Lake acts as a storage basin which reduces the amount of runoff entering the lake. Therefore, only during a series of exceptionally wet years is runoff able to enter Devils Lake.

Hydrology of Devils Lake

Prehistoric Water-Level Fluctuations:

Devils Lake fluctuated greatly in elevation throughout prehistoric times. The maximum elevation, which occurred during the melting of the Pleistocene glaciers, was at 443 m (1,453 feet) asl as determined by the elevation of the Big Stony spillway located near Stump Lake and the city of Tolna (Aronow 1957). When the lake ceased to flow through the spillway into the Sheyenne River, the closed drainage basin of Devils Lake came into existence. Since this time, the lake level has declined with intermittent fluctuations and on occasion has completely dried up.

The intermittent water-level fluctuations have been documented by using indirect evidence. Upham (1895) noted various abandoned strand lines around Devils and Stump Lakes which indicated a much higher lake level. Later, Aronow (1957) also cited these strand lines as evidence of a higher lake elevation. Two lines in particular, the highest at 443 m (1,453 feet) asl and the next lower 440 m (1,445 feet) asl, are especially well developed and correspond to major spillway threshold elevations. The 1,453-foot strand line encircled both Devils and Stump lakes and correlates with the Big Stony spillway that connected Devils-Stump Lake to the Sheyenne River valley. Both the strand line and the spillway were developed in late glacial time when meltwater flowed continuously into the lake on its way to the Sheyenne River.

The lower 1,445-foot stand line surrounds only Devils Lake. It was developed by a water elevation that was maintained by the threshold of the Jerusalem outlet. The Jerusalem outlet, though most often dry, was the outlet from Devils Lake to Stump Lake during wet years. In addition to the observation of the strand lines, Aronow (1957) also cited buried soil and vertebrate remains found in lacustrine sand and gravel deposits and rooted tree stumps from Stump Lake (hence the name) as evidence for past lake fluctuations.

The fluctuating water levels were also documented by the analysis of sediment core samples that were taken from the lakebed. The samples were analyzed for their physical, chemical, and mineralogical properties by Callender (1968), who concluded that the lake had fluctuated greatly in the past and on more than one occasion was completely dry. He constructed a lake level chronology (Fig. 8), and his findings were analogous to those of Aronow (1957).

Historic Water-Level Fluctuations:

The earliest recorded elevation of 450 m (1,476 feet) asl was taken by Fremont in 1839. In comparison, Upham (1895) estimated that the lake stood at an elevation of 439 m (1,441 feet) asl in 1830. He based this estimation upon tree-ring chronology. The tree selected was the largest tree that stood below 1,441 feet asl. Above this elevation stood a large dense stand of trees, while below it were only scattered trees and brush. From 1839 to 1867 no water level observations were recorded, while from 1867 to 1901 only sporadic lake elevations were recorded. Finally, in 1901 the U.S. Geological Survey established a gage at Devils Lake.

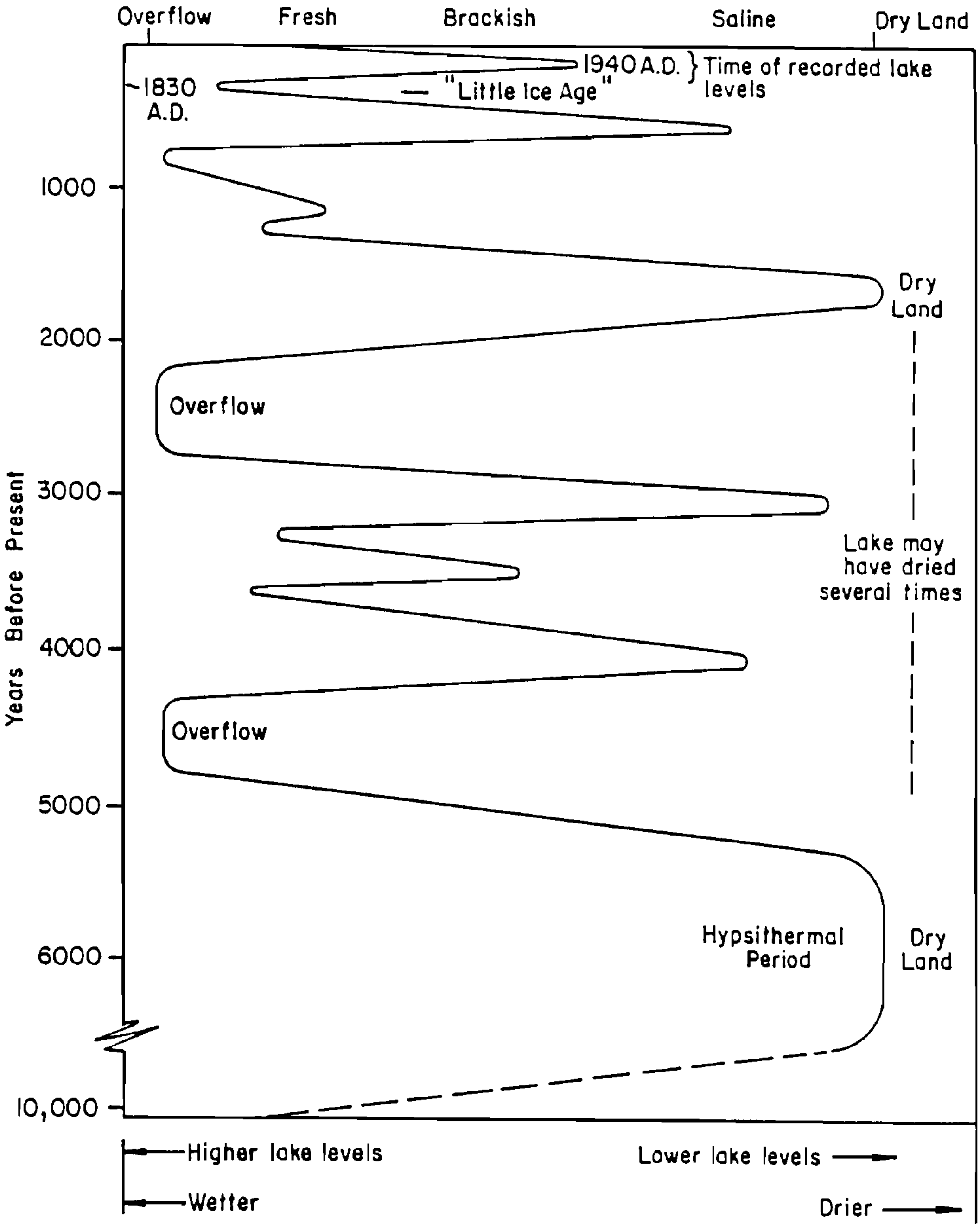


Figure 8. Prehistoric water elevation fluctuations of Devils Lake as reported by Callander. Adapted from Hobbs and Bluemle (1987).

According to established records, the maximum lake elevation occurred in 1867 when the lake was 438 m (1,438 feet) asl. From 1867, the lake level declined until 1940 when it reached its lowest elevation of 427 m (1,400 feet) asl. The water level rose from 1940 to 1956 and declined from 1956 to 1968. From 1968 it rose again in an irregular fashion until it reached its recent maximum elevation of 435.5 m (1,428.8 feet) asl in 1987 (Harkness et al. 1987). During this time, the lake fluctuated at elevations great enough to pose a flood threat to the surrounding region (Wiche 1986). The historic water fluctuations of Devils Lake is shown in Figure 9. More recent water elevations of Devils Lake are shown in Figure 10.

Causes of Water Fluctuations:

The water level decline that took place in Devils Lake from 1867 to 1940 was, at one time, believed to have been caused by the breaking of the "impermeable" sod as ever-growing numbers of settlers within the drainage basin began farming. In theory, the "booming" cultivation practices increased the infiltration that took place in the drainage basin, thereby decreasing the volume of runoff entering the lake. As a result, the lake level declined due to evaporation (Horton et al. 1910). This theory was disproved when in the 1940's the lake level began to rise. Today, the argument most widely accepted is that the lake elevation fluctuates as a result of climatic conditions.

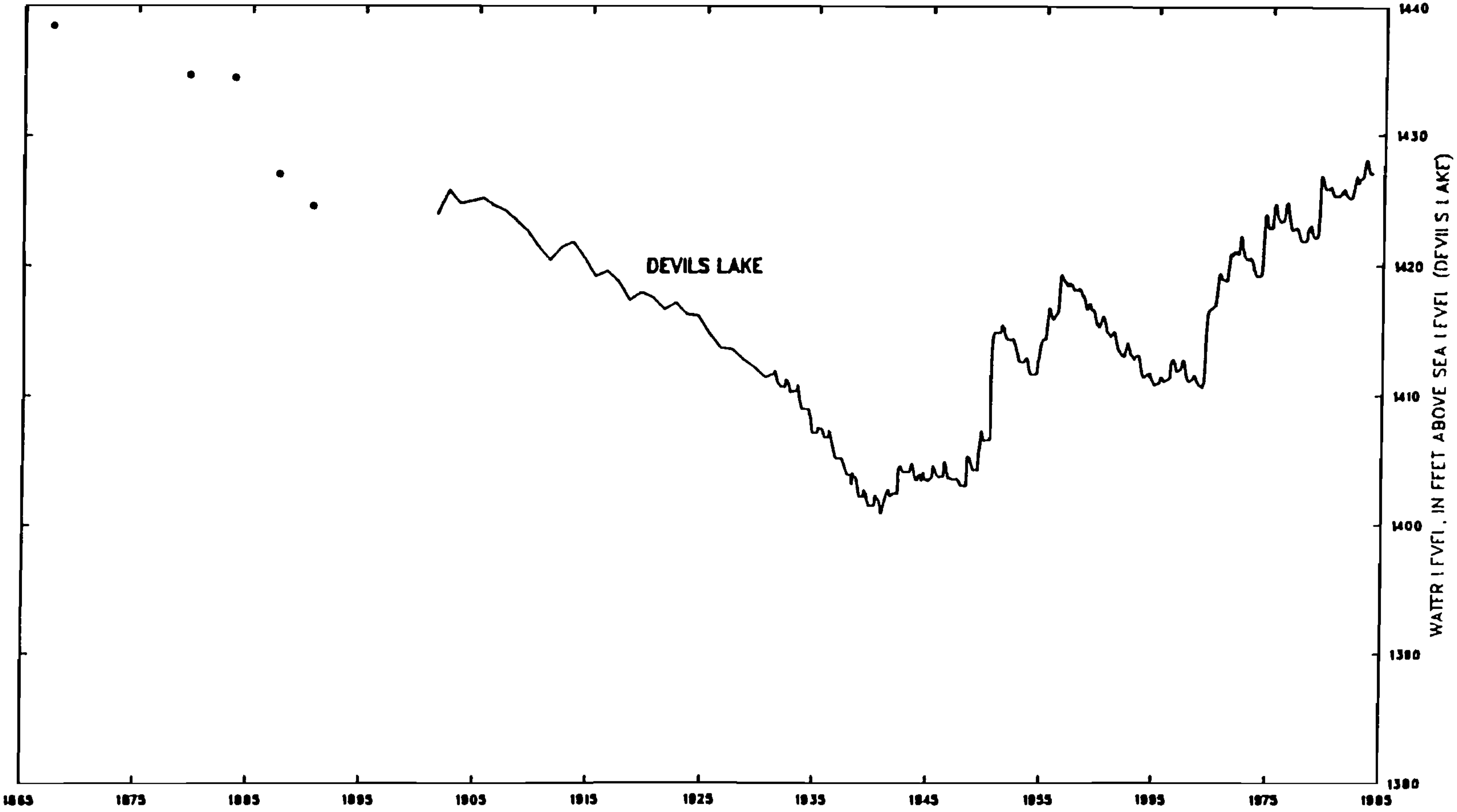


Figure 9. Historic water elevation fluctuations of Devils Lake. —— = recorded water levels, and • = infrequent water level measurements of Devils Lake (modified from Wiche 1986).

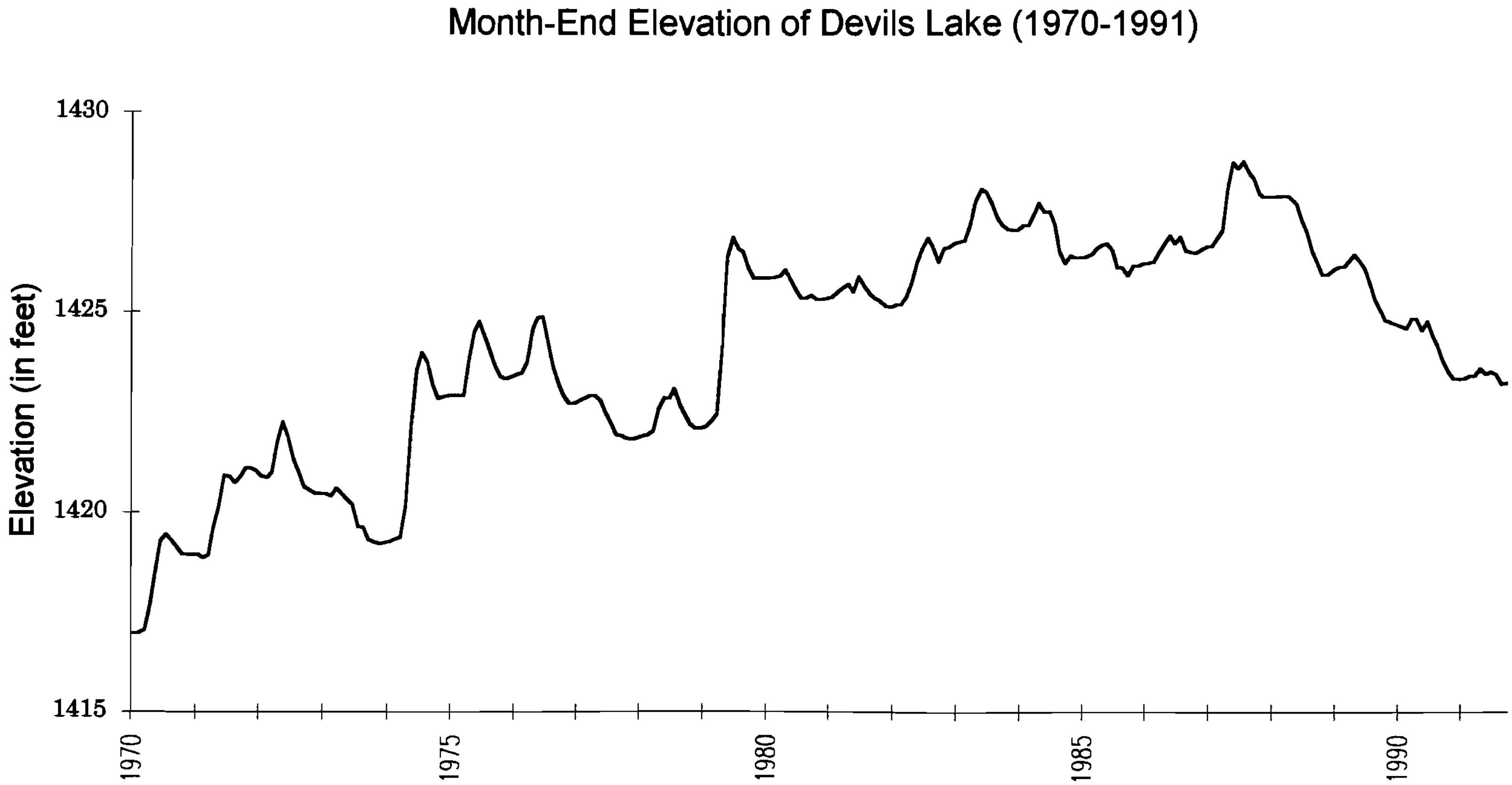


Figure 10. Water elevation fluctuations that have occurred in Devils Lake from 1970 to 1991. Based on Harkness et al. (1991).

Support for the climatically controlled explanation of the lake's fluctuating water level is strong. As Callender (1968) stated, "the lake has fluctuated considerably during the past 6000 years in response to shifting climatic and hydrologic conditions" (p. xxii). He also noted that major fluctuations of prehistoric water elevations correspond to major events in the Earth's climate. He stated, for example, that "significantly higher lake levels occurred around 4300, 3500, 2300, 1250, 1000, 750, and 250 years ago" and that "most of these dates coincide with periods of cooler, wetter climate in the Northern Hemisphere" (p. 258). Likewise, he stated that "significantly lower lake levels occurred around 6000, 4000, 3000, and 500 years ago which coincide with periods of warmer, drier climate in the Northern Hemisphere" (p. 258). In addition, recorded history also shows that periods of wet and dry climate correspond with rises and declines in the water level of Devils Lake.

Although the water level of Devils Lake correlates with general climatic variations, an additional factor that controls the water level of the lake is the physiography of the drainage basin. Because Devils Lake is near the end of the chain of lakes and at the southern edge of the drainage basin, the amount of runoff that enters Devils Lake is dependent upon the spillway elevation and the storage capacity of the lakes upstream (Wiche et al. 1986) as well as on the storage capacity of the depressions within the basin (Ludden et al. 1983). These upstream lakes and depressions behave as storage basins during dry years that reduce the volume of water entering Devils Lake. As Ludden et al. (1983) found, the storage capacity of the many small depressions alone can "store about 72 percent of the total runoff volume from a 2-year-frequency runoff" (p. 45). Therefore, the fluctuating water level of Devils Lake is caused by climatic variables, but is further modified by the physical characteristics of the basin.

Hydrological Simulation Studies

In order to develop a water management plan for the Devils Lake drainage basin, it is not only important to understand the causes of the lake level fluctuations, but also to be able to predict future lake levels. Several attempts at lake level simulation have been made by Wiche (1986), Wiche et al. (1986), and Ryan and Wiche (1988). Using hydrometerological data, runoff data, and lake basin data, these investigators developed an equation for modeling the past water elevations of the lake. Once the past events were accurately modeled, estimates of future climatic and lake data were used to simulate future lake water elevations.

Water Quality

Chemical/Physical Quality:

Due to the lack of an outlet, Devils Lake is saline, alkaline, shallow, and is often hypereutrophic in nature. In the past, for example, large thick algal mats have developed on the lake's surface (Shubert 1976). These algal mats have proven to be a serious problem for the economy of the Devils Lake community, because periods of maximum algal growth (late summer) often bring sport fishing to a near halt.

The salinity of the lake has fluctuated drastically. An inverse relationship exists between the salt concentration and the lake's water elevation; a decrease in the water level results in an increase in salinity, and an increase in water level causes the salinity to decrease. For example, when the lake was high in the early 1800's the salt concentration of Devils Lake was about 1,000 ppm (De Groot 1982). When the lake was at its lowest recorded elevation of 427 m (1,400.9 feet) asl in 1940, the salt concentration was about 25,000 ppm (compared to 32,000 ppm for sea water). Since this time, the salt concentration has been diluted by rising water levels to a concentration of 2,000 to 3,000 ppm.

Salt concentrations also vary with respect to the time of year. During winter, ice often forms on the surface of the lake causing the salinity of the water beneath to increase. Thus, low water levels, in combination with thick ice cover, often produce the highest salinity. This situation can have adverse effects on the ice-fishing industry as high salinity causes fish activity to decrease.

According to Komor (1992), the major ions in Main Bay of Devils Lake are sulfate, chloride, bicarbonate, sodium, magnesium, and calcium. Mitten et al. (1968) reported that sodium and sulfate ions are the predominant dissolved solids. Other salts are less soluble and form a solid that precipitates to the bottom of the lake. The runoff entering the lake has a high concentration of nitrogen and phosphorus which is derived from fertilizers applied to nearby fields (Peterka 1979). In addition, within recent years, large fish caught in Devils Lake have reportedly contained high concentrations of methylmercury (Jondahl 1992). The source of this mercury contamination has not been identified with certainty, though atmospheric deposition is currently believed to be the cause.

Biological Quality:

Although the water of Devils Lake is saline, it supports an abundance of life. Nitrogen and phosphorus nutrients occur in high concentrations (3 mg/l and 0.3 mg/l respectively) in the runoff from specific sub-basins of the Devils Lake basin (Peterka 1979). This nutrient rich runoff entering the lake stimulates algal growth and results in the conditions responsible for the lake's hypereutrophic classification. Also, due to the high concentrations of nutrients, Devils Lake has a high rate of phytoplankton primary productivity (Anderson 1969).

Often in late summer and early fall, the lake experiences large "blooms" of algae, which collect oxygen and float to the surface of the lake. When the large mats of algae die, the decaying biomass places a high demand for oxygen upon the surrounding area. In turn, the oxygen concentration in the water decreases and, in extreme cases, can result in fish kills within the immediate area. Although such an event has occurred during periods of low water elevations, it becomes less likely as the volume of water increases. This is due to the fact that a greater volume of water is capable of dissolving a larger volume of oxygen and is therefore able to meet the oxygen demand of the decaying algae (De Groot 1982).

* * *

CHAPTER 4

SATELLITE REMOTE SENSING

Introduction to Remote Sensing

Remote sensing is the process of detecting the nature or conditions of something without actually touching it. The simplest example is that of photography. A camera has the ability to gather information about an object or ground area and store it in the form of a latent image. Later, when the film is developed, the nature of the object can be studied and important observations made. Likewise, the multispectral scanner (MSS) onboard the Landsat series of satellites has the ability to gather information about the Earth from which a visual image can be created and observations made.

Remote sensing has had a profound impact on our understanding of the Earth. In the past, scientists had the ability to study only what they could directly observe with their unaided eye. The invention of the microscope, provided an important window through which the newly discovered microscopic world could be explored. Similarly, the detectors used in remote sensing now allow scientists to view, from a distance, large-scale features of the Earth's surface. This new macroscopic view, has reformed the previous independent-local-region impression of the Earth to a more holistic appreciation.

Remotely sensed data have given scientists the ability to study environmental elements (geology, weather patterns, vegetation, landuse, regional variations, etc.) of the Earth as a complete, delicate, and interconnected global system, and have proven to be an invaluable source of information. Geologists, soil scientists, cartographers, landuse planners, ecologists, foresters, and the general public have used this information to complete maps, detect landuse changes, identify habitats, locate and monitor forest fires, observe natural events such as volcanic eruptions and to access the Earth's resources. In addition, remotely sensed data have been combined with other data bases by means of geographic information systems (GIS), thereby expanding the usefulness of remotely sensed data. Undoubtedly, this form of information gathering is a great asset to all of mankind.

Principles of Remote Sensing

Elements of Remote Sensing Systems:

All remote sensing systems consists of four main elements: a source of electromagnetic energy, a sensor that can detect the electromagnetic energy, a platform on which the sensor can be mounted, and a way to store, process, and interpret the detected energy. When designing a remote sensing system, various combination of these elements must be considered so as to obtain desirable information. For example, the sensor can be a simple camera held by hand at ground level, or installed onboard an airplane. Another possibility is a mechanical scanner onboard an airplane or a satellite. In the case of Landsat, the platform is the satellite, the sensor is the MSS, and the detected electromagnetic energy is solar energy reflected from the Earth's surface. Finally, the means of processing, storing and interpreting the data is completed by scientists with the aid of computers.

Advantages of Satellite Remote Sensing:

Designed as an Earth Resource Observation Satellite (EROS) program, the Landsat series of satellites offer many advantages compared to conventional ground observation methods. These advantages, based on Short (1982), are as follows:

- *Synoptic view*: As the satellite orbits 900 km (560 miles) above the Earth's surface, it acquires images of large contiguous regions. These regions are much larger than could be observed on the ground and even by air. This "big picture" of the Earth allows large regional features to be recognized and studied.
- *Multispectral data*: The MSS onboard the Landsat satellites series detects reflected solar radiation in four spectral bands. Because two of these bands lay beyond the range of the human eye, information that is otherwise "invisible" can be observed. Thus,

multispectral detection greatly increases the information about an object within a scene.

- *Repetitive coverage*: Landsat satellites have been placed in a near-polar orbit. This allows the satellites to pass over and acquire information about the same land area many times each year. This information facilitates the documentation of yearly changes.
- *Low-cost data*: Once in orbit, satellites can continuously acquire enormous volumes of comprehensive information in a very short span of time. In contrast, conventional information gathering methods are labor intensive, and operate for a limited time period. Thus, satellite data can be used to provide a rapid and inexpensive means of information acquisition, especially in a first-look situation.

Electromagnetic Energy:

Electromagnetic (solar) energy in the remote sensing process has the important role of transmitting the information from an object on the Earth's surface to the sensor. Electromagnetic energy travels at a constant speed in the form of waves. Waves have traditionally been classified according to their wavelength, which is the distance between two successive wave crests. The entire range of wavelengths constitute the electromagnetic spectrum (Fig. 11). Visible light has wavelengths that

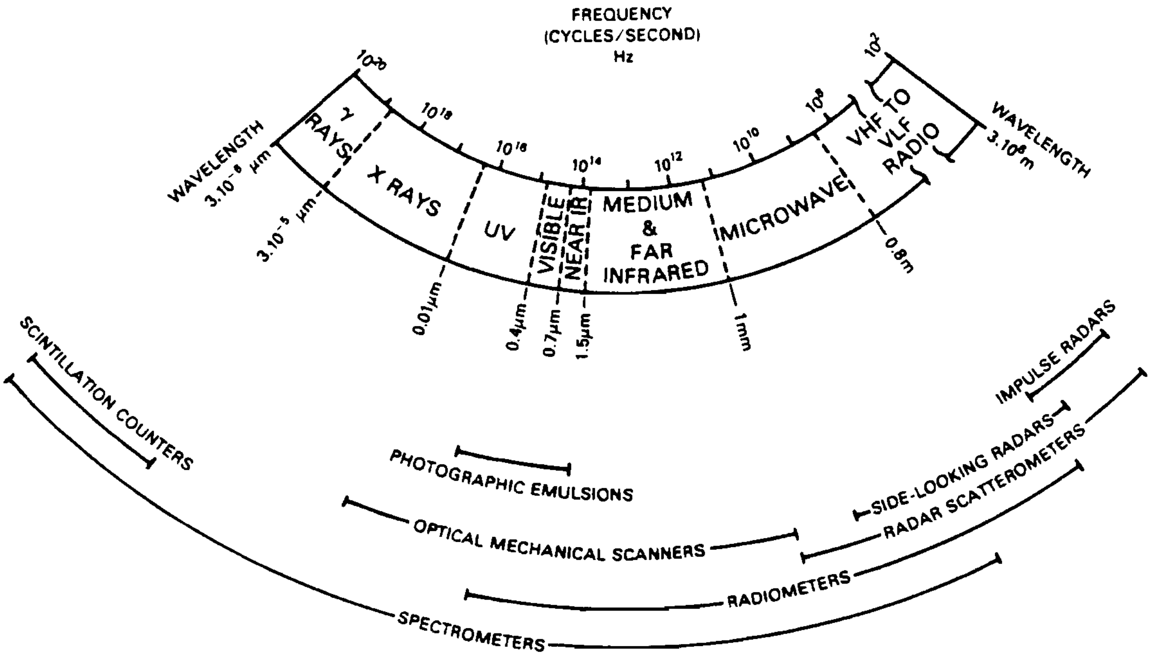


Figure 11. - The electromagnetic spectrum and the operational ranges of various instruments. Taken from Hall and Martinec (1985).

range from 0.4-0.7 micrometers or microns. Other classes of electromagnetic energy, listed by increasing wavelengths, are cosmic rays, gamma rays, x-rays, ultraviolet (UV), near-infrared (IR), mid-infrared, thermal-infrared, microwaves and television, and radio waves.

As Figure 11 shows, visible light falls between UV and near-IR light. Visible light can be further divided into the bands of the additive primary colors of blue (0.4-0.5 microns), green (0.5-0.6 microns) and red (0.6-0.7 microns). Although the electromagnetic spectrum has been divided into these wavelength classes, only four carefully selected bands of reflected solar energy are detected by the multispectral scanner onboard the Landsat series of satellites. They are the green and red visible light bands as well as two near-infrared bands (0.7-0.8 and 0.8-1.1 microns).

Electromagnetic energy incident on objects at the Earth's surface is absorbed, reflected, or transmitted in portions that depend upon the physical composition of the object, and on the wavelength and angle of the incident radiation. A smooth, uniform, surface that reflects most of the incident radiation in one direction is called a spectral reflector, while a diffuse reflector is a rough surface that reflects the incident radiation in all directions. Diffuse reflectors are most important in remote sensing because incoming radiation interacts with and is altered by these objects. Therefore, reflected radiation from diffuse reflectors contains information about the particular surface it has interacted with. As the satellite passes overhead, a portion of the reflected energy is received by the MSS instrument. This information is then measured and converted to a digital number and transmitted to receiving stations on the Earth.

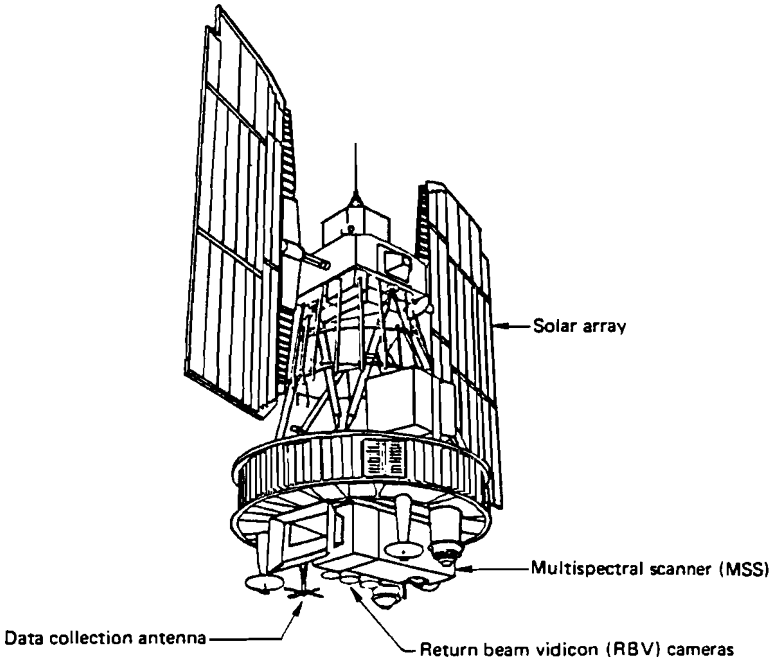
History of the Landsat Satellite Program

The Landsat program (originally called ERTS for Earth Resources Technology Satellite) originated in 1966, when the Department of the Interior announced plans to construct a satellite for observing the Earth and its resources.

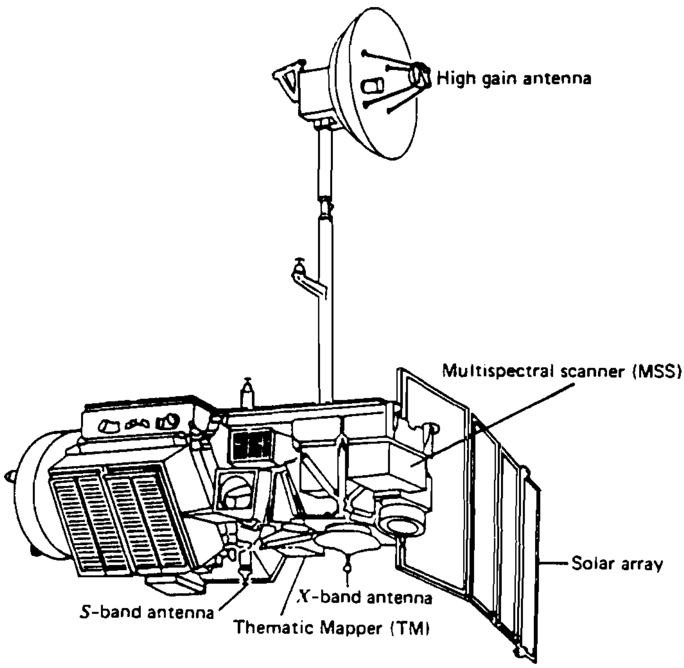
After much debate, private companies and U.S. governmental agencies, under the direction of the National Aeronautics and Space Administration (NASA), began designing and constructing the first of a series of satellites. On July 23, 1972, the first satellite, Landsat 1 (also known as ERTS-1), was launched.

The Landsat program was operated by NASA until 1979 as a high-tech experiment. On November 10, 1979, President Carter no longer considered the program experimental and transferred Landsat to the Department of Commerce's National Oceanic and Atmospheric Administration (NOAA). In addition, President Carter also initiated plans to privatize Landsat. In 1984, President Reagan authorized the privatization of the Landsat program and on September 27, 1985, Earth Observation Satellite Company (EOSAT), a private firm, was granted the operating rights to Landsat.

To date, five Landsat satellites have been launched (Fig. 12). Their launch dates and deactivation dates, if applicable, are shown in Table 1. Landsat-4 and -5 are currently being used to acquire multispectral scanner data. With the occurrence of major power failures shortly after launch, Landsat 4 was placed on "reduced mission mode" in 1983 and is now used only for the collection of MSS data. Landsat-5, on the other hand, is currently being used to collect routine data. The next Landsat satellite, Landsat-6, is scheduled for launch sometime in late 1993.



(a) Landsat-1, -2 and -3 configuration.



(b) Landsat-4 and -5 configuration.

Figure 12. Satellites of the Landsat series. Landsat-1, -2, and -3 were similar in construction as were Landsat-4 and -5 (from Short 1982; Lillesand and Kiefer 1987).

Satellite	Launch	Deactivation	MSS Bands	Orbit
Landsat-1	7/23/72	1/06/78	4 5 6 7	18 day/900 km
Landsat-2	1/22/75	2/25/82	4 5 6 7	18 day/900 km
Landsat-3	3/05/82	3/31/83	4 5 6 7 8	18 day/900 km
Landsat-4	7/16/82	---	1 2 3 4	16 day/705 km
Landsat-5	3/01/84	---	1 2 3 4	16 day/705 km
Landsat-6	mid-sum '93	---	1 2 3 4	16 day/705 km

Table 1. Orbital characteristics of the Landsat series of satellites (based on Lillesand and Kiefer 1987).

Landsat Satellite Orbit Characteristics

The orbital characteristics of the Landsat-1, -2, and -3 were different from those of Landsat-4 and -5. Landsat-1, -2 and -3 were placed in near-polar orbits, passing within 8 degrees of the North and South Poles, at an altitude of 900 km (560 miles). Each satellite orbited the Earth 14 times per day and repeated its coverage in 18 days (252 orbits). The orbits are also sun-synchronous. This means that each satellite passes over all places on the earth with the same latitude at approximately the same local sun time. In comparison, Landsat-4 and -5 are also in near-polar (inclined at 98.2 degrees) and sun-synchronous orbits, but at a lower altitude, 705 km (438 miles). This lower orbit results in a global coverage time of 16 days (233 orbits). The orbits of Landsat-4 and -5 are shown in Figure 13.

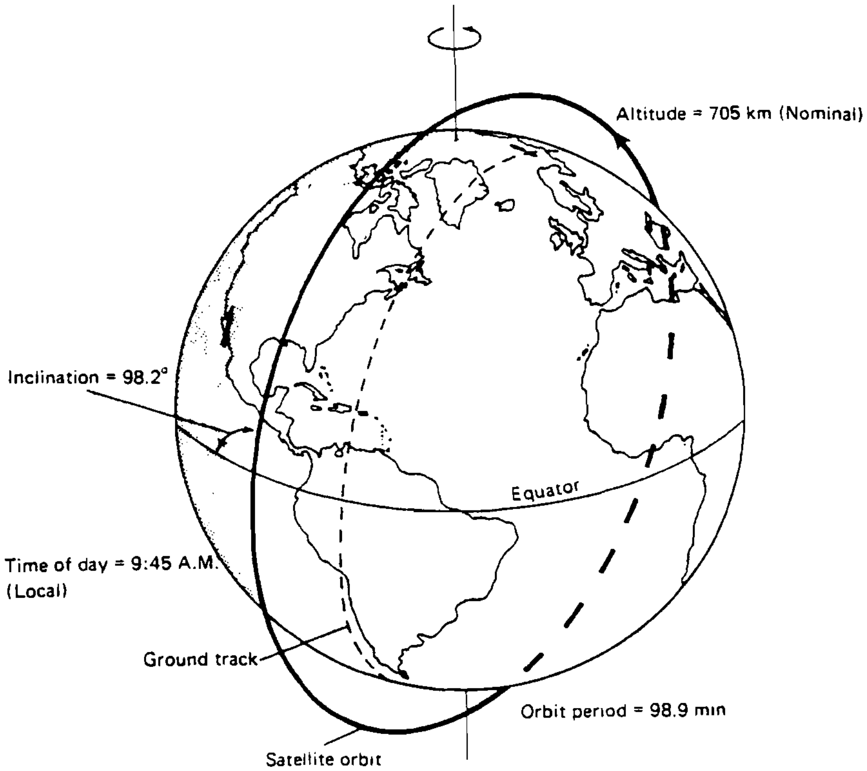


Figure 13. Satellite orbits of Landsat-4, and -5. The orbits of Landsat-1, -2, and -3 are similar. Taken from Lillesand and Kiefer (1987).

Characteristics of the Landsat Mss Scanner

The multispectral scanner (MSS) was mounted onboard all Landsat satellites. Though each was an individual unit they were very comparable in their design. The MSS collects electromagnetic energy in four bands indicated in Table 2. Note that bands 1, 2, 3, and 4 of Landsat-4 and -5 correspond to bands 4, 5, 6, and 7 of Landsat-1, -2, and -3. Respectively, these bands are the green, red, and two near-infrared portions of the electromagnetic spectrum. This numbering convention is due to the fact that the MSS

Landsat -4, -5	Landsat -1, -2, -3	"Color"	Wavelength
1	2	Green	.5-.6
2	4	Red	.6-.7
3	5	Near-IR	.7-.8
4	7	Near-IR	.8-1.1
	8*	Thermal	10.4-12.6

* Landsat-3 only - failed shortly after launch.

Table 2. Characteristics of the MSS onboard the Landsat series of satellites. Adapted from Lillesand and Kiefer (1987).

on the first three Landsat satellites was the secondary sensor, but is the primary sensor onboard Landsat-4 and -5.

The MSS works by using an oscillating mirror that reflects the incoming light onto stationary detectors (Fig. 14). There are a total of 24 detectors, six for each band. This allows the MSS to detect six scan lines with each sweep of the mirror. As the mirror rotates back and forth, the detectors convert the energy into digital numbers. The angular field of view (AFOV) for MSS onboard Landsat-1, -2, and -3 was set at 11.58 degrees. This means that each sweep of the mirror was 185 km wide. Due to the lower orbiting altitude of Landsat-4 and -5, the AFOV of these two satellites was increased to 14.9 degrees to ensure a scanning width of 185 km. The ground resolution of the first three Landsat satellites was 79 x 79 meters. For

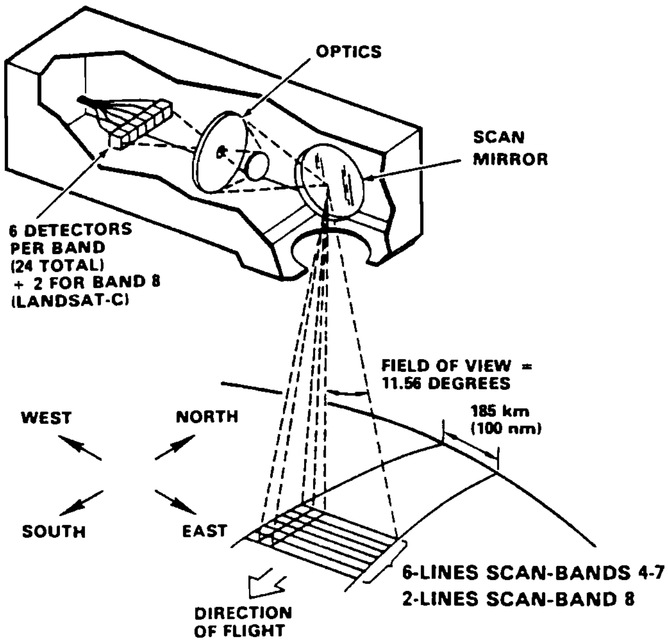


Figure 14. The multispectral scanner (MSS) operation and configuration. Taken from Short (1982).

Landsat-4 and -5, it was 82 x 82 meters. This corresponds to a processed pixel size of 57 x 79 meters for Landsat-1, -2, and, -3, and 56 x 56 meters for Landsat-4 and -5.

Characteristics of Landsat MSS Data

Because each MSS band represents a specific range of wavelengths of visible and infrared light, each band can be used to detect specific materials on the Earth's surface. Spectral response curves illustrating the percent reflectance of various common objects are shown in Figure 15. Each of the four bands and their characteristic applications are briefly described below.

- *Band 1* (green, 0.5 to 0.6 micrometers) - Light of this wavelength can penetrate clear water to greater depths than can other wavelengths of light. As a result, this band is most useful for detecting water features. One drawback of this band is that it is sensitive to atmospheric haze, resulting in poor image contrast.
- *Band 2* (red, 0.6 to 0.7 micrometers) - Light of this wavelength is absorbed by the chlorophyll found in green plants. Therefore, this band is useful for showing contrasts between vegetated and non-vegetated areas. Also, wavelengths of this band do not penetrate water as deeply as those of band 1. Thus, this band is effective for showing contrasts between clear water and sediment-laden waters.
- *Band 3* (near-infrared, 0.7-0.8 micrometers) - Light of this wavelength is useful for determining the amount of active vegetation, which strongly reflects short-IR energy. As water strongly absorbs near infrared radiation, this band is useful also for distinguishing between water and land surfaces. Another use is in the detection of differences in soil moisture; moist soils appear darker than drier soils. Atmospheric penetration with this band is very effective.
- *Band 4* (near-infrared, 0.8-1.1 micrometers) - This band is similar to band 3, because they both fall within the near-infrared range. However, this band is often preferred over band 3 for visual interpretations

reflect infrared energy. On the other hand, band 2 is absorbed by vegetation and weakly reflected by water. Dividing band 4 by band 2, results in a ratio image that has high values (greater than 1) for land and low (less than 1) values for water. This ratio image can then be reclassified into a boolean image that represents land and water surfaces.

Application of Landsat MSS Data to Hydrology

Landsat satellites were originally designed for agricultural applications; however, the spectral characteristics of the MSS data have proven useful in a great many other fields as well. In the field of hydrology, satellite data have been used to study a wide variety of water resource problems. Some of these applications include, snow field mapping, continental ice sheet monitoring, watershed flood assessment, locating and mapping of groundwater, irrigation inventories, and the evaluation of surface water quality (Anderson 1979; Rahn and Moore 1979; Short et al. 1976; Short 1982; Rundquist et al. 1989; Williams and Carter 1976). In many cases, satellite information is used not as a replacement of conventional hydrological techniques but as a tool for locating areas that warrant detailed study.

Many water bodies have been studied using Landsat MSS data. Harrington and Schiebe (1989) studied the water quality of Lake Chicot in Arkansas using Landsat MSS imagery. Lake Chicot is a narrow oxbow lake with a surface area of 17.2 km^2 (6.64 sq miles) and a width of 1.0 km (0.62 miles). A road constructed across the lake divided the lake into northern and southern portions. The northern part receives water from a very small drainage area, while the southern part receives sediment and chemical laden runoff from nearby cotton and soybean fields. Harrington and Schiebe documented the cleanup efforts of the lake and concluded that "frequent and synoptic coverage of remote sensing satellites permits the monitoring of temporal and geographic variations in lake and reservoir water quality" (p. 59).

Matson and Berg (1981) demonstrated that Landsat data could be used to detect wind produced seiches in Great Salt Lake, Utah. They showed that strong winds displaced the water level in the shallow, northern portion of the lake from its equilibrium position. Later when the winds ceased, the water oscillated from side to side until once again it reached equilibrium. These seiches produced sediment laden waters as the oscillating water stirred lake bottom sediments into suspension. The water in Landsat MSS images acquired during such episodes, appeared bright in comparison with the southern portion of the Great Salt Lake indicating highly turbid waters.

Another water body monitored by satellite is Lake Chad located in western Sahel. Lake Chad, like Devils Lake, is a terminal lake with a climatically dependent water elevation. In response to a major drought that began during the 1960's, the lake has decreased to less than one-tenth of its 1963 maximum surface area of 23,000 km^2 (8,885 sq miles) (Wald 1990). In his studies, Wald used Meteosat imagery, as well as published works that included images/photographs taken during the Gemini, Skylab, and Space Shuttle missions, to formulate a historical account of the water level decline. He found that surface area estimates by satellite data closely agreed with those obtained by conventional means.

The Aral Sea in the south-central part of the former Soviet Union has been declining for the past 32 years. With a surface area of 67,000 km^2 (25,880 sq miles) in 1960, the Aral Sea was the fourth largest inland body of water on Earth; today, it has a surface area of only 37,000 km^2 (14,290 sq miles) (Micklin 1993) and has dropped to sixth in its ranking (Landsat Data Users Notes 1990) . The water-level decline is due to unrestricted agricultural irrigation development within the terminal drainage basin. Landsat MSS data have been used to detect changes in the region and identify possible solutions to restore the Aral Sea (Landsat Data Users Notes 1990).

The advantages of using Landsat MSS data to study certain water bodies are well documented. The Qom, Shiraz and Neriz Playas of Iran, which are often inaccessible to field observations, are fine examples. Using MSS data, the surface area of these lakes have been estimated (Krinsley

1976a, 1976b). Three multidate MSS images of Utah Lake south of Salt Lake City, Utah, have been used to document lake processes that would otherwise proceed unnoticed. They show Utah Lake at times of clear water (summer), with huge algal mats floating on the water surface (fall), and with a high sediment content from meltwater runoff (spring) (Short et al. 1976; Strong 1976). Also, Best and Moore (1979) showed that changes in surface area of prairie lakes and wetlands in South Dakota could be monitored using Landsat MSS imagery.

Satellite hydrological studies that focus on the Devils Lake drainage basin have also been conducted. The Devils Lake Basin Advisory Committee (1976) used a Landsat MSS image dated September 23, 1974, to identify twelve landuse/landcover classes that were grouped into four categories. The classes they identified were deep water, shallow clear water, shallow water with emergent vegetation, saline water, small grains-unharvested, summer fallow/recently tilled, dry grasslands/pasture, forested/woody vegetation, saline soils, uncategorized and very wet, thick hay or wet, short thin hay grasslands. These classes were then grouped into one of four categories: agricultural lands, grasslands, wetlands/large water bodies, and woodlands/other.

Using Landsat MSS imagery, the committee found that only wetlands greater than 1.1 acres in size could be estimated. They also found that some wetlands were cultivated when dry and therefore not detected as wetlands. The area of each category was determined and used by the committee to make important decisions about water use in the basin and to establish policies accordingly.

*   *   *

CHAPTER 5

RESEARCH METHODOLOGY

Data Selection

The data used in this study consist of images that were carefully selected from the Landsat MSS archives at the Earth Research Observation Satellite (EROS) Data Center located in Sioux Falls, South Dakota. Although the Landsat satellites provide a large number of images for most locations, not all the images are usable due to such imperfections as excessive cloud cover, poor data quality, wrong time of year, incomplete land area coverage, etc. Also, because each image costs $200, care must be taken to select only usable images. Confidence in the quality of the purchased satellite images was achieved by developing a minimum criteria list for screening potential images. A list of the minimum criteria used to select the images is as follows:

- *Cloud Cover*: Clouds obstruct the view of the earth's surface eliminating all possibility of interpreting the ground area below. Therefore, the maximum cloud cover acceptable for the selected images was set at ten percent.
- *Data Quality*: Because high quality data are more reliable than data of low quality, only high quality data were considered. The data are ranked from eight (8) to zero (0), where 8 is high quality and 0 is low.

- *Time of Year*: The water level of Devils Lake generally rises in spring due to melting snow and spring rains, and declines during the late summer/fall months due to evaporation. Therefore, the time of the year is an important consideration for image selection. Ideally, two images from every year between 1972 to 1991 would be purchased. One image would represent the high (spring/early summer) water elevation and the other would represent the low (late summer/fall) water level. In reality, the ideal sampling rate of two images from every year proved to be impossible due to financial limitations and the elimination of many images that did not meet all data selection criteria.
- *Land Area Coverage*: As the Landsat satellites do not fly over the same spot on the Earth's surface, the position of the study site in the image will vary. The study site is generally located in the northwest corner of the images, so any image whose northwest corner excludes part of the lake was not selected.

The image selection process began by obtaining an image search from the EROS Data Center and EOSAT. The search parameters specified were the minimum requirements listed above. The Worldwide Reference System (WRS) coordinates specified were: Path 33, Row 27 for Landsat-1, -2, and -3, and Path 31, Row 27 for Landsat-4 and -5. The images that met the minimum requirements did not represent each year of the 1972-1991 time frame. Also, not all months or years had the same number of images to select from. The selected images were decided upon according to the time of year and the year with an emphasis on the representation of both seasonal and yearly variations.

The final list of selected images is shown in Appendix 1 and include images from Landsat-1, -2, -4 and -5 (no images from Landsat-3 met the minimum requirements). These images, twenty-three in all, were purchased with the intentions of using them for two concurrent studies. The non-winter images were the focus of the lake surface-area estimation study. They were used to represent the spring (high) and fall (low) surface areas of the lake as well as to document the changes that occur with seasonal variation. The low sun angle, lack of vegetation, and potential snow cover of the winter images were the desired elements for purchasing the winter images. They were used to study the glacial and glaciotectonic landforms for purposes of another investigation.

Equipment

The images were processed using *IDRISI* (version 4.0). *IDRISI*, is a raster-based remote sensing (RS) and geographical information system (GIS) software package, developed by the Cartographic Department at Clark University in Worcester, Massachusetts. It is capable of processing both raster and vector databases and is therefore well suited for the processing of Landsat MSS imagery. In addition, *IDRISI*, which is distributed at a very moderate cost, is widely used for teaching and research. These factors make it ideal for this study.

The computer used to process the images was a 486DX - 33MHz micro-computer with a DOS operating system. It was equipped with a 685 MB SCSI hard drive, 16 MB RAM memory, a 120 MB Colorado Jumbo 8-track cartridge backup drive, a SONY compact-disk drive, a 5.25-inch floppy drive, and a 3.5-inch floppy drive. The processed images were displayed on a NANAO 16-inch Super VGA color monitor.

Ground Observations

To complete a study of this nature, direct field observations of the study site were required for ground truth verification. This stage of the study was crucial to the proper interpretation and processing of the Landsat images. This field work took place in June of 1992. While at Devils Lake, selected areas were visited, photographed, and noted for future reference. Such observations as the location of cities, roads, wooded areas, grasslands, croplands, irrigation, pastureland, large man-made structures, human landuse patterns, and topography were made. The importance of this stage cannot be stressed enough as the information gathered can strongly assist in the final interpretation of the images; especially when individual pixels of an image were difficult to identify.

In addition to observing the study site, materials were gathered and interviews were conducted in Bismarck, North Dakota. Bismarck is the location of the North Dakota Geological Survey (NDGS) and the North Dakota State Department of Health and Consolidated Laboratories (NDSHCL), which co-funded the study. The major tasks of these meetings were to learn more about Devils Lake by consulting local experts who have access to Devils Lake records and reports. Also, various other governmental agencies were visited and relevant information collected.

Image Processing Techniques

As explained above, the Landsat MSS converts reflected solar energy, into a proportional electronic signal and then stores the signal as a numerical value. Once transmitted to Earth, the numerical values are then used to construct a digital image. A digital image is a matrix of m columns and n rows that is filled with the remotely sensed values. Because digital images are numerical in form, they can be mathematically manipulated. This process is called digital image processing.

Digital image processing consists of four major operations: image preprocessing, image restoration, image processing/enhancement, and image interpretation. Image preprocessing consists of importing the images into the work station computer and changing their format, if needed, to make them recognizable by the image processing software (*IDRISI*). Image restoration is concerned with improving the quality of the image. This involves noise reduction, geometric correction, and atmospheric haze correction. Image enhancement deals with the visual detectability of objects and patterns within the image. Processing and enhancement techniques include contrast stretching, spatial filtering, edge enhancement, band ratioing, and image compositing. Finally, the image interpretation operation relies heavily upon the knowledge and skills of the interpreter. Facts about the ground area become very helpful at this point. The more knowledge the interpreter has about the ground area the more likely the correct interpretation will be made.

The image preprocessing, image restoration, and image enhancement techniques conducted in this study are explained below, but the image interpretation will be discussed in chapter 6. The image restoration and enhancement techniques are outlined in the flow chart in Appendix 2.

Image Preprocessing:

The images were received on 6250 bits-per-inch (BPI), 9-track, computer-compatible tapes (CCT). Images acquired prior to 1979 were arranged on the CCT tapes in band-interleaved by pixel-pair (BIL-2) format, while those acquired after 1979 were available in band sequential (BSQ) format. The format of the data determines the amount of preprocessing required before the images were transformed into a usable state. BIL-2 format CCT tapes require a great deal more time to prepare than do BSQ format CCT tapes (see Appendix 2).

The 6250 bpi CCT were read onto smaller 8-track backup cartridges by the Emporia State University Computer Center, copied to the hard-drive of the image-processing computer, and imported into the *IDRISI* RS/GIS software. The images were imported into *IDRISI* by renaming the images with an ".IMG" extension followed by the creation of image documentation files as required by *IDRISI*. The number of columns and rows used for Landsat-4 and -5 whole images were set at 3596 and 2983 respectively. These values correspond as listed to the number of pixels per line and the number of lines in the images. Images from Landsat-1 and -2 on the other hand had rows that were constant (2340), but columns that varied from one image to another. Furthermore, these images were divided into vertical strips and arranged on the CCT in the BIL-2 format. This arrangement meant that all four bands of each strip were mixed together and needed to be separated before further processing could be done.

To complete the task of converting the BIL-2 arrangement, the header from each strip was removed using the *PARE* module followed by *CONVERT*. The *CONVERT* module changed the data format from the original byte binary data type to integer ASCII. Next, each strip was processed using *BIL-2*, a Pascal computer program specially written by a colleague for this purpose. This program worked by placing two bits of information from the input strip into four separate data files that represented the four MSS bands. When the strips had been processed, the same band from the four different strips were joined together using the *CONCAT* module. At this point the image importation procedures were complete and the images were ready to be processed.

Image Restoration:

The images acquired since 1979 have been preprocessed by the EROS Data Center in Sioux Falls, South Dakota, more completely than earlier images (Holkenbrink 1978). One of the pre-processing procedures performed is a resampling process that converts the MSS pixel size from 79 x 56 m to the square pixel size of 56 x 56 m. This correction procedure eliminates foreshortening effects when the images are displayed on a computer monitor. Unfortunately, this foreshortening correction was not performed on the MSS images acquired by Landsat-1 and -2. Thus this procedure is necessary for proper visual interpretation of these images.

The foreshortening correction technique, as explained by Short (1982) in the Landsat Tutorial Handbook, was used to correct the May 14, 1973 and the July 7, 1973 images.

Once these images were imported into *IDRISI*, a large window that extended well beyond the final window dimensions was extracted and used as the input images for the *RESAMPLE* module. A correspondence file was created as directed by the *IDRISI* manual. The correspondence file consisted of four points that related the corners of the input image with the corners of the output image. Because the width of the pixels were correct the number of columns in the output image was set at the width of the input image. In contrast, the vertical scale of the input image was distorted causing the smashed appearance of the image when displayed. To correct this distortion, the number of rows specified for the output image was equal to the number of rows in the input image plus a calculated number of additional rows. The number of rows that were added was calculated, as explained by Short (1982, p. 199):

$$R = (yr/x) - r$$

where R is the number of rows to be add to the original image, y is the height and x is the width of the pixel cell (in meters) and r is the number of rows in the original image. After the image had been resampled, the study window was ready to be extracted.

Image Processing/Enhancement:

A fully processed Landsat scene is about 185 x 185 km (115 x 115 miles). Such a scene requires a large amount of time and hard-drive storage space to process. In addition, enhancement techniques produce only moderate results within the study site because of strong influences by the remainder of the image. Also, the ground area covered in each scene varies due to differences in satellite orbits. To alleviate problems of this nature, a subscene is normally extracted to more fully concentrate on the features within the study site. The ground area of the subscene extracted for this study is shown in Figure 16.

The subscene consists of 730 scan lines (rows) with 1000 pixels per line (columns) and corresponds to a ground area of about 2400 km^2 (920 sq miles). These row and column dimensions are the maximum ground area coverage possible without pixel thinning and were determined by the display capabilities of the monitor and the *COLOR85* module in *IDRISI*. The subscene focuses on the basins of Devils Lake and the related ice-shoved hills located to the south and east. Other features in the window include the city of Devils Lake and other smaller towns, major roads and ancient glacial landforms.

The subscenes were extracted from all images in a like manner. First a reference pixel was identified and used as a common point between all images. A reference pixel is, ideally, a pixel in each of the images which corresponds to a point on the ground that can be identified at any time of the year in any given year. The reference pixel chosen for this study was the intersection of highways 2 and 281.

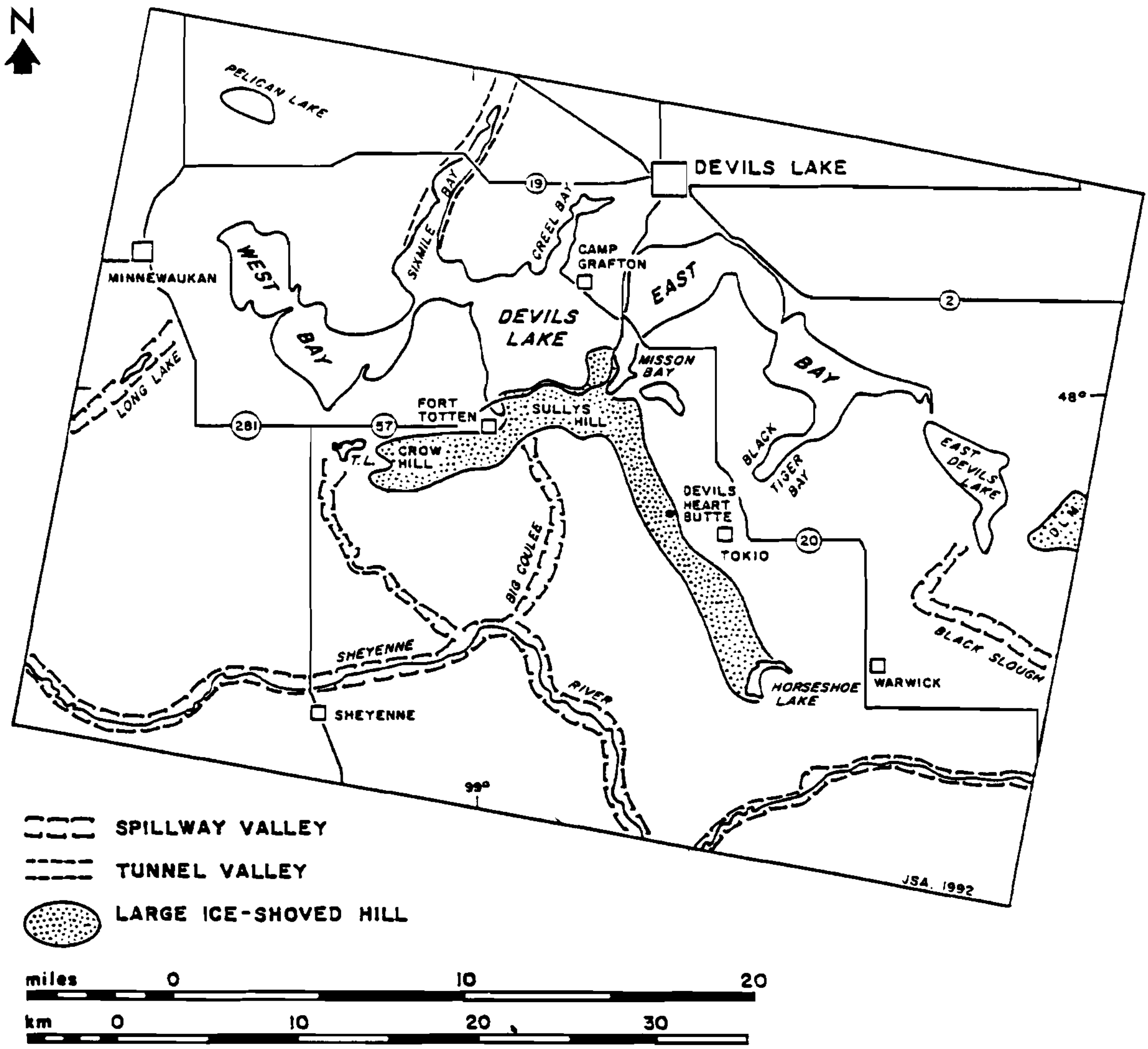


Figure 16. Map showing the ground area covered in the selected subscene. Note the location of Devils Lake, Sullys and Crow ice-pushed hills to the south, and major spillway valleys. The rotated orientation (approximately 10 degrees from north) is due to the orbital path of the satellite. Taken from Aber et al. (1993).

This point was most easily distinguished in band 2 of each image but could also be distinguished in the other bands as well.

Once the reference pixel was identified within the raw data of each scene, the column and row coordinates were recorded and used to extract the "window" subscene using the *WINDOW* module in *IDRISI*. The window extraction method produced satisfactory results. The ground area of the images was generally equivalent in all images and was within acceptable limits. The one exception was the July 7, 1973 image. This image fell a short distance (approximately 0.5 km) to the east of the reference pixel. As a result, a secondary reference pixel was used to extract the window from this scene.

Area Calculations:

Once the windows were extracted, they were ready to be processed. Batch processing was applied to increase image processing efficiency, and to decrease the possibility of human errors such as the misnaming of bands or the accidental entering of incorrect image names. The batch program was created in a text editor using the command line parameters outlined in the *IDRISI* manual. The methods and modules used are shown in the flow chart in Appendix 2 and described below.

- *OVERLAY*: The overlay module was used to create a 4/2 image ratio of band 4 and band 2 from each scene. This step is a technique used to separate water from land. Water has a value less than 1 and land has a value greater than 1.

- *RECLASS*: The reclassification module was used to create a Boolean image. Land areas were assigned a value of 0 and water areas were assigned a value of 1.
- *GROUP*: The group module was used to create an image that contained groupings of contiguous cells within the reclassified 4/2 image. Each cell was diagonally linked to adjacent cells of equal value and assigned an integer identifier unique to that group.
- *AREA*: The area module was used to calculate the area of each group within the group image. This module works by counting the number of cells within each group and reporting the results in terms of cells or other user-specified units. The results can be reported in the form of a table, an image or a values file. In this study the output was opted to be in units of cells and in image format.

In most cases, the procedures in the batch program produced desirable results. Occasionally, the spectral responses from bands 4 and 2 produced a 4/2 ratio that required a water-land cutoff point below the standard value of 1. Another minor problem occurred when the reclassified image joined Devils Lake and East Devils Lake, which resulted in one area measurement that included both lakes. Such situations required user interactive image process procedures in place of batch processing.

The 4/2 ratio technicality was remedied by reclassifying the ratio image, in increments of 0.1, for all pixel values between 0 and 1, thereby allowing the water-land boundary to be specifically located. The original 4/2 ratio was then reclassified again, this time using the newly determined water-land boundary value. Once the 4/2 ratio image was reclassified, the remainder of the procedure was unchanged.

Dividing Devils Lake from East Devils Lake and other such connected areas was a simple task. The images were viewed using the *COLOR85* module and the areas of water body contact located. The column and row coordinates of the joining pixels were then determined from the module's cursor mode and changed from either 1 to 0 or from 0 to 1 using the *UPDATE* module. The image was processed with the group module, followed by *UPDATE* again. The second *UPDATE* session was to *CONVERT* the previously changed pixels to its designated group, thereby preserving the area calculations. The line of division used to separate two areas into individual groups was considered to be the narrowest point between them.

Image-Enhancement Techniques:

Many image-enhancement techniques were examined in this study. Some of those used were false-color compositing, thematic extraction, density slicing, principal component analysis, contrast stretching, etc. Of these techniques, the standard false-color composite was found to be superior for viewing purposes. These composite images were therefore used to visually compare one image to another.

False-Color Composites:

The standard false-color composite images were created by selecting three individual images, color coding them, then mathematically computing the pixel value of the output image using the three corresponding pixel values of the three input images. The bands used to make composite images were 1, 2, and 4 color coded blue, green and red respectively. Each band was contrast stretched with a saturation of 2.5% (which was evaluated as the most effective for visual enhancement). In *IDRISI* the composite images were created using the *COMPOSIT* module.

Atmospheric and sunlight conditions vary considerably at the time each image is acquired. These variables produce differences that interfere with attempts to compare images from different dates. Therefore, in order to compare multidate images, the effects of these variables must first be removed from the original data. In normal image processing procedures, atmospheric and sunlight variables are corrected using radiance calibration techniques that introduce a correction factor. However, the radiance correction technique was not used in this study because it drastically reduced the clarity of the composite images.

Density Slicing:

Certain images were specially processed using a technique known as density slicing. This technique involves the extraction of specific features (thematic extraction) from three bands of a given scene, followed by the creation of a false-color composite image using the thematically extracted images. Finally, the various thematic composite images are usually added back together to create one complete image. This technique is generally used to produce images with greater detail within the specific features (i.e. water). The density slicing technique was used, with limited success, to enhance sediment-laden waters and algal blooms within water bodies.

Aerial Photographs

Aerial photographs, taken within the 1972-91 time frame, were used as reference in the analysis of the Landsat MSS images. The color-IR aerial photos, at a 1:62,500 scale, were used to identify small features within the Devils Lake region that were not evident on the Landsat images. For example, small washboard moraines between the Creel and Six Mile bays are visible on the photos, but not on the MSS images. The aerial photos were also viewed stereoscopically to learn more about the topographic relief of the area.

*   *   *

CHAPTER 6

RESULTS AND INTERPRETATIONS

The results of the image-processing procedures were lake-surface-area estimations and visual image interpretations. Satisfactory surface-area estimations of the lake were obtained from 13 of the 15 processed non-winter images. Additionally, it was shown that the images could be handled in a batch processing mode thereby increasing the efficiency of the image processing step. Visual interpretations of processed images revealed many important observations of the study site. These visual interpretations help build an overall understanding of the environmental elements affecting the Devils Lake region.

Visual Image Interpretations

General Observations and Orientation:

Many important observations were made by examining the Landsat MSS standard false-color composite images of the study window. These observations include the location of various features within the region, the detection of changes that have taken place, the quality of the water in the lake, the documentation of sediment and algal bloom patterns within Devils Lake, and other such observations. Also noted were general landuse/landcover patterns. These observations were combined with other knowledge of the area to enhance the understanding of the region. Each of these elements are discernible to varying degrees on individual band, composite, and multidate images. The interpretations explained below are based upon the standard false-colored composite images. (See Appendix 3 for images on disk).

Landuse/Landcover:

The landuse/landcover patterns are clearly evident when viewing the standard false-color composite images. The landuse/landcover within the region consists of open water, wetlands, pasture/grasslands, agricultural fields, cities/urban areas, roads, and forested areas.

Agricultural versus non-agricultural regions are often identified by the type and density of vegetation in addition to the nature of boundaries. Agricultural regions appear in various shades of red, green and white with straight linear boundaries, while forested areas are generally bright red to brown in color and have irregular boundaries. Sullys and Crow Hills, for example, are covered by forest; the surrounding areas are used for agriculture.

Other landcover patterns include the identification of center-pivot irrigation systems. These systems are often supplied by ground water and therefore indicate the presence of an aquifer. Such is the case in the region southeast of the Devils Lake. The Warwick aquifer (in the lower right corner of the study window) is used to supply irrigation water for agricultural crops. Depending on the season, these center-pivot irrigation systems often appear as red, green, or white circular features. The number of these systems has greatly increased from 1973 to 1991.

Vegetation:

Vegetation appears in shades of greens, reds and browns, depending upon the season. Very mature active vegetation is generally red to brown, while young immature vegetation shows up in shades of green. This variation in vegetation type accounts for the seasonal differences that occur in the spring and summer/fall images. In early spring, the predominate color of the composite images is green, whereas summer and fall brings more active vegetation and a more dominant red color.

The boundaries of different physiographic regions can be distinguished using geobotanical techniques (Bruce and Hornsby 1987; Punkari 1982). This technique uses vegetation as a guide to determining the boundary between various regions. During the growing season, the region of ice-thrust hills appear bright red on the standard false color composites. This region is a hilly area that is covered by small pot-hole lakes and wetlands and is therefore used predominately for pastureland or natural forest. Outside this region, the land is more level and is used predominantly for agriculture. Other areas, in which this technique is useful, are in the identification of meltwater spillways and abandoned strand lines.

Cultural Features:

Most man-made objects (cities, roads, railroads, buildings, etc.) often produce a bright, light blue to white color in the standard false-color images. Of these features, the city of Devils Lake is the most obvious. It is located in the top-center of the study window near Creel Bay. Roads leading into and away from the city are also evident as thin white lines. The most obvious road is U.S. Highway 2 which follows an east-west orientation across the upper right corner of the window. Another is State Highway 20 which approaches the city from the south, crossing the lake between Main and East Bays. Other state and county roads are also identifiable within the window. Still other roads, which crossed the lake in 1973, were completely flooded in the later images. This was the situation at Ziebach Pass between West and Main Bays.

Devils Lake:

In standard false-color composite images, water appears in shades of blue to black. Black and dark blue colored areas are associated with open, clean water, while shades of light blue indicate either shallow and/or silty water. As the sediment content increases, the color of blue becomes lighter. In general, the central and eastern bays of Devils Lake are deeper and therefore appear dark blue to black in most images. The West Bay, on the other hand, often appears in shades of bright blue to white.

The colors evident in West Bay are the result of two conditions. First, the West Bay region of the lake is very shallow with an extremely gentle bottom slope. Thus, incident solar energy is able to penetrate the depth of the water and reflect off the bottom sediments. This results in the spectral response similar to that of barren soil. Secondly, and more important, the brightest spectral responses evident in the West Bay portion of the lake often correlate with and were presumably caused by high winds. Because this bay is so shallow, strong winds that blow across the bay are able to produce waves deep enough to disturb and suspend lake-bottom sediments. A similar situation was also noted by Matson and Berg (1981) in their study of the Great Salt Lake.

For Devils Lake, during times of strong winds, West Bay appears bright milky-blue in color (due to high reflectance responses in bands 1 and 2); when the wind is calm, the sediment is allowed to settle and the water appears darker. Figure 17 illustrates this point. This image was acquired on September 23, 1988, following an episode of relatively high winds the day before. On the previous day, the average windspeed was 16.3 miles per hour (Sether and Wiche 1989). On September 23, the day the image was acquired, the average windspeed was 10.2 miles per hour. These windspeeds were in excess of the monthly average of 8.7 miles per hour. Under the same conditions, Main Bay, which is much deeper, is dark in color. Thus

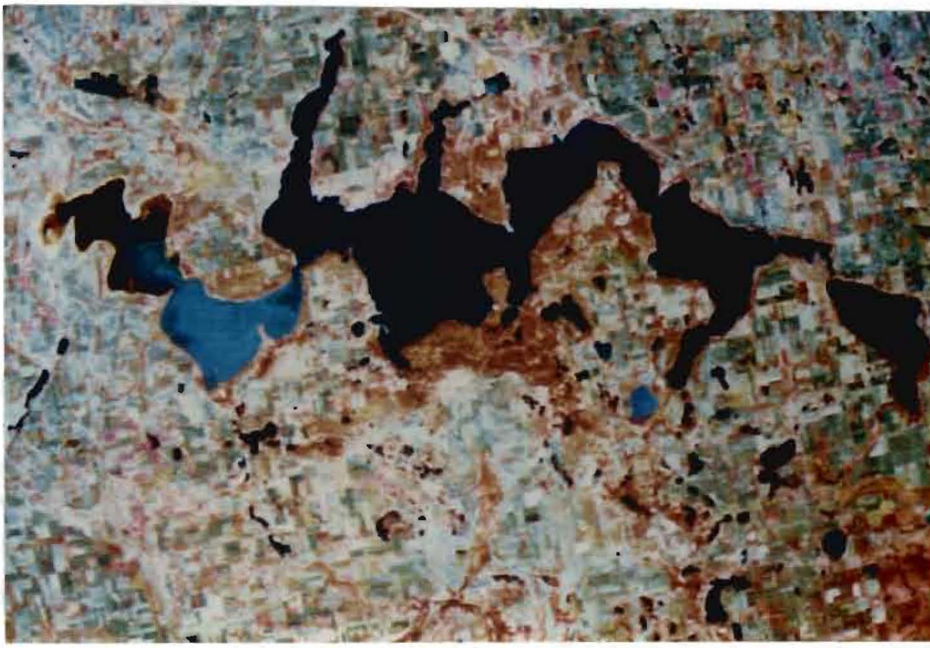


Figure 17. September 23, 1988, Landsat MSS false-color image of Devils Lake acquired in windy conditions. Note especially the milky-blue color in West Bay. The ice-thrust hills appear reddish-brown while fallow fields are shades of white and fields with crops and/or pasturelands are green.

strong winds were able to produce waves great enough in depth to increase water turbidity and produce a brighter reflectance signal in West Bay. A similar situation also took place on October 25, 1988.

Algal Blooms:

As many studies have documented, algal blooms can be detected and studied using Landsat MSS imagery (Short et al. 1976; Strong 1976; Best and Moore 1979). In MSS imagery, algal blooms have a spectral response pattern very similar to that of land vegetation; they appear dark in

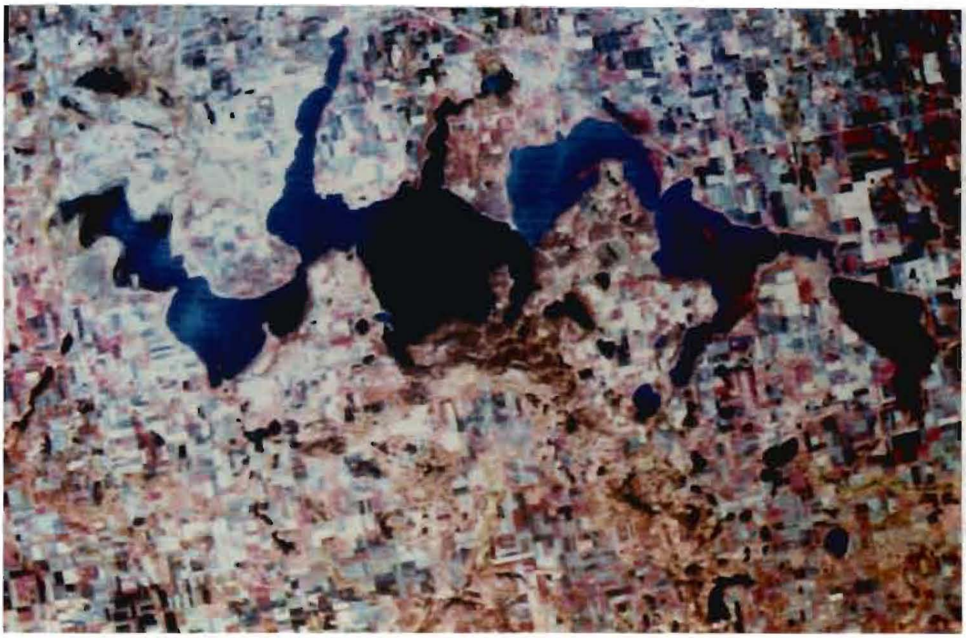


Figure 18. Landsat MSS false-color image acquired on October 20, 1986. Note algal blooms (bright red) present in East Bay of Devils Lake.

bands 1 and 2, and bright in bands 3 and 4. Often they occur during the late summer/fall months when incident solar energy is high and lake water is the warmest. As mentioned earlier, Devils Lake is susceptible to the development of large algal blooms, which can have a negative impact on the economy of the region. The areal extent of such blooms can be fully appreciated by viewing them with Landsat MSS imagery (Fig. 18).

Two images, October 20, 1986, and June 30, 1989, showed very large algal blooms respectively in East Bay and Main/Creel Bays of Devils Lake. These massive algal mats are apparently more common in the open, clear waters of Main and East Bays as opposed to the silty waters of West

Bay. The October 20, 1986, image (Fig. 18) shows the algal bloom in East Bay as bright red regions within the lake. Prevailing northwest winds have blown these mats to the southern shores where they collect giving a spectral response similar to land vegetation. As a result, this image and others like it cannot be used in surface area calculations, because the shore line between land vegetation and the algal bloom cannot be determined. Large algal mats are also apparent in Main Bay on June 30, 1989.

Winter Images:

Winter imagery has proven useful for studying regional topography (Eyton 1989; Skoye and Eyton 1992; Aber et al. 1993). The low sun angle combined with a deep, uniform snow cover which is often associated with winter images produce favorable conditions for topographic enhancement. Within such images, the southeast sides of elevated surfaces are illuminated while the northwest sides are shaded. For topographic depressions the opposite is true; the southeast side is shaded and the northwest side is illuminated. The December 23, 1983, image (Fig. 19) is a fine example of how topographic features can be enhanced by a low sun angle and an even snow cover.

Figure 19 shows a regional view of Devils Lake. The area covered includes not only the study site, but also Stump Lake to the east, Sheyenne River to the south, and a portion of the "Chain-of-Lakes" to the north. This

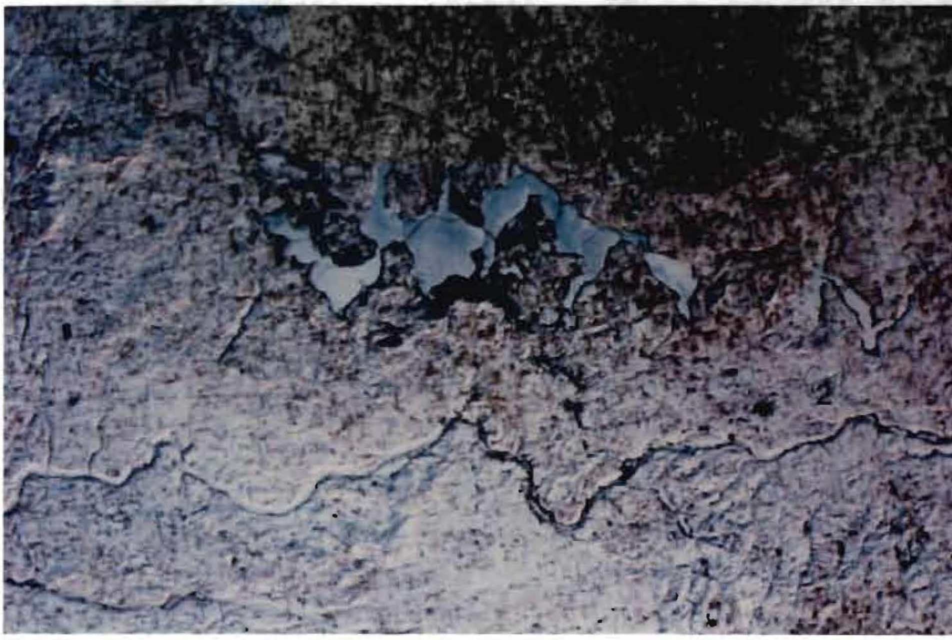


Figure 19. Winter false-color image acquired on December 23, 1983. With a low sun angle and even snow cover it highlights the regional topography. Important observations include Sullys and Crow ice-thrust hills (black) on the southern shores of Devils Lake (Main Bay), and the Location of spillway channels. The Jerusalem spillway (#1), which at one time flowed eastward into West Stump Lake, and the Big Stony spillway (#2) that once flowed into the Sheyenne River are marked. Various other meltwater channels can also be detectable.

subscene enhances many topographic features within the Devils Lake region. Some of the meltwater spillways which were carved during the last glaciation are nicely highlighted. The Jerusalem spillway (#1), appearing as a wide, flat-bottomed channel, is located between East Devils Lake and West Stump Lake. During the last glaciation, overflow meltwater bridged the spillway threshold of East Devils Lake and flowed eastward into Stump Lake forming the channel. Another spillway, the Big Stony spillway (#2), is less obvious but is distinguishable. It is evident to the south of West Stump Lake winding its way to the Sheyenne River. Other spillway channels are also visible, especially when viewing the images on a computer monitor.

The ice-thrust topography of Sullys and Crow Hills are also highlighted in this image. These structures are predominately forested and appear in shades of blacks against the white snow background. A relatively bright strip of white is evident below the dark tree patches. This bright region is located along the southern side of the hill structures, and is more strongly illuminated by the morning sun.

Landsat MSS Area Estimation Results

The results of the MSS-based surface-area estimations of Devils Lake are shown in Table 3. Though surface-area estimations of Devils Lake have been reported in the past, the bays included in these estimations vary. For example, some reports consider only Main Bay and Creel Bay as part of Devils Lake, while others include all connected water bodies. This inconsistency is most likely due to variations in the water elevation at the time each study was conducted. In this study, the areas considered to be parts of Devils Lake are as reported on the USGS topographic maps covering the lake. Thus the bays included as parts of Devils Lake are as shown in Figure 1.

Devils Lake Area Calculations			
Image Date	Cells	Sq. Miles	Sq. km
05/14/73	37726	47.3	122.6
07/07/73	37212	46.7	120.9
07/16/83	55652	69.8	180.8
05/31/84	60690	76.1	197.2
07/18/84	55832	70.0	181.4
09/28/84	57021	71.5	185.3
10/01/85	56140	70.4	182.4
05/29/86	59835	75.1	194.4
06/19/88	56924	71.4	184.9
09/23/88	57410	72.0	186.5
10/25/88	57990	72.7	188.4
08/28/90	52890	66.3	171.8
08/31/91	51230	64.3	166.4

Table 3. Surface-area-estimation results for Devils Lake based upon Landsat MSS imagery.

The Landsat MSS area-estimation results show three main water level stages that have occurred in Devils Lake from 1973-1991 (Fig. 20). In 1973 the surface area of Devils Lake was at a minimum extent of 123 sq km (47 sq miles). From 1973 to 1983 the lake rose in elevation and spread in area, giving rise to the concerns of local citizens. The lake level then stabilized with minor fluctuations from 1983 to 1988 and a recent peak in 1987. The lake surface area at this time was around 190 sq km (72 sq miles). In 1988, the elevation of Devils Lake began to decrease again. On August 31, 1991, the lake level stood at an elevation of about 434 m (1,423 feet) asl (Harkness 1991) with a surface area of 166 sq km (64 sq miles) recorded on the September 4, 1991 image.

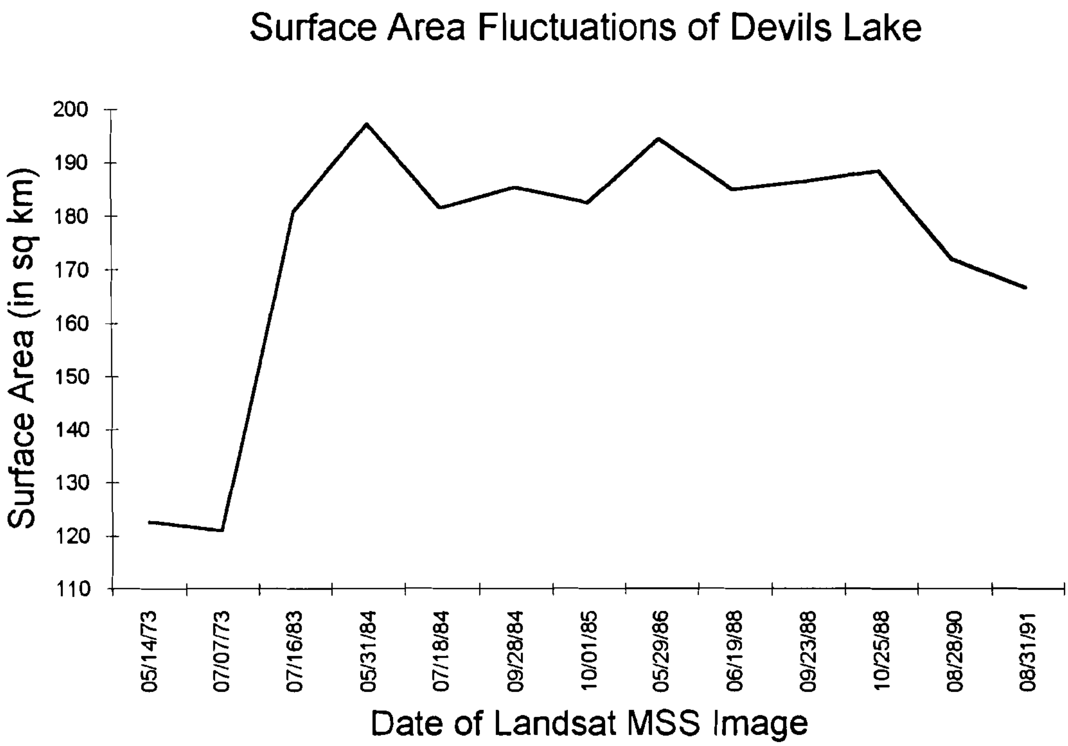


Figure 20. Surface-area fluctuations of Devils Lake based upon Landsat MSS imagery. Note variable time scale.

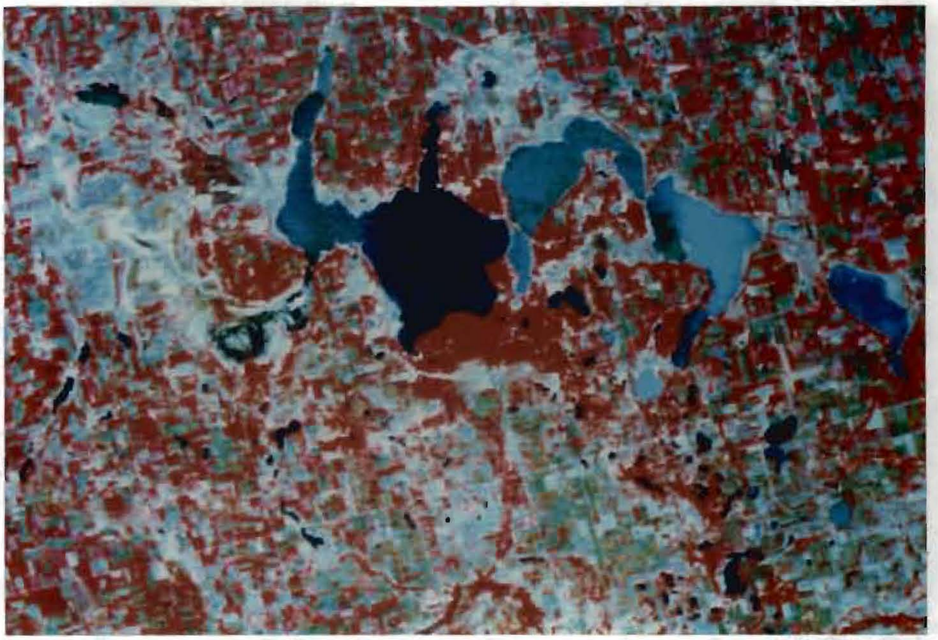
This graph (Fig. 20) follows the same general tendencies that are evident in Figure 10. As expected, when the water elevation of Devils Lake rises, the surface area increases. These consistencies support the surface-area estimation effectiveness of the 4/2 ratio techniques. Though far from a replacement of ground data, this technique could be used to estimate the surface area of water bodies, but uncertainties, such as the shape of the lake-bottom, and shallow areas, must be taken into account.

Visual verification of Devils Lake's water level fluctuations is possible also by examining Landsat MSS standard false-color composite images. Figure 21a shows the water elevation of Devils Lake at a low point on July 7, 1973. By examining this image, it is seen that the Minnewaukan Flats area was completely dry at the time of image acquisition, while West Bay was a small, shallow, marshy area. Also, a large peninsula is evident in East Bay of Devils Lake.

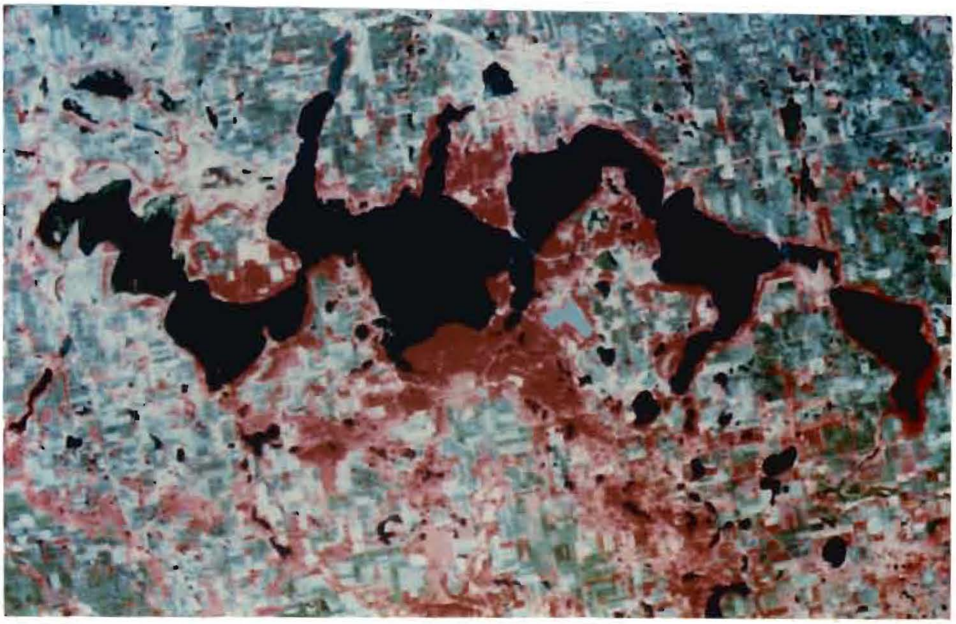
In contrast, the May 29, 1986, false-color composite image (Fig. 21b) shows Devils Lake near its 1987 high of 1428.8 feet asl. The peninsula, evident in the previous image, has disappeared due to the elevated water level. Finally, the August 31, 1991, false-color composite image (Fig. 21c) illustrates a water level somewhat lower than the recent maximum of 1428.8 feet asl. In this image, West Bay of Devils Lake has declined to a small, shallow and narrow arm extending into the Minnewaukan Flats area. Undoubtedly, the water level decline that took place between 1989 and 1991 is due to the 1988-89 drought that affected the region.

Error Analysis

Several conditions exist in the Landsat MSS data that create potential errors in surface-area estimations. The most obvious of these is caused by the instantaneous field of view (IFOV) of the MSS scanner. The spatial resolution of the MSS limits the size of objects that can be distinctly identified at 79 x 79 m. The spectral signals of objects smaller than this are combined with those of

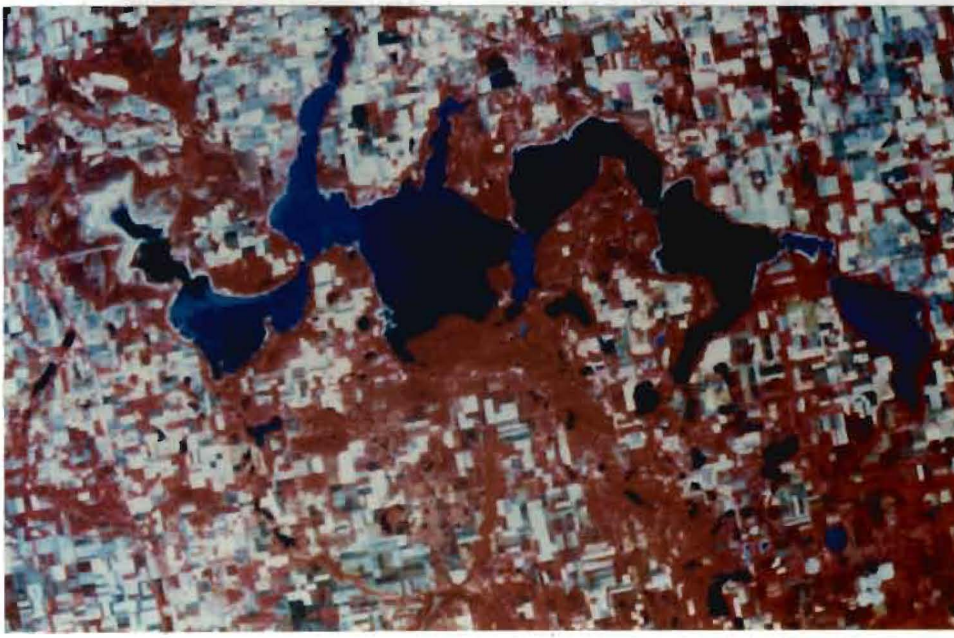


(a) Low water level of Devils Lake (July 7, 1973).



(b) High water level of Devils Lake (May 29,1986).

Figure 21. Landsat MSS false-color composite images of the Devils Lake subscene. (a) July 7, 1973, shows Devils Lake at its low water elevation, (b) May 29, 1986, depicts the lake near its 1987 maximum and (c) August 31, 1991, shows Devils Lake at a recent stage. Note shoreline differences and road flooding between West and Main Bays.



(c) Recent water level of Devils Lake (August 4, 1991).

Figure 21. (continued).

surrounding surfaces to produce a mixed spectral response. The spectral identities of such small objects are further complicated by geometric correction procedures, by which the data are resampled into 57 x 57 (or 79) m sized pixels. The data contained within the final pixels are therefore altered from the original sampling.

Recognition of these limitations is especially important in the case of transition zones (i.e. water and land boundaries). Because the water to land transition occurs rather abruptly, it cannot be distinctly recognized by the MSS detector. The spectral reflectance of the transition zone is therefore combined with reflectance signals from the surrounding area to form a "mixed pixel." Some ground areas are represented by mixed pixels that contain more water than land, and others are composed of more land than water. As a result, the exact location of the shoreline is represented by a band that may be a few pixels wide. In theory, the effect of this band of mixed pixels is minimal as they can be averaged to produce an image shoreline representative of the actual shoreline. Such an assumption has been made in this study.

Haze correction is another important consideration when estimating the surface area of the lake. Slightly different results are obtained from 4/2 ratio images that have been corrected for atmospheric interference. Because haze correction procedures change the values of the input images (band 4 and band 2) of the 4/2 ratio image, different pixel values are obtained. The difference between the haze-corrected and the non-haze-corrected values were minimal.

The accuracy of the final surface-area images was visually checked by comparing them to 1:250,000 and 1:24,000 scale USGS topographic maps. Islands and other shoreline features were noted for their location and relative size. These comparisons showed a high correlation between the features on the final images and those on the maps.

Other unforeseeable problems of variable degrees also surfaced as the study progressed. For example, the two

Landsat-2 images did not cover the desired ground area; they include only East Devils Lake. Unfortunately, these scenes (May 7, 1976 and May 15, 1978) were excluded from the study, thereby creating a large gap in the data (from 1973 to 1983).

* * *

CHAPTER 7

CONCLUSIONS

The results of this study show that Landsat MSS satellite data can be used to document the water-level fluctuations of water bodies by measuring their surface area. A technique was developed and used to estimate the surface area of Devils Lake, located in northeast North Dakota. This technique was based upon the creation of a 4/2 ratio image to separate land and water area. Using this image, the water bodies were reclassified, grouped and measured to obtain a surface-area estimation. This technique could be used in a batch processing mode to rapidly produced usable results. Occasionally, the batch processed 4/2 ratio image did not separate the land and water area satisfactorily. This event prompted interactive processing. Results show three general surface-area fluctuations of Devils Lake, which correlate with water elevation records: (1) a low surface area of 121 sq km (47 sq miles) in the early 1970's, (2) a high surface area of about 190 sq km (73 sq miles) during most of the 1980's, and (3) a decline to a recent surface area of 166 sq km (64 sq miles) after 1988.

In addition to the surface-area estimations, specific observations of the Devils Lake region were also made. Two images documented the existence of large algal mats on the surface of the lake. Wind data were correlated with the spectral responses of several images to show a relationship between high winds and high water turbidity within West Bay of Devils Lake. Winter images, with a thick, even snow cover, showed the regional topography and were used to detect glaciotectonic landforms. Also, a time series, consisting of 13 images from 1973 to 1991, was used to display seasonal and environmental changes.

It was learned that the task of selecting images for a specific purpose is very difficult. Many elements (cloud cover, data quality, time of year, land area coverage, soil conditions, snow/ice cover, climatic conditions, etc.) must be considered before the images can be selected. The development of minimum acceptable requirements is necessary along with knowledge of the natural and cultural factors that affect the study site.

Finally, a number of related studies that involve the use of the Landsat MSS data are recommended. One in particular involves the merging of the MSS data with digital elevation models (DEM) to create a 3-dimensional view of the area as it appeared on the date of image acquisition. Three-second DEM data were purchased for this purpose, but due to data format complications and time restraints, this procedure was not conducted. The results could provide city planners, engineers, wildlife managers, etc. with a new understanding of the Devils Lake Basin.

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Appendix 1

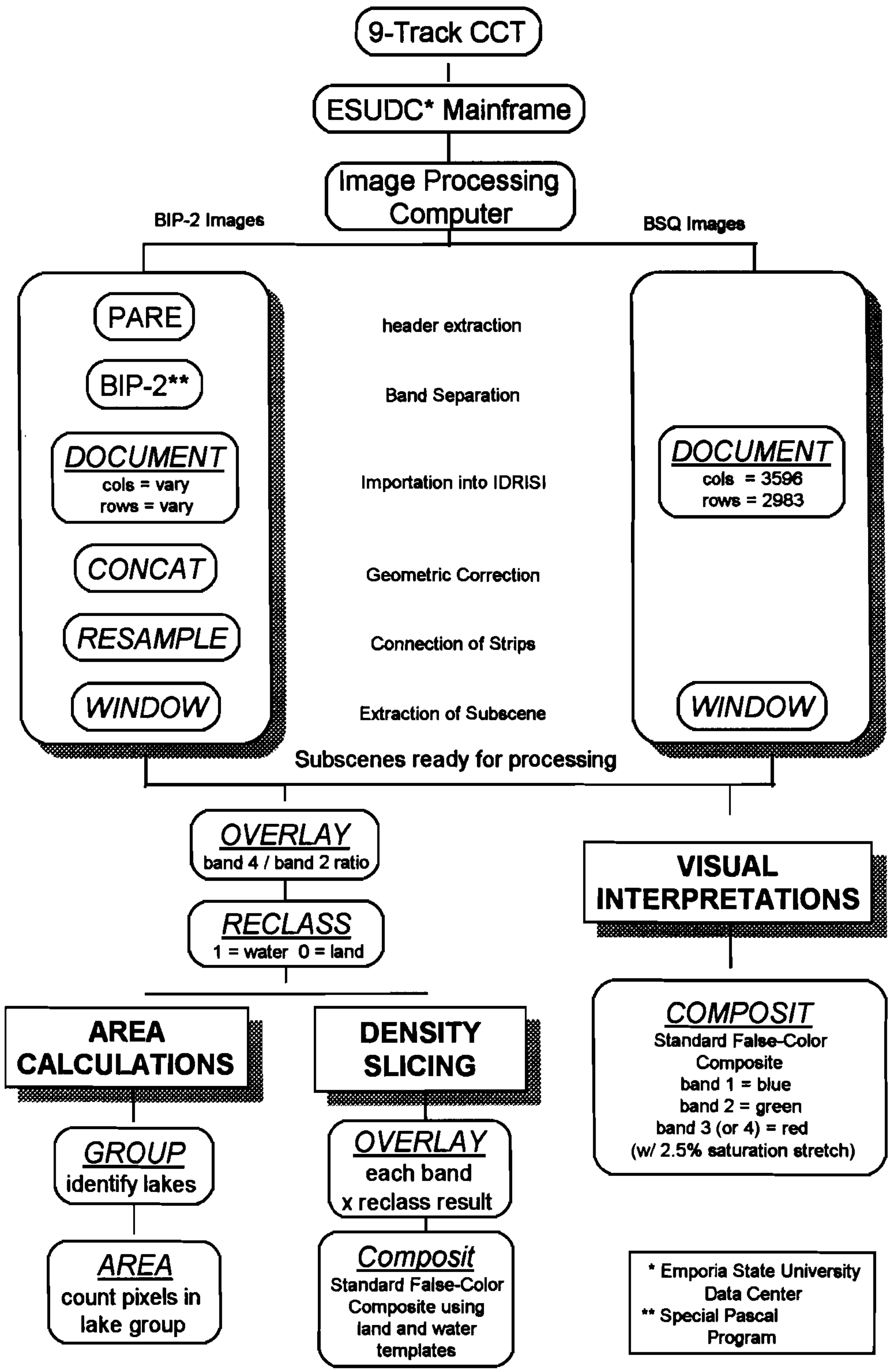
LANDSAT MSS COMPUTER COMPATIBLE TAPES (CCT)
PURCHASED FOR STUDY

Scene ID Number	Date	Format	Landsat	Cloud Cover
85273916463XO	08/31/91	BSQ	5	00%
85237116424XO	08/28/90	BSQ	5	10%
84254116562XO	06/30/89	BSQ	4	10%
85169916533XO	10/25/88	BSQ	5	10%
85166716533XO	09/23/88	BSQ	5	10%
85157116533XO	06/19/88	BSQ	5	00%
58139516514XO	12/26/87	BSQ	5	00%
85107516433XO	02/09/87	BSQ	5	00%
85096316422XO	10/20/86	BSQ	5	00%
85081916471XO	05/29/86	BSQ	5	00%
85057916520XO	10/01/85	BSQ	5	00%
85033916532XO	02/03/85	BSQ	5	00%
85024316525XO	10/30/84	BSQ	5	00%
85021116530XO	09/28/84	BSQ	5	00%
84073316480XO	07/18/84	BSQ	4	00%
84068516483XO	05/31/84	BSQ	4	00%
84057316505XO	02/09/84	BSQ	4	00%
84052516512XO	12/23/83	BSQ	4	00%
84036516524XO	07/16/83	BSQ	4	00%
82120916191XO	05/15/78	BIP-2	2	00%
8247116373500	05/07/76	BIP-2	2	00%
8134916543500	07/07/73	BIP-2	1	00%
8129516550500	05/14/73	BIP-2	1	00%

(BSQ) - Band sequential / (BIP-2) - Band-interleaved-by-pixel pair
Landsat-1 and -2 : Path 33 Row 27
Landsat-4 and -5 : Path 31 Row 27

Appendix 2

IMAGE PROCESSING FLOW CHART



Appendix 3

Landsat MSS Images on Computer Disk

There are two images on the enclosed disk. To save disk space they have been slightly reduced in size compared to those used in the study. *IDRISI* (version 4.0) is needed to view these images. Set the *IDRISI* environment drive equal to the 5.25-inch drive designation of the computer (usually drive A), and use COLOR85 with the false-color palette (#5). The file names and dates are listed below.

File Name	**Image Title**
Low	Low Water Level of Devils Lake (July 7, 1973).
High	High Water Level of Devils Lake (May 29, 1986).

Appendix 3. (continued).

I, Everett Spellman, hereby submit this thesis/report to Emporia State University as partial fulfillment of the requirements for an advanced degree. I agree that the library of the University may make it available for use in accordance with its regulations governing materials of this type. I further agree that quoting, photocopying, or other reproduction of this document is allowed for private study, scholarship (including teaching) and research purposes of a nonprofit nature. No copying which involves potential financial gain will be allowed without written permission of the author.

Everett E. Spellman
Signature of Author

May 6, 1993
Date

Environmental Study of Devils Lake, North Dakota, Using Landsat Multispectral Imagery

Title of Thesis/Research Project

Signature of Graduate Office Staff Member

May 6, 1993
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