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Scientific Investigations Report 2005–5181

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	2.471	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

NOTE TO USGS USERS: Use of hectare (ha) as an alternative name for square hectometer (hm^2) is restricted to the measurement of small land or water areas. Use of liter (L) as a special name for cubic decimeter (dm^3) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter. Metric ton (t) as a name for megagram (Mg) should be restricted to commercial usage, and no prefixes should be used with it.

Hydrologic Conditions and Lake-Level Fluctuations at Long Lost Lake, 1939–2004, White Earth Indian Reservation, Clearwater County, Minnesota

By Victoria G. Christensen and Andrea L. Bergman

Abstract

Long Lost Lake, a closed-basin lake in Clearwater County, Minnesota, has had a substantial rise in lake level since 1990. The increased level and surface area of the lake has led to the inundation of nearby homes and roads. The U.S. Geological Survey, in cooperation with the White Earth Band of Chippewa Indians, conducted a study to document the historical lake-level fluctuations, to investigate reasons for hydrologic change, and to develop a general understanding of the hydrology of lakes that have had rapid changes in lake level.

Lake levels were recorded continuously from August 2003 through December 2004. The purpose was to establish a temporal, detailed record of lake levels and to connect this record to precipitation and ground-water-level data. A long-term record is critical to understanding the relation between surface water and ground water. This is especially true for closed-basin lakes. Between August 2003 and December 2004, the lake level generally declined. The highest lake altitude was 492.58 meters above NAVD 88 on August 5, 2003, and the low of 492.11 meters above NAVD 88 occurred on August 29, 2004.

Results of water-level measurements in 5 observation wells and 14 wetlands and ponds show that the water-table level is substantially higher on the north side of the lake than the lake level, providing the head pressure necessary for ground-water discharge into Long Lost Lake. In contrast, on the south and east sides of the lake, water-table levels are similar to the lake level. This indicates a general north-northwest to south-southeast ground-water flow direction. Results of a synoptic survey of lake temperature and other measurements supported the direction of water inflow and outflow.

Aerial photography and a geographic information system were used to construct a historical lake record from 1939 to 2001. Lake-level increases match similar increases in precipitation, indicating a strong link between the two. Results show that lake-level increases in Long Lost Lake appear to primarily be due to natural rather than anthropogenic effects.

Introduction

Long Lost Lake is an approximately 200-ha closed-basin lake within the boundaries of the White Earth Indian Reservation in southeastern Clearwater County, northwestern Minnesota (fig. 1). A closed-basin lake (sometimes called a seepage lake) has no surface-water inflows or outflows and, therefore, receives most of its inflow from ground water and precipitation. The lake is near the headwaters of the Mississippi River, approximately 10 km west of Lake Itasca (fig. 2), the source of the Mississippi River. The lake level of Long Lost Lake has risen substantially since about 1990. Since the establishment of a lake gage in 1992 by the Minnesota Department of Natural Resources (MNDNR), the lake level has risen about 4.0 m. Since 1992, the lowest recorded lake altitude was 489.0 m above NAVD 88 during May 1993, and the highest was 493.1 m above NAVD 88 during July 2002 (Minnesota Department of Natural Resources, 2003). Twelve Tribal residences, several roads, and about 20 ha of Tribal lands are submerged. Thirty Tribal members have been displaced from their homes due to increases in the lake level. The remote location, sparse population within the watershed, and limited access to much of the watershed contribute to a lack of information about the hydrology of the lake. There was concern that the improvement of County Highway 39 along the south and east side of the lake may have contributed to the rise in lake level by restricting ground-water outflow from the lake.

Several forces influence the activity and processes of a lake and its ecological systems. Precipitation, climate, and ground-water dynamics are just a few of the many factors that influence lake level. These factors become particularly important when dealing with closed-basin lakes. There have been many studies that use various methods for measuring and quantifying relations between lake level, lake volume, and climate change.

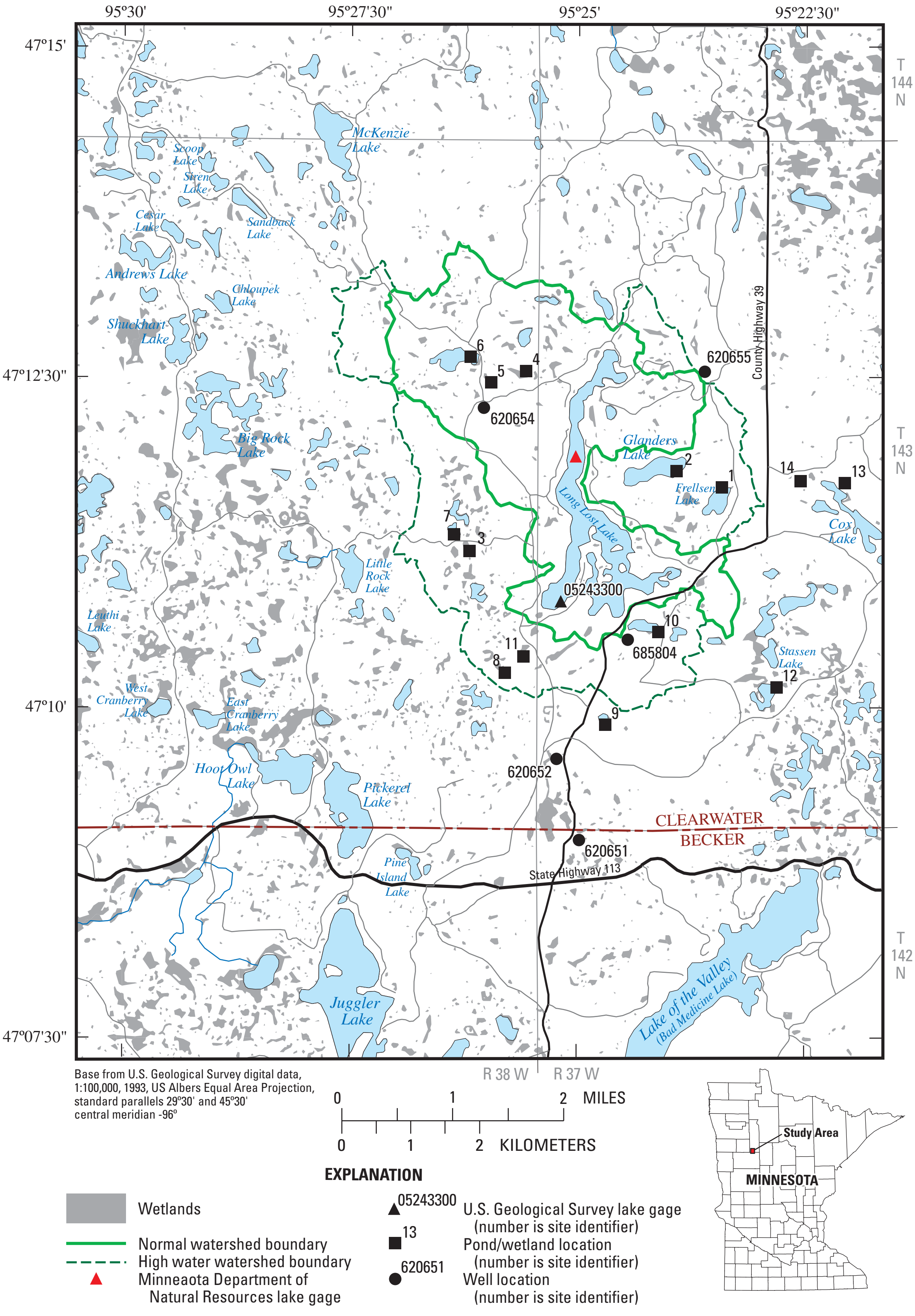

Figure 1. Long Lost Lake watershed, lake gages, observation wells, wetlands, and ponds, White Earth Indian Reservation, Clearwater County, Minnesota.

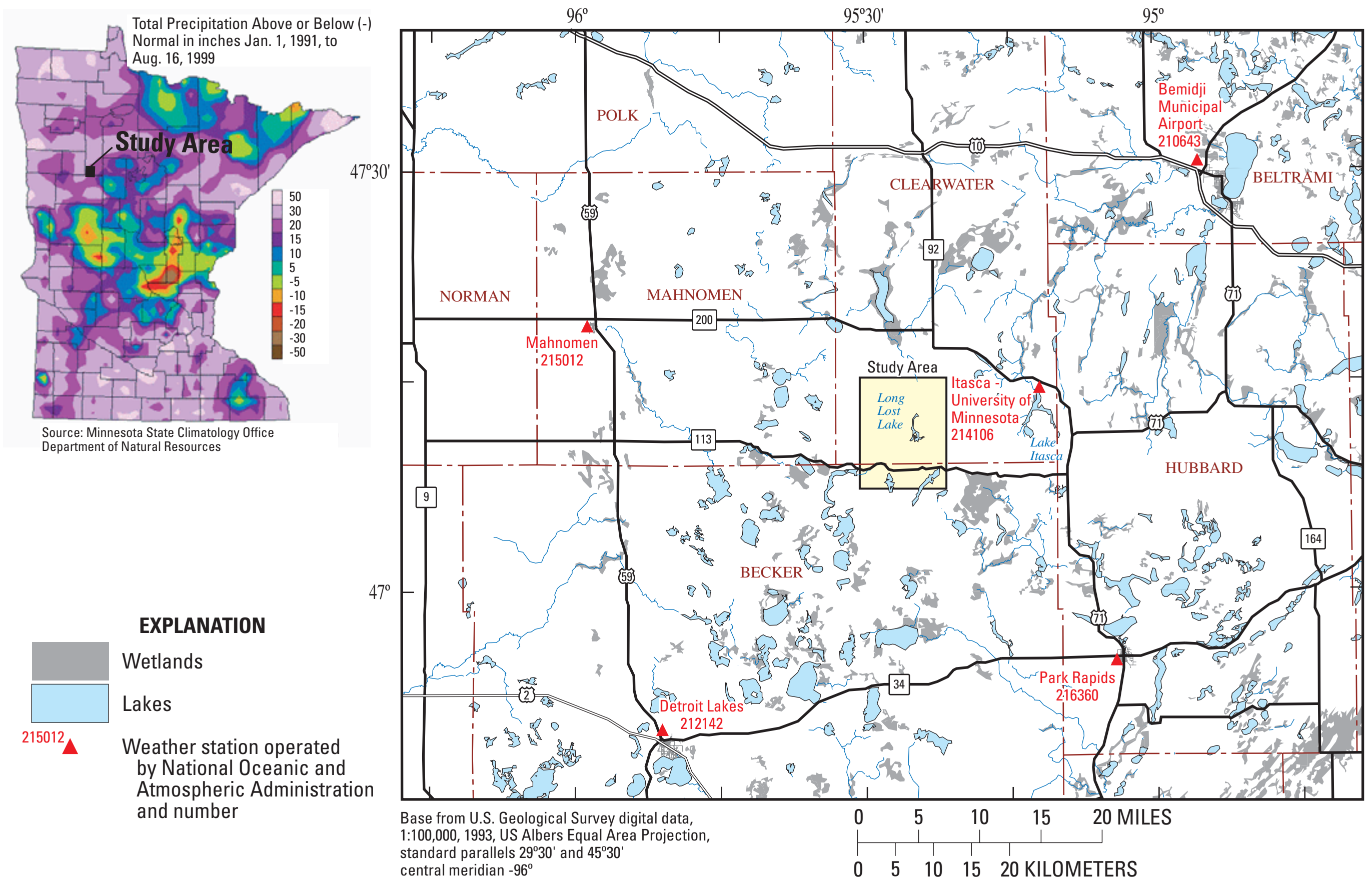

Figure 2. Total precipitation above normal, January 1, 1991, to August 16, 1999, and location of weather stations surrounding Long Lost Lake, White Earth Indian Reservation, Clearwater County, Minnesota.

Several other lakes in the region have had an increase in lake level during the 1980s and 1990s. These include lakes connected to streams and rivers, as well as closed-basin lakes. Because closed-basin lakes are more susceptible to factors such as climate, these lakes have been the topic of recent studies. The lake level at Devils Lake in North Dakota rose about 7.5 m between 1993 and 1999 (Wiche, Vecchia, Osborne, Wood, and Fay, 2000). Williams Lake and Big Marine Lake in Minnesota also had lake-level increases in the 1980s (Winter, 1997; Brown, 1985). At Big Marine Lake, residential development largely occurred during periods of low lake levels. Subsequently, residential damage due to flooding occurred later, when precipitation increased.

Climate and precipitation change is thought to be a major contributor to the fluctuation in levels for many lakes in the region. Investigations into climate change, such as Karl and Knight (1998), indicate an overall increase in precipitation throughout the 20th century. This increase includes frequency of heavy precipitation events as well as total annual precipitation.

An understanding of similarities and differences in lake-level changes in Long Lost Lake and in nearby lakes is necessary to understand hydrologic changes in Long Lost Lake. In addition, understanding conditions that affect the lake is important to the management of Tribal resources and for the protection of Tribal treaty rights. To address these needs, a study of the hydrologic conditions and lake-level fluctuations at Long Lost Lake was conducted by the U.S. Geological Survey (USGS) in cooperation with the White Earth Band of Chippewa Indians. The purpose of this study was to document historical lake-level fluctuations of Long Lost Lake, to determine the cause and effect relations that have resulted in the increased lake level, and to develop a general understanding of the hydrology of lakes that have had rapid changes in lake levels.

An understanding of cause and effect relations in closed-basin lakes is an important component in addressing concerns about continued increases in lake level. The methods used in this study could be used at other sites in Minnesota and the Nation to document historical conditions that have resulted in rising lake levels. The results of this study can be used to gain an understanding of the issues involved and the problems associated with rapid changes in lake levels. This information will help in the lake and watershed decisions that are needed to address the problem.

Purpose and Scope

The purpose of this report is to describe the hydrologic conditions and lake-level fluctuations at Long Lost Lake during 1939–2004. Water levels in five observation wells were monitored from October 2003 to December 2004, and water levels at 14 ponds and wetlands were measured in July 2004. Lake levels were measured continuously from August 2003 through December 2004. Additionally, a synoptic survey of temperature, specific conductance, pH, and dissolved-oxygen measurements was made along the shoreline of Long Lost Lake in July 2004. The water-level, lake-level, and synoptic survey data were used to describe hydrologic conditions.

Historical lake-level fluctuations were evaluated using aerial photography available from 1939 to 2001. Temperature and precipitation data that were compiled for the study were used to provide insights about whether the water-level fluctuations at Long Lost Lake are due to natural or anthropogenic effects.

Acknowledgments

The authors thank the volunteers, Becky Bergerson and Greg Scherzer, from the Long Lost Lake Association. Their measurement of ground-water levels provided this investigation with a better understanding of ground-water flow and direction. Their readiness to share data and assist with the study was appreciated.

Description of Study Area

The hydrologic setting of the study area surrounding Long Lost Lake (fig. 1) is not well understood due to the remote location, sparse population, limited lake access, and the hummocky and internally drained relief around the lake. Little information is available about the hydrology and hydrogeology of the watershed and about precipitation, lake level, ground-water levels, or ground-water recharge. Only anecdotal information is available about the level of Long Lost Lake prior to 1992, and about changes in the watershed that may have contributed to the increase in the level of Long Lost Lake.

Long Lost Lake is located within the Quaternary-age Itasca Glacial Moraine Complex, a massive accumulation of glacially deposited sediment with local relief of several hundred feet (Kanuit, 1996). The moraine, an east-west trending ice stagnation complex in north-central Minnesota, is approximately 130 km long and 30–50 km wide. The landscape of the moraine is heterogeneous. The moraine is topographically high and hummocky with many small lakes and hills typical of a glacial stagnation complex. The area is heavily dissected by tunnel valleys filled with glacial drift. Tunnel valleys were formed when meltwater was drained through long tunnels beneath the glaciers (Ojakangas and Matsch, 1982). Some tunnel valleys can provide a route for ground-water flow due to high permeability. Because of the relatively high topographic relief and broad geographic extent of the moraine, tunnel valleys may be a source of recharge for regional ground-water flow. The glacial deposits contain a surficial aquifer that is hydraulically connected to Long Lost Lake and to wetlands and ponds in the study area.

Early references included Long Lost Lake as part of the Crow Wing River watershed (U.S. Geological Survey, 1974); however, a recent re-classification of the area includes Long Lost Lake as part of the Mississippi River watershed (Chris Sanocki, U.S. Geological Survey, oral commun.). The contributing area for the lake is relatively small, about 13 km^2 (Bergman, 2004).

Potential sources of contamination, such as septic systems, may be especially important to water-quality issues because of the small contributing area. In 1993, the summer mean phosphorus concentration was 13 micrograms per liter (µg/L) (Paakh and Heiskary, 1994), indicating that the lake was mesotrophic. Changes in lake levels can have a substantial effect on water quality and eutrophication (Christensen and others, 2004). In addition, when the water table is high, the contributing drainage area increases to approximately 25 km^2 (Bergman, 2004), which may increase the number of potential sources of nutrients and other water-quality constituents within the watershed.

The land in the study area is primarily reserved for Tribal hunting and fishing, and for forestry and recreation. The watershed is 78 percent forest and 15 percent water (Paakh and Heiskary, 1994). Many of the homes surrounding Long Lost Lake are seasonal cabins occupied only during the summer. Additionally, the lake is a fishing destination with two public access points and a parking facility. These areas are now partially submerged. At one location boaters must access the lake directly from the entrance road, and the other access point is closed until the lake level recedes (Paakh and Heiskary, 1994). To reduce the effects of lake activity on the surrounding environment, a speed limit of 10 miles per hour (16.1 kilometers per hour) has been imposed across the entire lake.

The climate in the study area is characterized as humid continental with cool summers. Mean annual precipitation is about 69 cm (Midwest Regional Climate Center, 2003). Mean annual temperature is 2.8°C, mean summer temperature is 18°C, and mean winter temperature is about -14°C. Evaporation data are not available for the Long Lost Lake watershed; however, mean annual evapotranspiration for the nearby Mississippi headwaters area has been estimated to be about 51 cm per year based on 80 years of climatological data (data from the Minnesota Climatology Office). Williams Lake, which is about 50 km to the southeast in neighboring Hubbard County, has an evapotranspiration rate of almost 50 cm per year (Winter, 1997). Evaporation rate is a factor that influences lake level. Evaporation rates decrease during cool wet periods and increase during warm dry periods.

Previous Studies

Although no previous water-level studies have been conducted in the Long Lost Lake area, research from other locations provides relevant background information for studying lake-level fluctuations. This section provides examples of previous studies with relevance to creating historical records of hydrologic changes, describing studies of closed-basin lakes in the vicinity of Long Lost Lake, and using aerial photography to understand landscape change.

Hydrologic Change

To construct a historical record of lake level, it was important to first understand hydrologic conditions that might lead to changes in lake level as well as other methods used by researchers to track changes. Jones and others (2001) studied lake levels at three lakes in Australia that were falling at a rapid rate, and found that climate change and its influence on precipitation/evaporation ratios was the dominant factor in explaining lake-level change in closed-basin lakes. Land-use change was not a significant contributor to lake-level change. Although the historical change in lake levels was modeled, Jones and others (2001) did not use Geographic Information Systems (GIS) or aerial photography as tools in their investigation.

A study by Noe-Nygaard and Heiberg (2001) looked at climate and base-flow change as reasons for the rising water level of a lake in Denmark. Using sediment cores, the researchers created a historical record of the lake in a geologic timeframe. Increased sedimentation and ground-water levels were attributed to climate change. These changes also were correlated with lake-level rise. Although these findings are relevant to the general behavior of lake systems, the timeframe is too broad to apply to Long Lost Lake.

Closed-Basin Lakes

In many lakes, the dominant source of inflow and outflow is from streams. In closed-basin lakes, water is replaced only by ground-water discharge or precipitation. Inputs from ground water require that the water table is higher than the lake level to achieve head pressure (Wetzel, 2001). Changes in the levels of surrounding water tables or in the lake level can alter flow into and out of a closed-basin lake. Ground-water inflow rates to lakes are more sensitive to seasonal variations than are outflow rates (Krabbenhoft and others, 1990). In some cases, water losses occur in the deeper parts of a lake, but this water must travel through sediments, which reduces the amount of water lost compared to the water entering the lake through the littoral zone (Wetzel, 2001).

Several closed-basin lakes in the vicinity of Long Lost Lake have been studied. The USGS conducted a study of Devils Lake in North Dakota, which also had a substantial increase in lake level in the 1990s. Devils Lake is located within the Red River of the North watershed at approximately the same latitude as Long Lost Lake. Although larger and more populated than Long Lost Lake, it has similar temperature and precipitation conditions. The level of Devils Lake rose about 7.5 m between 1993 and 1999 (Wiche, Vecchia, Osborne, Wood, and Fay, 2000), yet is still approximately 4.0 m below its natural spill altitude to the Sheyenne River (a tributary to the Red River of the North). The rise and fall of the water level at Devils Lake also has contributed to water-quality concerns (Wiche, 1998). About 2,000 km^2 of surrounding land have been flooded, which exacerbates erosion problems around the lake. Emergency outlets and a diversion are currently (2005) under construction to alleviate some of the current and potential flooding and water-quality issues.

Temperature and precipitation changes were thought to be a major contributor to the lake-level changes at Devils Lake. A drought in the late 1980s led to a drop in lake level; this was followed by above-normal precipitation during the 1990s, which coincides with the most recent rise in the level of Devils Lake. This rise is important because of the damage caused by rising waters. There is geologic evidence that a similar lake-level rise occurred possibly twice within the past 4,000 years (Wiche, Vecchia, Osborne, and Fay, 2000). Radiocarbon dating of organic matter and sediments from surrounding beaches and soils were used to create a historical record for the early 1800s and before (Wiche, Vecchia, Osborne, Wood, and Fay, 2000). Wiche, Vecchia, Osborne, Wood, and Fay (2000) and Todhunter and Rundquist (2003) used lake measurements combined with satellite imagery. Although satellite imagery is a valuable resource in observing landscape change, the available resolution is too coarse for measurements of Long Lost Lake, which is much smaller than Devils Lake.

Williams Lake in northern Minnesota also is a well-studied closed-basin lake (Winter, 1997). Williams Lake is located in the upper end of the Shingobee River watershed and is situated in poorly sorted glacial drift. Environmental isotopes and sediment cores were used to determine hydrologic budgets and historical lake-level fluctuations. Sediment cores indicated that the lake level has fluctuated at least 6 m in response to climatic changes recorded in the lake sediments. Rosenberry (1998) concluded that a lake having no surface-water inflow or outlet is much more susceptible to changes in climate, even when the lake is well connected to ground water. It only takes about 3 years to replace all the water in Williams Lake (Rosenberry, 1998), despite having no surface water inflows or outlet.

Big Marine Lake in Washington County, Minnesota, does not have a surface-water inlet, and the altitude of the outlet is higher than the altitude of lake-shore properties. Considerable flooding of lake-shore properties occurred in the 1980s; the residential development took place during periods of relatively low lake levels in the 1950s and 1960s (Brown, 1985). Long-term trends in annual precipitation indicate that recharge has been increasing since the 1940s, and this corresponds to rises in lake levels.

Aerial Photography in Landscape Change

Aerial photography is an excellent resource for viewing the past and for monitoring temporal change in landscapes. Availability, high resolution, and low cost are reasons for using aerial photography as a tool for monitoring landscape changes. Aerial photography as a method for interpreting and analyzing geographic phenomena has gone through great advancements in the past half century. The technology available for processing aerial photographs has advanced from manual practices using stereoscopes to digital-processing methods available with advanced GIS software (Jensen, 1986). Despite these advances, an understanding of fundamental concepts using aerial photography for any purpose is necessary to apply these tools. Early works by Stone (1964) and Estes (1966) emphasized the value of using aerial photography as an additional tool for researchers. However, both authors stressed that aerial photographs should not be a substitute for field work, analog map interpretation, or other source material. These articles are nearly 40 years old, but they are similar to some literature written within the past 10 years (Smith, 1995; Baltsavias, 1996; Brostuen and Cox, 2000; Grip and others, 2000; Mayfield, 2000). Many fundamental concepts in aerial photograph processing and interpretation have not changed despite technological advances. Some of those important concepts described in the articles include obtaining appropriate coverage of the study area, becoming familiar with the quality of the images available, understanding rectification techniques, and learning the skills required for interpreting objects in the images.

The literature focuses on techniques and errors when processing aerial photography. Aerial surveys generate stereo-pair photography. This means that flight lines are flown such that the photographs have 60 percent overlap between images within one flight path as well as 20 percent overlap with images from adjacent flight paths. As a photograph is taken, only the ground surface at the center of the photograph directly below the camera is true to scale, and features become distorted towards the edge of the image. The overlap between images allows for the correction of these distortions when the photographs are viewed with a stereoscope. Ground-control points, identified from points of known locations, serve as the key to rectifying the images. Using the control points with elevation information allows researchers to rectify the images and use them to make direct measurements of landscape change.

Technological advances in photograph rectification have increased the capacity with which aerial photographs can be used. From serving as a map background to a source for precise measurements, aerial photography provides a unique perspective of the landscape and is an excellent resource for monitoring temporal changes.

Some studies used aerial photography as the sole data source for historical observation. To monitor landslide evolution, Casson and others (2003) used aerial photography and a digital elevation model (DEM) to track landslide movement and average velocity. These authors found that other imagery sources, such as remotely-sensed images, were not at an appropriate spatial resolution for their study. Reinfelds (1997) and Mount and others (2003) used aerial photography for measuring bankfull widths in streams by looking at horizontal changes at the water-land interface. These studies did not use other sources of imagery or spatial data.

Several studies have used aerial photography as a primary source for measuring landscape change (specifically shoreline dynamics), and abundant literature is available on monitoring the horizontal movement of landscape features. Byrnes and others (1995) studied shoreline change along the Louisiana coastline and developed a shoreline-change database using historical aerial photographs and global positioning system (GPS) coordinates. Using GPS coordinates in addition to aerial photographs provided these authors with more research options. Other resources that have been used with aerial photography include remotely sensed imagery (Hess and others, 1995) and digital photography and video (Livingstone and others, 1999). Similarly, Palandro and others (2003) used historical aerial photography and high-resolution Ikonos satellite imagery to study coral-reef changes. This study also focused on horizontal change and had the advantage of color photography and satellite imagery. In each of these studies, aerial photography provided a useful method for constructing historical records of shoreline change.

Although much of the literature shows promise for using aerial photography as a method for reconstructing historical records and for making temporal-change measurements, none of these studies have dealt specifically with lake levels and volume. Most studies focus on the horizontal movement or change of features. All the studies similarly identify the problem of photographic coverage and rectification as a substantial portion of their methodology. The literature supports the use of aerial photography and that information has been applied to Long Lost Lake and the creation of its historical record in this report.

Methods

Climatological changes and anthropogenic modifications within the Long Lost Lake watershed were considered as potential factors related to increased lake level. Addressing these factors required collection and interpretation of data on the hydrologic setting of the watershed and changes in climate, lake level, and ground-water levels. A monitoring network was established to understand the hydrologic setting and hydrologic budget of the lake relative to other lakes in the area. The initial hypotheses were that lake-level changes in Long Lost Lake may be caused by above-normal precipitation, climate change, land-use change, or changes in ground-water response. As a closed-basin lake, Long Lost Lake has no natural outlet and would be particularly sensitive to changes in any or all of these factors.

Information was collected and analyzed to assess historical changes in lake levels and to assess factors that may have contributed to these changes in Long Lost Lake and nearby lakes. These initial efforts also provided preliminary information about the hydrologic setting of Long Lost Lake.

Ground-Water Levels

Five observation wells were drilled into the surficial aquifer in the area surrounding Long Lost Lake (fig. 1) in September 2002. The locations of the wells were determined using a GPS device that has a horizontal accuracy of about 6 m. Altitudes of the wells were determined using techniques described by Kennedy (1990). These wells were monitored approximately monthly from October 2003 through December 2004 by volunteers from the Long Lost Lake Association using a steel tape, and verified quarterly using an electronic tape by USGS personnel. Selected information for these wells is presented in table 1. Additional data on these wells can be accessed on the World Wide Web at URL *http://waterdata.usgs.gov*.

Lake Level

Reliable data about lake level was essential for this study. The USGS installed an automatic recorder on Long Lost Lake in July 2003 (station 05243300). Water level was recorded from August 2003 through December 2004 using methods described in Buchanan and Somers (1968). The automatic recorder was serviced quarterly. Water-level data are available in Mitton and others (2005). The lake also was surveyed using differential GPS during July 2004 to get an altitude to use as the datum to relate lake level to levels of surrounding ponds, wetlands, and observation wells.

Pond and Wetland Levels

Fourteen ponds and wetlands (fig. 1) near Long Lost Lake were surveyed on July 7 and 8, 2004, to determine water levels. These ponds and wetlands may be hydraulically connected to the water table. By measuring the water level of these ponds and wetlands, it was possible to get a better understanding of the relation to adjacent ground-water levels and direction of ground-water flow. Two GPS devices were used to establish an altitude using a method known as differential GPS to reduce error (Chivers, 2003). This is a method whereby one GPS receiver, the base station, is located on a precisely known location and altitude (for this study, well number 620651). The known altitude was constantly compared to that given by the GPS receiver. The difference was applied to the data recorded by the second GPS receiver (located at the pond or wetland). Greater accuracy was obtained (standard deviation of 0.009–0.152 m) by using differential GPS over using a single GPS device alone. Three sites were measured more than once during the 2-day period. For these three sites, the altitude measurement with the smallest standard deviation was reported.

Lake Synoptic Survey

During July 2004, a synoptic survey of Long Lost Lake was conducted to help determine the direction of ground-water flow and areas of ground-water recharge to the lake. A multi-probe sonde was used to record water temperature and other field measurements (specific conductance, pH, and dissolved oxygen). Measurements were made at 45 locations approximately evenly spaced along the lake perimeter. The latitude and longitude of each measuring point was determined with a GPS device (with an accuracy of about 6 m) and recorded. These latitudes and longitudes were then used to plot the measurements on a map. Contour lines were generated using the Inverse Distance Weighting (IDW) method (Lam, 1983). This method assumes that each data point has local influence that diminishes with distance. These contour maps are not presented in this report, but are on file at the USGS Minnesota Water Science Center in Mounds View, Minnesota. Data for field measurements are available on the World Wide Web at URL *http://waterdata.usgs.gov*.

Table 1. Selected information for observation wells located near Long Lost Lake, White Earth Indian Reservation, Clearwater County, Minnesota.

[m, meters; ls, land surface]

USGS identification number	Minnesota well number (site identifier in fig. 1)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Land surface altitude (m above NAVD 88)	Screened interval (m below ls)	Well depth (m)	Date drilled	Water level (m below ls)
470852095250801	620651	47 08 52	095 25 08	497.72	11.35–12.88	12.88	09-16-2002	9.37
470943095250701	620652	47 09 43	095 25 07	499.12	11.43–12.95	12.95	09-17-2002	8.24
471218095260201	620654	47 12 18	095 26 02	521.98	8.73–10.29	10.29	09-19-2002	6.14
471229095233301	620655	47 12 29	095 23 33	516.49	22.10–23.62	23.62	09-18-2002	22.46
471058095233701	685804	47 10 58	095 23 37	496.62	10.85–11.77	11.77	09-17-2002	4.90

Historical Lake Levels and Climate Data

Historical analysis of lake levels at Long Lost Lake was done in three parts: (1) the collection and rectification of seven aerial photographs; (2) the processing and analysis of those photographs to create a historical record of lake levels and volume; and (3) the collection and analysis of concurrent climate and precipitation data to evaluate and explain hydrologic changes to the lake.

Aerial Photograph Collection, Rectification, and Processing

Aerial photograph imagery from 1991 and 2001 was relatively easy to obtain. It was in digital format, with good quality and high resolution, and was part of the USGS Minnesota Water Science Center spatial-data library. Aerial photograph coverage prior to 1990 was available from different agencies, and was collected in different formats, at different scales, and at different times of the year. The best resource for photography was the John R. Borchert Map Library at the University of Minnesota. Information on aerial photography is given in table 2. Bergman (2004) provides additional information on the aerial photographs used for this study.

In addition to aerial photography, supplementary data were needed for analyzing hydrologic and lake-level fluctuations at Long Lost Lake. These data included a National Elevation Dataset digital elevation model (NED DEM) (U.S. Geological Survey, 2003) and topographic maps for the area around Long Lost Lake. A bathymetric map, produced in 1972, was available from the MNDNR Lake Finder Web site (Minnesota Department of Natural Resources, 2003). Other spatial data collected included land cover, National Wetland Inventory, and Soil Survey Geographic (SSURGO) soil data, also from the MNDNR. Base data for the area also were compiled and used for representation and analytical purposes. These data layers include transportation features (roads, highways), hydrologic features (lakes, streams, wetlands), and political or administrative units.

The Long Lost Lake watershed also was delineated. The watershed is hummocky with many internally drained depressions, ponds, and wetlands. The normal contributing surface area (delineated as the normal watershed boundary in fig. 1) was determined by observing the topography on a USGS 1:24,000-scale topographic map. The potential contributing surface area (delineated as the high-water watershed boundary in fig. 1) included areas of non-contributing basins surrounding the normal contributing watershed. These non-contributing areas were identified as areas where the pond/wetland level would need to rise above two 10-ft contours (approximately 6 m) before contributing to the Long Lost Lake watershed. If that unlikely situation happened, those areas would flow into the Long Lost Lake watershed before flowing elsewhere.

Data Processing and Analysis

A base-surface model was used to calculate lake level and volume. The NED DEM required processing before it could be used in the analysis. The original NED DEM (U.S. Geological Survey, 2003) was created according to USGS national mapping standards with a 30-m grid cell. The problem with using the NED DEM as a surface model is that it was created from aerial photography and topographic maps and has inherent error in its production. For Long Lost Lake, the 30-m grid cell was too coarse to use for lake boundary altitude calculations, so the NED DEM was resampled to a 1-m grid cell. Another problem with using the NED DEM for analyzing the lakeshore is that the NED DEM levels off, following the surface of the lake rather than continuing into the lake to represent the bathymetry (fig. 3).

Table 2. Aerial photograph information and registration error per photograph, Long Lost Lake, White Earth Indian Reservation, Clearwater County, Minnesota.

[Modified from Bergman (2004). dpi, dots per inch; m, meters; --, not applicable]

Year	Scale	Resolution	Number of control points	Standard deviation (in meters)	Registration error (in meters)
1939	1:20,000	1000 dpi	10	X = 2.69 Y = 1.92	X = 2.55 Y = 1.82
1960	1:20,000	1000 dpi	12	X = 4.36 Y = 2.93	X = 4.17 Y = 2.81
1974	1:40,000	1000 dpi	14	X = 4.41 Y = 5.19	X = 4.25 Y = 5.00
1975	1:15,840	1024 dpi	10	X = 2.00 Y = 1.71	X = 1.90 Y = 1.63
1983	1:15,840	1024 dpi	13	X = 2.94 Y = 3.24	X = 2.82 Y = 3.12
1991	1:40,000	3 m	--	--	--
2001	1:40,000	600 dpi	13	X = 4.38 Y = 5.06	X = 4.21 Y = 4.86

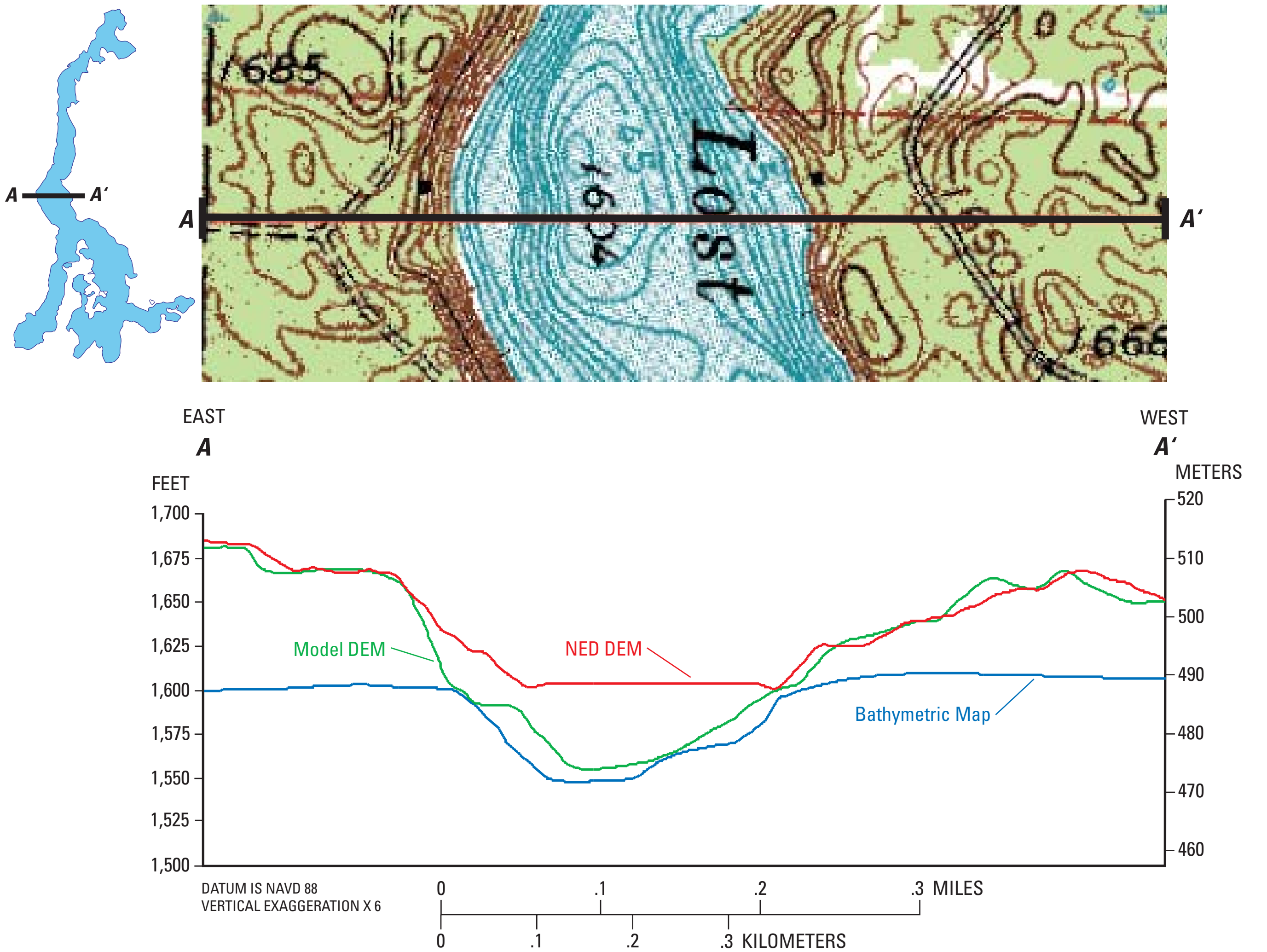

Figure 3. Profile comparison of bathymetric map, National Elevation Dataset (NED) digital elevation model (DEM), and model DEM for Long Lost Lake, White Earth Indian Reservation, Clearwater County, Minnesota.

The alternative method used for constructing a base-surface model was to use the contour lines from the USGS 1:24,000-scale Long Lost Lake topographic map. The bathymetric contour lines from within the lake as well as contour lines surrounding the lake were used to generate custom 10-m and 1-m surface grids. Despite the required manual corrections, this generated DEM (model DEM) represents a better approximation of the surface than the NED DEM. The 1-m surface was used as a base model for the analytical methods in this study, and is referred to hereinafter as the model DEM (fig. 3).

All spatial data and imagery were stored and analyzed using ArcInfo and ArcGIS software, developed by Environmental Systems Research Institute (ESRI) (Environmental Systems Research Institute, Inc., 2002, ARC 8.3). To add the hard copy photographs to the GIS database, they were scanned at 1,000 dots per inch (dpi) using a Microtek Scanmaker 9600XL office scanner. The photograph negatives were scanned at 1,016 dpi using a DSW500 Digital Scanning Workstation at the Minnesota Department of Transportation. These scanned images were at different scales, were not rectified, and thus did not line up in geographic space.

After creating digital versions of the aerial photography, it was necessary to identify a method for rectifying the images. OrthoMapper, a photogrammetric rectification software package developed at the University of Wisconsin at Madison, was used because this study required accurate photograph rectification to make direct measurements from the images. OrthoMapper allows the user to manually enter information about the photograph, such as flight height and camera focal length, or the user can accept default values common to most aerial photography (Image Processing Software, Inc., 2003). When using these features, along with well-placed ground-control points and a DEM, the images can be accurately rectified. A 1991 USGS Digital Orthophoto Quad (DOQ) provided horizontal positional accuracy, and the NED DEM was used for vertical control.

Accurate ground-control point selection allows the aerial images to line up in geographic space. Because some of the changes in the lake boundary may be very small, even slight errors in ground-control points may induce great error in the results as the image is adjusted. For most images, it was not difficult to identify ground-control points at road intersections, sharp bends in roads, or other prominent features. The 1939 and 1960 images showed very few roads or other visible permanent cultural features. In some cases, ground-control points had to be placed on natural features, such as a distinct point on a tree line or the center point of an island or peninsula. This was done only where the same feature was still evident on the 1991 DOQ.

For each image, the root mean square error was minimized by tracking the residual that OrthoMapper records and updates with each added or deleted control point (table 2). The output orthophotos were produced at a 0.5-m pixel resolution. Because the horizontal control was provided by the DOQ, all the orthophotos matched the DOQ projection (Universal Transverse Mercator), datum (North American Datum of 1983), and ellipsoid (Geodetic Reference System of 1980) (U.S. Geological Survey, 1996). The output grids were stored in a Tag Image File Format (TIF), which can be viewed with ArcInfo and ArcGIS.

Lakeshore Delineation

Initial qualitative analysis of the changes to the lake was done by adding the rectified photographs to a desktop GIS application. Observations of general changes to the lake such as the appearance or elimination of islands, and connections or separations to side pools were noted. To record more detailed information on changes, and to perform quantitative analyses, the shoreline of the lake was recorded. Two approaches were taken to record this boundary— automated pixel classification and digitizing.

Automated pixel classification was initially favored because the result could be repeatable and was less subjective. The photographs were processed using unsupervised classification techniques in ERDAS Imagine (Leica Geosystems, 2002; Lillesand and Kiefer, 2000). Boundary digitizing was the other method used for identifying the lake edge. Although this method has inherent subjectivity and human error, it also allows for individual attention and interpretation in questionable areas. Where the lake boundary was clear in a photograph, the automated classification worked well. However, there were many places where the lake boundary was ambiguous. Digitizing was determined to be the best method for identifying the lake boundary. In several photographs, the edge of the lake showed the presence of marshy, vegetated areas, so boundaries were not definitive. Background knowledge and photograph interpretation skills helped to determine the boundary where the automated classification failed. For example, the automated classification outlined every detail along the lakeshore, including algae blooms and overhanging trees. With digitizing, these details can be generalized to where the shore likely falls. A comparison of lake surface areas between the digitized boundaries and automated pixel boundaries yielded an average of 5 percent difference in surface area. Although this indicates that either method would be feasible for representing the lake boundary, the post processing for automated classification was more time consuming.

An additional issue with defining the lake boundary is that, although OrthoMapper is a sophisticated tool for rectification, the resulting orthophotographs were not perfectly rectified. There were still some minor differences and shifts among the different years of photography. This is not a substantial problem when making qualitative observations, but it becomes more so when the boundaries need to be used for direct comparisons and measurements. To resolve this situation, the boundaries were carefully shifted to line up close to a common center of gravity on the base-surface model. For example, if the lake boundary from one year was consistently shifted slightly to the northwest from the base-surface model, it was shifted to the southeast until it was centered on the base-model lake boundary. This adjustment was most effective on the west shoreline in the middle section of the lake, where the landscape becomes very steep and contour lines are very close together. If the digitized boundary was out of line due to error in rectification, it could result in the line crossing two or more contours, altering the results.

Lake Level and Volume

The lake level was determined based on the lake boundary and its relation to the model DEM. After converting the digitized lake boundary vector to 1-m grid cells, it was overlaid on the model DEM. By adopting the model DEM values, the lake-boundary grid could be analyzed to estimate the lake level using simple statistical analyses. The mean and mode of the resulting grids were recorded, and histograms of the data were plotted. The digitized boundary grids also were overlaid on the resampled DEM merged with the MNDNR bathymetric map as an altitude comparison.

Lake volume was calculated based on the model DEM and the determined lake levels. A grid representing the lake was assigned the value of the surface altitude. The model DEM was subtracted from this grid to obtain the depth of each 1-m grid cell. These grid cells were summed to obtain the total volume for each measured year.

Climate and Precipitation

Climatological data were needed to establish the relation between trends in precipitation and evapotranspiration with changes in the level of Long Lost Lake. Available regional climatological data were compiled and assessed to determine historical trends. Precipitation and climate data were obtained from the Minnesota State Climatology Office. Data were compiled for the closest weather stations (fig. 2): Itasca (214106), Bemidji (210643), Detroit Lakes (212142), Mahnomen (215012), and Park Rapids (216360). Records compiled included monthly precipitation, maximum temperature, minimum temperature, and snowfall. Different periods of record were available for each of the five weather stations. The closest station (Itasca) was used as the base station. Records from this station were from 1911 to 2003. Climate calculations for all stations were based on a period from January 1911 to December 2002. Any years with missing records were not used in the analysis; no attempt was made to interpolate missing values. Other climate data compiled included storm events for Clearwater, Becker, Hubbard, and Mahnomen Counties, regional median frost dates, and soil freeze dates. Precipitation and temperature for years prior to each aerial photograph were separated from the period of record in 5- and 10-year increments to evaluate how precipitation and temperature may have influenced the lake measurement in the photograph.

Hydrologic Conditions and Lake-Level Fluctuations

Hydrologic conditions for Long Lost Lake are described using analyses of recent surface and ground-water levels collected during 2003–2004 and using water temperature, specific conductance, pH, and dissolved-oxygen data collected during a synoptic lake survey in July 2004. Historic lake-level fluctuations are evaluated using aerial photography available from 1939 to 2001. The relation between historical lake levels and volume and climate is evaluated using temperature and precipitation data compiled for the study.

Recent Surface- and Ground-Water Levels

Lake levels were recorded continuously from August 2003 through December 2004. The purpose was to establish a temporal, detailed record of lake levels and to connect this record to precipitation and ground-water-level data. A long-term lake-level record is critical to understanding the relation between surface water and ground water. This is especially true for closed-basin lakes. Between August 2003 and December 2004, the lake level showed a general decline. The highest lake altitude measured on Long Lost Lake during August 2003 to December 2004 was 492.58 m above NAVD 88 on August 5, 2003, and the lowest was 492.11 m above NAVD 88 measured on August 29, 2004 (fig. 4).

The continuous lake-level data were used to evaluate lake-level fluctuations with corresponding changes in ground-water levels and the water levels of surrounding ponds and wetlands. Water levels were measured in five observation wells (fig. 1) from 2002 to 2004. These data were used to prepare maps of the water table in the surficial aquifer to determine the extent of the area that contributed ground water to Long Lost Lake. These ground-water-level measurements are listed in table 3 and shown in figure 4. Wells 620654 and 620655, which are on the north side of the study area, have water-level altitudes that are higher than the lake, whereas wells 620651, 620652, and 685804 have water-level altitudes that are lower than the lake. Because the ground-water level information was sparse, additional data were needed to determine areas of ground-water contribution. GPS equipment was used to gather additional information regarding water-surface altitudes of lakes, ponds, and wetlands because they likely are expressions of the water table. The surface-water data were used to supplement the data from existing wells.

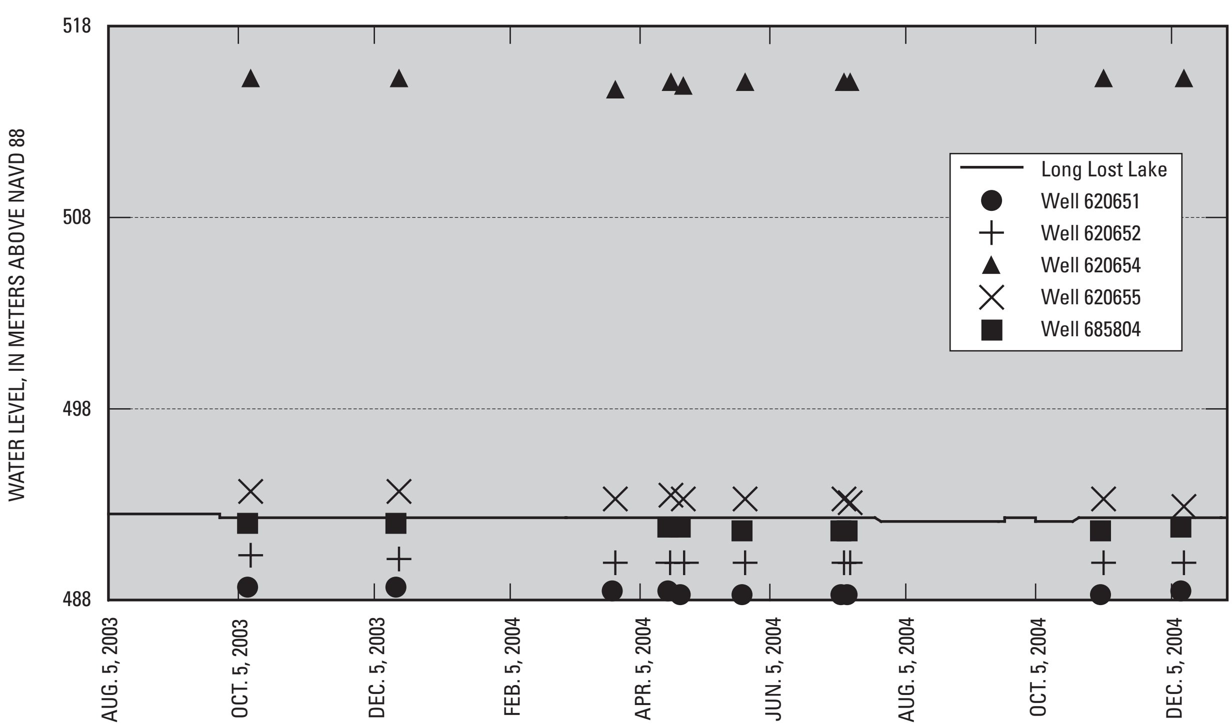

Figure 4. Lake-level readings from Long Lost Lake and ground-water levels, August 2003 through December 2004.

Table 3. Water-level altitudes for observation wells surrounding Long Lost Lake, White Earth Indian Reservation, Clearwater County, Minnesota, 2002–2004.

[--, no data]

Date	Water-level altitude, in meters above NAVD 88				
	Minnesota well number (site identifier in fig. 1)				
	620651	620652	620654	620655	685804
09-2002[1]	488.35	490.88	515.84	494.03	491.65
10-10-2003	488.64	490.33	515.35	493.73	491.86
12-17-2003	488.53	490.22	515.21	493.62	491.83
03-24-2004	488.35	490.03	514.67	493.30	--
04-20-2004	488.33	489.99	515.01	493.47	491.76
04-25-2004	488.27	489.96	514.95	493.23	491.63
05-23-2004	488.25	489.94	514.99	493.21	491.61
07-07-2004	488.23	489.94	515.06	493.36	491.61
07-11-2004	488.22	489.91	515.05	493.05	491.55
11-04-2004	488.18	489.95	515.19	493.26	491.49
12-13-2004	488.20	489.95	515.31	492.99	491.70

[1]Initial water levels were measured between September 16 and 19, 2002.

During July 2004, water levels of 14 surrounding lakes, ponds, and wetlands were surveyed along with the 5 observation wells to determine altitudes (table 4). Initial interpretation of the altitudes assumed that the surface-water bodies were part of the ground-water table and were not isolated or perched. Upon observation, many water levels of these water bodies appeared to have risen substantially in recent years. This evidence included submerged trees, roads, and trails. All data collected during July 2004 was plotted on a map of Long Lost Lake (not shown), which indicated that the general direction of ground-water flow is north-northwest to south-southeast. The level of the ground-water table to the north of Long Lost Lake is substantially higher than the lake level. This provides the required head pressure for ground water to flow into Long Lost Lake.

Five of the pond/wetland sites (sites 9, 10, 12, 13, and 14) and two wells (685804 and 620651) are on the southeast side of County Highway 39 (fig. 1). If County Highway 39 was an impediment to ground-water flow, the water level of Long Lost Lake would be considerably higher than the levels of ponds/wetlands and the ground-water level to the south and east of the highway. Pond/wetland sites 12, 13, and 14 had levels higher than Long Lost Lake, whereas site 10 had the same water level as the lake during the GPS survey. Well 685804 is directly southeast of the Long Lost Lake gage and on the southeast side of County Highway 39 and had a water level of 491.61 m during the GPS survey, which is consistent with the regional water-table gradient. In addition, the lake had a water level of 492.25 m, indicating that the highway is not substantially restricting ground-water recharge from southeast Long Lost Lake to the surficial aquifer.

Table 4. Pond and wetland levels near Long Lost Lake, White Earth Indian Reservation, Clearwater County, Minnesota, July 2004.

Pond/wetland identification number (fig. 1)	Water level (meters above NAVD 88)
1	494.12
2	493.50
3	508.89
4	505.65
5	511.33
6	510.59
7	507.35
8	492.04
9	491.28
10	492.16
11	492.25
12	492.25
13	492.84
14	492.53

Synoptic Lake Survey Results

On July 13, 2004, a synoptic survey of Long Lost Lake was conducted. Synoptic surveys show a snap-shot of conditions at a particular moment in time. The purposes of a synoptic survey are to provide a better understanding of environmental conditions and to determine where further investigation may be necessary. This synoptic study was an efficient method of assessing lake conditions, requiring only a multi-parameter probe and no other analytical equipment or samples. Conditions measured were water temperature, specific conductance, pH, and dissolved oxygen.

The synoptic survey focused on the lake's perimeter because the silt at the bottom of most lakes restricts the ground-water flow into the lake (Wetzel, 2001), and most flow into a lake occurs in the littoral zone (Winter, 1978). Temperature-survey data collected during the synoptic survey showed that temperatures were colder at the northern end of the lake than at the southern end of the lake, indicating a north to south flow. The coldest lake temperature (17.5°C) was measured on the eastern shore of the northern part of the lake. Temperature patterns in the southern part of the lake are less apparent. Temperatures along the eastern shore are slightly less than those along the western shore, but these differences may not be significant. The temperature data indicate a north-northeast to south-southwest flow in the northern part of the lake; however, this direction does not appear to be maintained in the southern part of the lake.

Specific conductance in the northern part of the lake increased slightly from north to south. Values on the eastern shore were less than those along the western shore. This pattern is similar to temperature data. Specific conductance in the southern part of the lake was greater on the southwest shore than on the southeast shore. One exception is a data point near the southern end of the peninsula (northeast of the USGS lake gage in fig. 1) where a specific conductance of 279 microsiemens per centimeter at 25°C was measured (compared to 269–271 microsiemens per centimeter at surrounding sites). The temperature at this point (18.0°C) was lower than surrounding data points (18.6–18.9°C).

Values of pH in the northeastern end of the lake were slightly less than those in other areas of the lake, but did not show a directional trend. The greatest dissolved-oxygen concentration was measured along the northern shore of the lake. Dissolved-oxygen concentrations were slightly greater on the northwestern shore than on the northeastern shore, and concentrations in the southeastern corner of the lake generally were less than those measured along the northern shore. No specific directional trends in dissolved-oxygen concentration were clear, due in part to the large range of dissolved oxygen measured over small distances.

The observed patterns determined during the synoptic survey indicate a north-northeast to south-southwest flow in the northern part of the lake, with an increasing east to west component in the southern part of the lake. The temperature, specific conductance, pH, and dissolved-oxygen data all identify one data point located at the southeast end of the southern peninsula (northeast of the USGS lake gage in fig. 1) with temperature and specific conductance values slightly different than surrounding values, and dissolved oxygen and pH values substantially different than surrounding values. This location may be influenced by some other water source (possibly a point discharge) and was not considered important in determining the overall north to south trend in the lake.

Aerial Photography for Measuring Historic Lake-Level Fluctuations

Determination of the extent of the contributing watershed, the contributing ground-water basin, and lake/watershed ratios is critical to understanding the hydrology of Long Lost Lake. This information was difficult to determine for Long Lost Lake because the topography in the vicinity of the lake's watershed is hummocky, and internally drained into small depressions, ponds, and wetlands. The extent of the watershed contributing runoff to Long Lost Lake was determined using existing GIS data from topographic and digital-elevation model information.

Maps of the watershed showing contributing (normal watershed boundary) and potential contributing (high-water watershed boundary) areas were prepared (fig. 1). Delineation of the area that contributes ground water to Long Lost Lake and the magnitude of ground-water recharge were critical to understanding lake and ground-water interactions. The extent of the area contributing ground water likely is different from the area that contributes to overland runoff to the lake. It is likely that ground-water recharge in the Long Lost Lake watershed is abnormally high because of substantial internal (closed basin) drainage.

Visual comparisons of unrectified images clearly showed a substantial rise in lake level from the 1939 imagery to 2001 (fig. 5a and b). Delineation of the lakeshore provided a method for quantifying the change in lake area. The lake boundary was determined for each of the aerial photographs described in table 2.

After rectification of the photographs and delineation of the shoreline, the changes became even more apparent when they were displayed in the same geographic space (fig. 5c). Based on the digitized boundaries of the lake, the surface area increased from 94 ha in 1939 to 206 ha in 2001.

The results from overlaying the lake boundaries on the model DEM showed the expected rise in lake level between the 1939 photograph and the 1960 photograph, a stable period, then an additional rise between 1991 and 2001 (Bergman, 2004). Although the lakeshore grid statistics reflect the rise in level of Long Lost Lake, they do not match the anticipated level exactly. For example, the estimated lake altitude for the 2001 photograph based on the digitized boundary is 491.74 m above NAVD 88 (Bergman, 2004). The MNDNR gage recorded an altitude of 492.71 m above NAVD 88 the day before the aerial

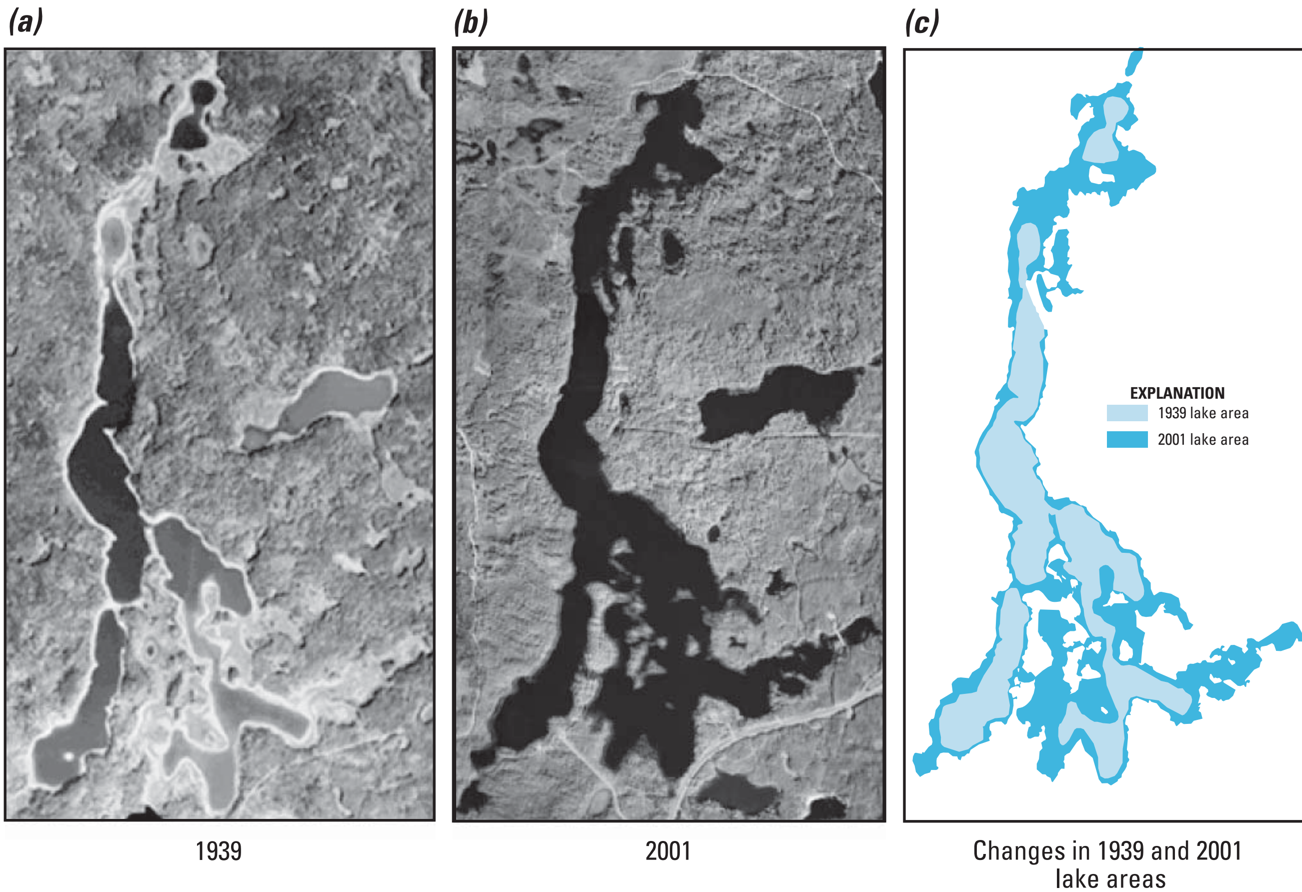

Figure 5. Historical aerial photographs of Long Lost Lake, (a) 1939 and (b) 2001, and (c) map showing changes in the 1939 and 2001 lake areas.

photograph was taken. The change in digitized lake altitude from 1991 to 2001 is less than 2.5 m, whereas readings from the MNDNR lake gage indicate that it was about 4 m. However, the estimated altitude of 492.77 m above NAVD 88 based on the automated pixel boundary for 2001 is similar to the MNDNR gage reading, and the change in lake altitude from 1991 to 2001 is 2.74 m. This strengthens the concept of using the automated pixel boundary for a guide; however, because digitizing was determined to be the best method for identifying the lake boundary, only digitized statistics are presented herein. Using the digitized boundaries with the model DEM, a historical lake record from 1939 to 2001 was compiled and is presented in table 5. Changes in lake altitude and volume at Long Lost Lake are presented in more detail in Bergman (2004), including a comparison of digitized and automated pixel grid statistics.

Table 5. Changes in surface area, water-level altitude, and volume, Long Lost Lake, White Earth Indian Reservation, Clearwater County, Minnesota.

[ha, hectare; m, meter; hm^3, cubic hectometer]

Year	Digitized surface area (ha)	Water-level altitude (m above NAVD 88)	Volume (hm^3)
1939	93.89	487.52	3.29
1960	151.94	489.23	5.28
1974	155.79	489.25	5.52
1975	155.56	489.20	5.44
1983	151.65	489.09	5.27
1991	160.98	489.42	5.81
2001	205.99	491.74	10.24

Relation of Historical Lake Levels and Volume to Climate

Throughout the 20th century, precipitation and temperatures in the study area generally have increased. This holds true for the Itasca weather station, as well as for the other nearby weather stations: Bemidji, Detroit Lakes, Mahnomen, and Park Rapids. The average annual low temperatures have increased slightly, while average annual high temperatures have remained stable. To characterize these trends, average temperatures were grouped in 10-year periods. Average low temperatures for Itasca increased from -4.2°C during 1910–1919 to -2.7°C during 1990–1999. Average low temperatures for the five stations increased from -3.5°C during 1910–1919 to -1.6°C during 1990–1999. Average high temperatures for Itasca, however, decreased slightly from 10.2°C during 1910–1919 to 9.8°C during 1990–1999. The average high temperature for the five stations increased slightly from 10.1°C during 1910–1919 to 10.5°C during 1990–1999.

Precipitation has increased in the area surrounding Long Lost Lake during the 20th century. The years preceding the 2001 aerial photograph were particularly wet—annual precipitation departures from normal were 25.4 cm (Minnesota State Climatology Office, 2003). Precipitation for 1999 ranked in the top 90 to 95 percent when compared to annual totals for the 100-year period, 1891–1990, and 1999 represents the maximum in departure from normal precipitation. The years 1998, 2000, 2001, and 2002 also had large departures from normal precipitation. Total precipitation above normal for January 1, 1991, to August 16, 1999, in Minnesota shows the study area received above-normal precipitation during the period (fig. 2). With average annual maximum temperatures remaining relatively stable, evaporation rates also were stable. With all other factors constant, an increase in precipitation and no increase in evaporation results in an increased lake level. As a closed-basin lake, increasing precipitation and stable evaporation can be a major factor in lake-level increases at Long Lost Lake.

Extended dry and wet periods also have influenced lake levels and volume. This is evident from the aerial photography; drier years from early in the 1900s, and possibly earlier, led to the low lake level in 1939. Around 1950, as precipitation began to increase, the lake level also increased. The late 1980s also were dry years in the study area. Many lakes in central Minnesota had declines in lake levels from 1986 to 1988 (Minnesota Department of Natural Resources, 1989). The level at Rice Lake, in Stearns County, dropped about 1.5 m, and the level at Mille Lacs, in Mille Lacs County, dropped nearly 1 m. There were no aerial photographs of Long Lost Lake for the late 1980s to evaluate whether there was a decline in lake level during this period; however, the lake level declined between 1974 and 1983, and only rose slightly between 1983 and 1991 (table 5).

Estimated lake volume of Long Lost Lake and cumulative precipitation were compared (fig. 6). The estimated lake volume shows a substantial rise through the early part of the 20th century, a leveling off during the mid to late part of the century, and a substantial rise during the final decade. Because Long Lost Lake is a closed-basin lake, the lake volume in any year is affected by the precipitation from the current year as well as previous years. Therefore, cumulative precipitation was plotted in figure 6 to compare estimated volume to the cumulative effect of yearly precipitation. The general trend in lake volume coincides with temperature and precipitation changes during the 20th century.

The substantial rise in lake level and lake volume between 1991 and 2001 coincides with the stable annual maximum temperatures (and thus, evaporation rates) and the increase in precipitation in the years preceding 2001. Although precipitation and estimated lake volume increased from 1939 to 2001, the leveling off of the lake volume between about 1960 and 1990, followed by the rapid rise in lake level and volume in the 1990s needs further investigation. Ground-water discharge to Long Lost Lake is not well understood, but may have stabilized lake levels through the drought period.

The explanation for the sharp rise in the lake level in the 1990s can be attributed to above-normal precipitation. The rapid lake-level rise seems to be a normal response to changes in climate. However, changes in land cover around the lake should be considered because increased impermeable surfaces can increase runoff to the lake. Aerial photography has shown that substantial road construction has occurred around the lake, with paving between the 1983 (Bergman, 2004) and 2001 photographs. The Clearwater County Engineering Department reported that County Highway 39, which runs along the south and east sides of the lake, was straightened during 1989 and 1990, and it was paved in 1992. The increase in impervious surfaces around a lake may increase both runoff and sedimentation to the lake. Because Long Lost Lake is a closed-basin lake with no outlet, the response to above-normal precipitation and increased impervious surface could be rapid.

To understand the ground-water component and the effect of impervious surfaces, further investigation and analysis, including a longer period of record, is necessary. Continuing to measure ground-water levels in existing observation wells would provide a longer period of record for additional analyses in the future.

It also is likely that the lake level at Long Lost Lake is historically normal. A direct comparison was made between the 1939 and 2001 aerial photographs (fig. 5). The lake level was very low in 1939, and a dry non-vegetated area surrounded the lake in 1939 that is nearly identical (5 percent difference) to the 2001 lakeshore boundary. This is evidence that the water level at Long Lost Lake may have been as high as the 2001 water level in the past. However, one cannot rule out the possibility that increased impermeable surfaces surrounding the lake had an effect on the most recent (1990s) rise in lake level.

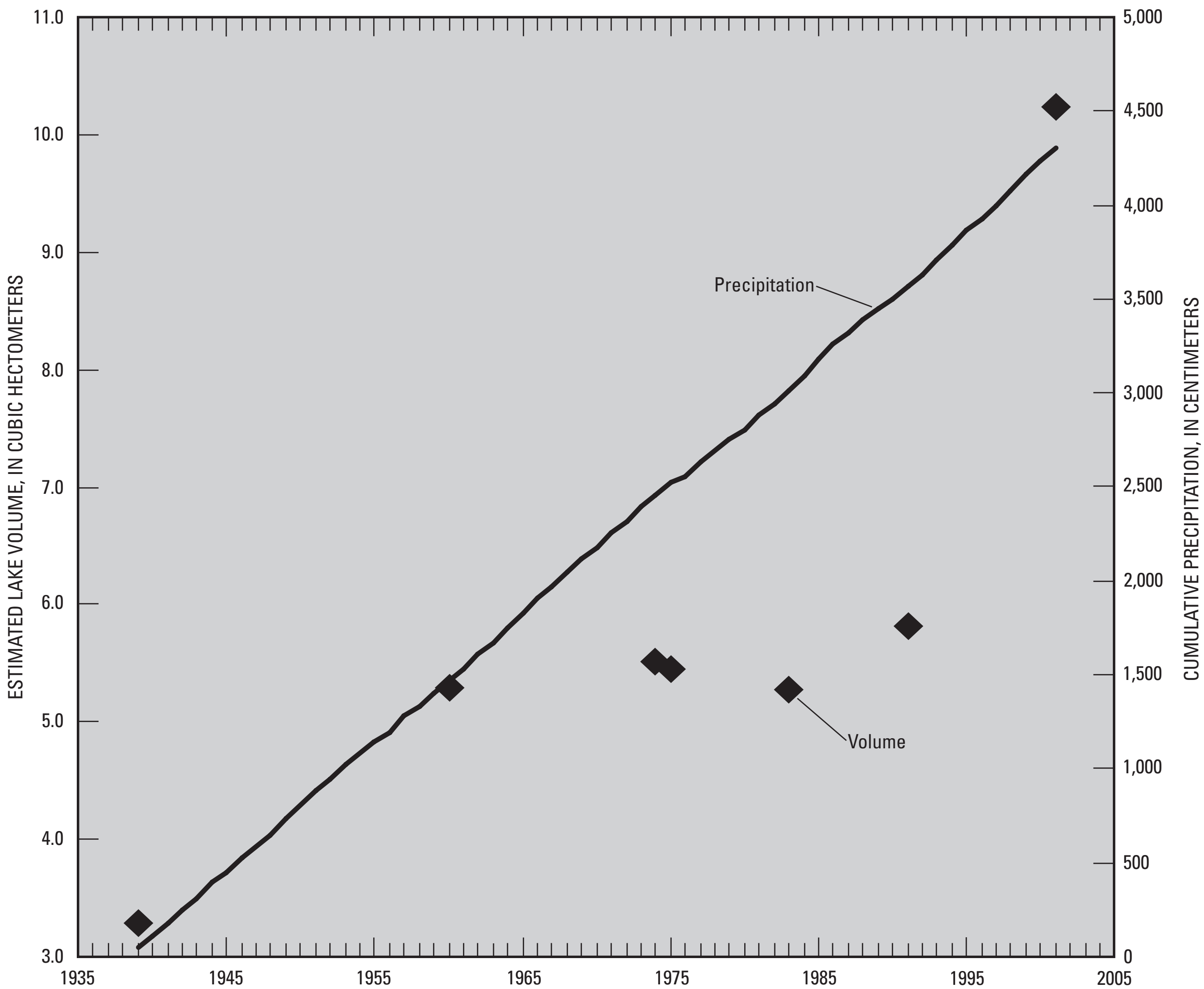

Figure 6. Lake volume estimated from digitized and photographic lakeshore boundary grids, compared to cumulative precipitation, Long Lost Lake, White Earth Indian Reservation, Clearwater County, Minnesota.

Summary

Long Lost Lake, a closed-basin lake in Clearwater County, Minnesota, has had a substantial rise in lake level since 1990. The increased level and surface area of the lake has led to the inundation of nearby homes and roads. There was concern that the improvement of County Highway 39 along the south and east side of the lake may have contributed to lake-level rise by restricting discharge from the lake to ground water. The U.S. Geological Survey (USGS) in cooperation with the White Earth Band of Chippewa Indians conducted a study to document historical lake-level fluctuations of Long Lost Lake, to determine the cause and effect relations that have resulted in the increased lake level, and to develop a general understanding of the hydrology of lakes that have had rapid changes in lake levels.

Lake levels were recorded continuously from August 2003 through December 2004. The purpose was to establish a temporal, detailed record of lake levels and to connect this record to precipitation and ground-water level data. A long-term record is critical to understanding the relation between surface water and ground water. This is especially true for closed-basin lakes. Between August 2003 and December 2004, the lake level generally declined. The highest lake altitude was 492.58 m above NAVD 88 on August 5, 2003, and the low of 492.11 m above NAVD 88 occurred on August 29, 2004.

Water levels were measured in five observation wells from October 2003 through December 2004. Because this information was sparse, additional data were needed to determine areas of ground-water contribution. For that reason, global positioning system (GPS) equipment was used to gather information on water-surface altitudes of lakes, ponds, and wetlands because they likely are expressions of the water table. The water table is substantially higher than the lake level on the north side of the lake, indicating potential ground-water discharge to the lake in this area. Five of the surface water sites are on the southeast side of County Highway 39. These sites along with two of the observation wells show that water-table levels south and east of Long Lost Lake are similar to the level of Long Lost Lake. These data indicate that the recent highway improvement has not restricted ground-water flow between Long Lost Lake and the surficial aquifer to the southeast; however, the increase in impervious surfaces surrounding the lake may increase runoff to the lake.

On July 13, 2004, a synoptic survey of Long Lost Lake was conducted. This synoptic survey was a method of assessing lake conditions, requiring a multi-parameter probe. Conditions measured were water temperature, specific conductance, pH, and dissolved oxygen. The observed patterns determined during the synoptic survey indicate that ground-water flow is from the north-northwest to the south-southeast.

Because of the lack of long-term hydrologic data, aerial photography was used to establish a historical record of lake level and volume for Long Lost Lake. Seven aerial photographs of the Long Lost Lake watershed were collected and rectified. Geographic Information Systems software was used to store, analyze, and visualize the data and results for Long Lost Lake. The main analytical steps began with the identification of the lake boundary from each photograph. This boundary was then used to identify the surface altitude of the lake based on the position of the lake edge on a digital elevation model (model DEM). Lake volume was calculated based on the surface altitude, lake boundary, and model DEM. Finally, the generated record of lake level and volume was compared with temperature and precipitation data to observe correlations and trends.

The lake levels and volume rose early in the 20th century, were stable during the middle of the century, and substantially increased during the final decade. These results coincide with temperature and precipitation changes. There is evidence in the 1939 photograph (a large non-vegetated area) that lake levels have been high in the past. The boundary of the non-vegetated area is nearly identical to the 2001 lake boundary. Based on this, changes to the lake are primarily natural and historically normal. Although other factors such as land-use change and ground-water response probably play a role in the rising level of Long Lost Lake, short-term ground-water-level data did not allow for that analysis. Continuing to measure ground-water levels at the existing wells may provide the information necessary to evaluate ground-water response. In addition, monitoring of the pond, wetland, and ground-water levels on both sides of County Highway 39 would provide additional information for evaluating the effect of that impervious surface.

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