Climatology, Hydrology, and Simulation of an Emergency Outlet, Devils Lake Basin, North Dakota

Abstract

Devils Lake is a natural lake in northeastern North Dakota that is the terminus of a nearly 4,000-square-mile subbasin in the Red River of the North Basin. The lake has not reached its natural spill elevation to the Sheyenne River (a tributary of the Red River of the North) in recorded history. However, geologic evidence indicates a spill occurred sometime within the last 1,800 years. From 1993 to 1999, Devils Lake rose 24.5 feet and, at the present (August 2000), is about 13 feet below the natural spill elevation. The recent lake-level rise has caused flood damages exceeding $300 million and triggered development of future flood-control options to prevent further infrastructure damage and reduce the risk of a potentially catastrophic uncontrolled spill. Construction of an emergency outlet from the west end of Devils Lake to the Sheyenne River is one flood-control option being considered. This report describes the climatologic and hydrologic causes of the recent lake-level rise, provides information on the potential for continued lake-level rises during the next 15 years, and describes the potential effectiveness of an emergency outlet in reducing future lake levels and in reducing the risk of an uncontrolled spill. The potential effects of an outlet on downstream water quantity and quality in the upper Sheyenne River also are described.

Introduction

The Devils Lake Basin is a 3,810-square-mile (mi^2) subbasin (fig. 1) in the Red River of the North Basin. About 3,320 mi^2 of the total 3,810 mi^2 is tributary to Devils Lake; the remainder is tributary to Stump Lake. At an elevation of 1,446.5 feet (ft) above sea level (asl), Devils Lake begins to spill into Stump Lake; and at an elevation of about 1,459 ft asl, the combined lakes begin to spill through Tolna Coulee into the Sheyenne River (fig. 2).

Since the end of glaciation about 10,000 years ago, Devils Lake has fluctuated from about 1,459 ft asl, the current natural spill elevation of the lake to the Sheyenne River, to about 1,400 ft asl. Although no documented records of lake levels are available before 1867, Upham (1895, p. 595), on the basis of tree-ring chronology, indicated the lake level was 1,441 ft asl in 1830. Lake levels were recorded sporadically from 1867 to 1901 when the U.S. Geological Survey (USGS) established a gaging station on Devils Lake. From 1867 to the present (August 2000), the lake level has fluctuated between a maximum of 1,447.1 ft asl in 1999 and a minimum of 1,400.9 ft asl in 1940 (fig. 3). The lake rose 24.5 ft from February 1993 to August 1999, and on August 1, 2000, the lake level was 1,446.1 ft asl.

The original survey of the Stump Lake area was conducted between 1881 and 1883. At that time, Stump Lake was between 1,420 and 1,425 ft asl, about 10 to 15 ft higher than its August 1, 2000, level of 1,409.8 ft asl. When Devils Lake peaked at 1,447.1 ft asl in the summer of 1999, water was just beginning to trickle into Stump Lake. Therefore, considering its small drainage area, for Stump Lake to be above 1,420 ft asl between 1881 and 1883, a substantial amount of water probably flowed from Devils Lake into Stump Lake sometime before 1880. Joseph Nicollet, who explored the Devils Lake area in 1839, described the area between Devils Lake and Stump Lake as big deep coulees (Bray and Bray, 1976). Nicollet stated "These are dry at the moment but in time of high water seem to receive water from Devil's Lake." This information indicates water flowed from Devils Lake to Stump Lake sometime between 1820 and 1840.

Radiocarbon dating of organic matter such as wood, bone, or plant matter found in buried soils or beaches was used to provide an understanding of lake-level fluctuations of Devils Lake before the early 1800's. In 1987 and 1997, North Dakota State Geological Survey geologists collected samples from beaches along Devils Lake and from sediments in the Jerusalem outlet for radiocarbon

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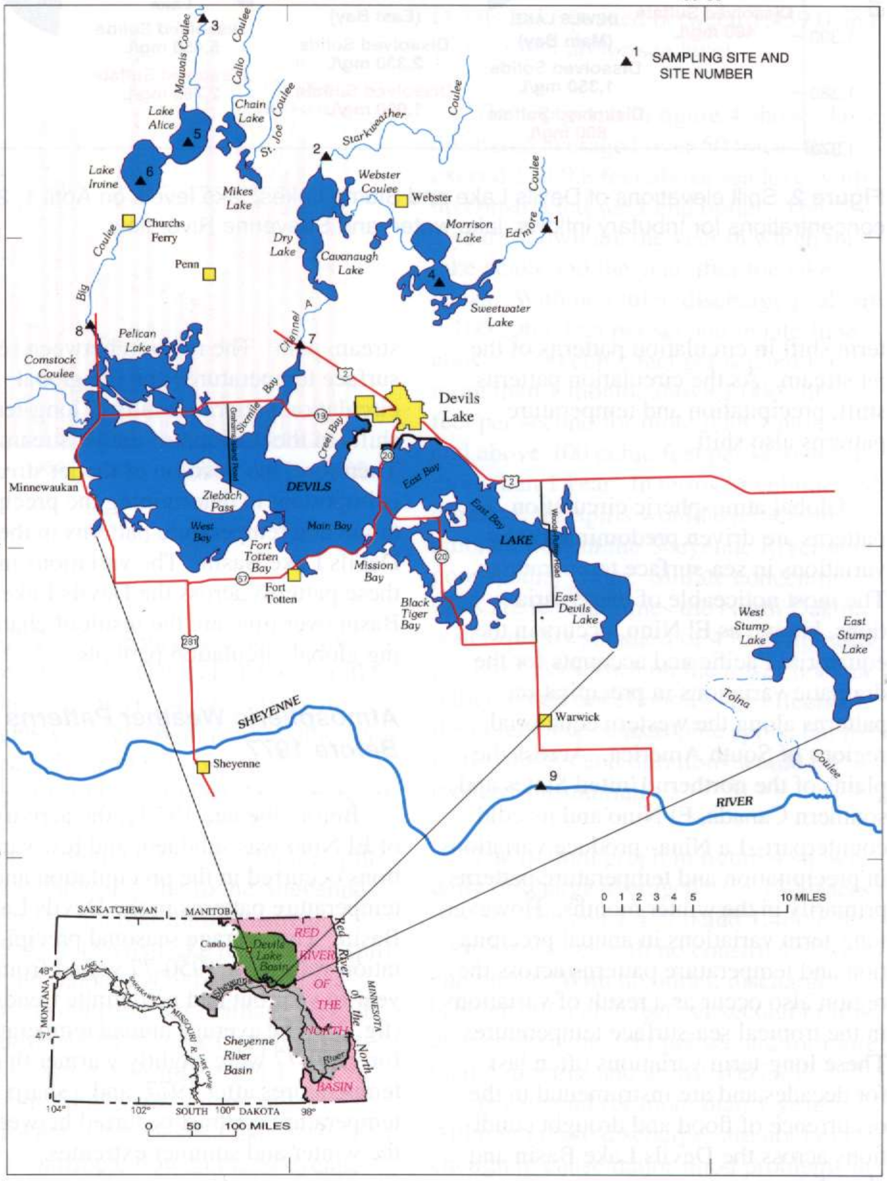

Figure 1. Location of the Devils Lake Basin, Devils Lake and Stump Lakes, and the Sheyenne River.

dating and interpretation. By dating the material, the lake level could be determined. For example, a sample of material was taken at an elevation of 1,454 ft asl from a soil profile. The soil was overlain by a clean sand beach that had a top elevation the same as the spill elevation to the Sheyenne River. Radiocarbon dating of the material provided an age of 1,800 years before the present. Therefore, the geologists were able to conclude that sometime in the past 1,800 years, Devils Lake overflowed into the Sheyenne River. Research by the North Dakota Geological Survey indicates Devils Lake has overflowed into the Sheyenne River at least twice and probably more often during the last 4,000 years and has spilled into Stump Lake several times (Bluemle, 1991; Murphy and others, 1997). The exact number of times Devils Lake has spilled into Stump Lake or overflowed into the Sheyenne River cannot be determined because when the lake rises to the spill elevation, the action of the water destroys dating material left from a previous high stand of the lake. John Bluemle, North Dakota State Geologist, concluded the natural condition for Devils Lake is either rising or falling. This conclusion is supported by lake-level data collected during the past 135 years (fig. 3).

The rapid rise in Devils Lake since 1993 is in response to above-normal precipitation from the summer of 1993 to the fall of 1999. The above-normal precipitation has resulted in the flooding of more than 70,000 acres of land around the lake and has caused flooding elsewhere in the Devils Lake Basin. State and Federal highways near Devils Lake have been raised, and some roads have been closed because of the flooding. According to North Dakota State Water Commission (NDSWC) estimates, flood damages from 1993 to the present have exceeded $300 million.

In response to the flooding, the NDSWC and the U.S. Army Corps of Engineers (COE) developed various flood-solution plans to reduce the flooding in the Devils Lake area. The flood-solution plans include options to manage and store water in the Devils Lake Basin, continue infrastructure protection, and provide an emergency outlet to the Sheyenne River via the West Bay of Devils Lake. However, current and accurate climatologic and hydrologic data are needed to assess the feasibility of the various options to reduce flood damages at Devils Lake. The purpose of this report, prepared in cooperation with the North Dakota State Water Commission and the Regional Weather Information Center, University of North Dakota, is to describe the climatology and hydrology of the Devils Lake Basin as related to the simulation of an emergency outlet.

Climatology

Nature of Climate Variability

Devils Lake responds directly to climate variability across the region. This climate variability generally can be regarded as the movement of the jet stream from season to season and from

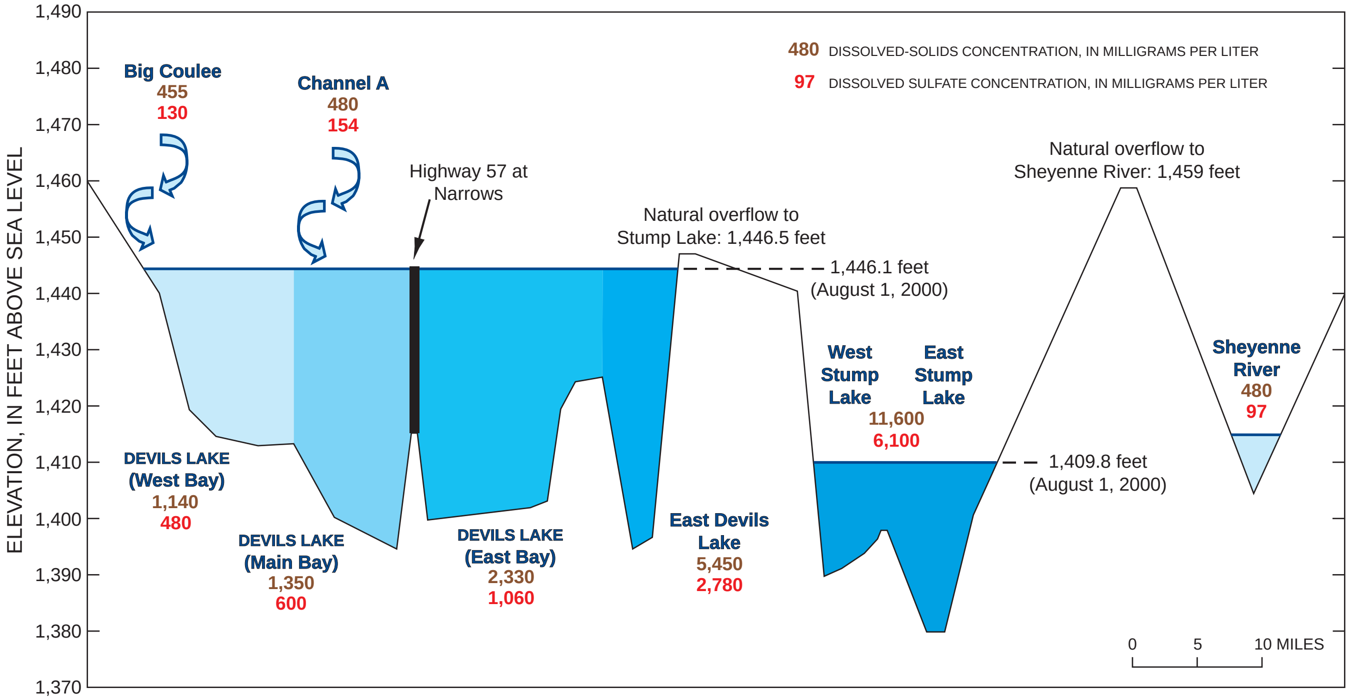

Figure 2. Spill elevations of Devils Lake and Stump Lake; lake levels on August 1, 2000; and relatively recent (see text) dissolved-solids and sulfate concentrations for tributary inflows, lake water, and Sheyenne River streamflow. (Natural spill is from West Stump Lake.)

year to year. The jet stream, which is a ribbon of high-velocity air located about 30,000 ft above the Earth's surface, exists because of temperature differences between air masses at the Earth's poles and at the equator. The movement of weather systems along the jet stream determines the distribution of precipitation about the globe. Climate variability results from a long-term shift in circulation patterns of the jet stream. As the circulation patterns shift, precipitation and temperature patterns also shift. Devils Lake has an enhanced sensitivity to long-term shifts in global circulation patterns as the level of the lake depends on many years of antecedent precipitation, runoff, and evaporation. If at any time precipitation, runoff, or evaporation is dominant, a corresponding dramatic response occurs in the lake level.

Global atmospheric circulation patterns are driven predominantly by variations in sea-surface temperatures. The most noticeable of these variations, known as El Nino, occurs in the equatorial Pacific and accounts for the dramatic variations in precipitation patterns along the western equatorial regions of South America. Across the plains of the northern United States and southern Canada, El Nino and its cold counterpart--La Nina--produce variations in precipitation and temperature patterns primarily in the winter months (Montroy, 1997). However, long-term variations in annual precipitation and temperature patterns across the region also occur as a result of variations in the tropical sea-surface temperatures. These long-

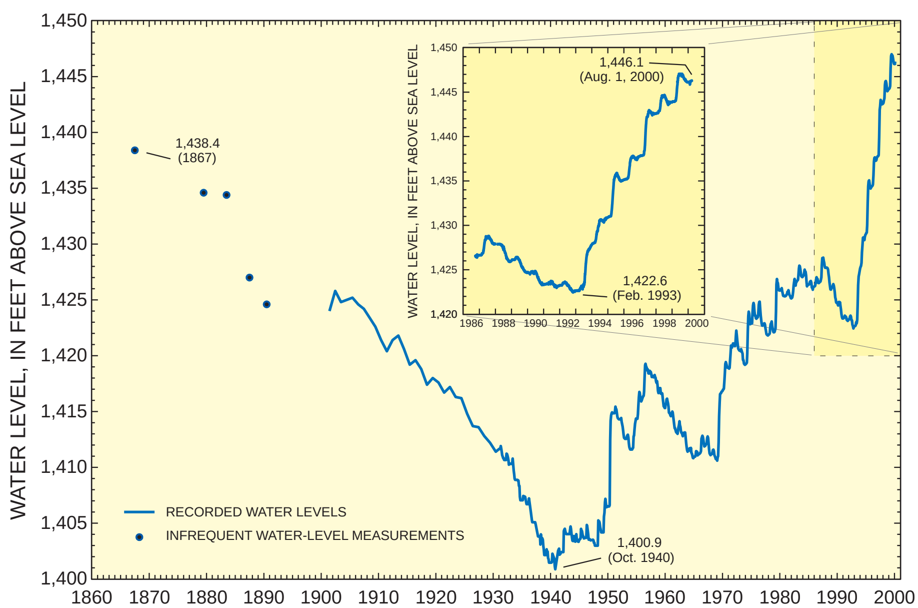

Figure 3. Historic water level for Devils Lake, 1867-2000.

term variations often span decades and are instrumental in the occurrence of flood and drought conditions across the Devils Lake Basin and elsewhere.

When the position of the jet stream across the western United States shifts to the southwest, strong storm systems move predominantly from the southwest at upper levels. These storm systems, typically referred to as Colorado Lows (fig. 4), cause unstable conditions across the Devils Lake Basin because warm, moist air from the Gulf Coast interacts with cool, dry air from Canada. The net result is a higher frequency of both warmer and wetter conditions across the Devils Lake Basin than during more stable periods. When the position of the jet stream shifts to the northwest, the Devils Lake Basin experiences a high frequency of Alberta Clippers, which are associated with cold, dry conditions in the basin. When the position of the jet stream shifts to a more westerly flow, referred to as a zonal pattern, the Devils Lake Basin generally experiences more normal precipitation and temperature patterns (patterns close to long-term seasonal average precipitation and temperature patterns).

Recent Atmospheric Weather Patterns

Before the late 1970's, the relatively subdued activity of El Nino and La Nina resulted in a low frequency of wet years in the Devils Lake Basin (fig. 5). Average seasonal precipitation values from the 1950's into the late 1970's varied from year to year, but precipitation amounts, particularly during July-December, generally were less than amounts since the late 1970's. This is consistent with a more even distribution of storm systems from the northwest, west, and southwest. Average annual temperatures from the 1950's into the late 1970's were relatively warm compared to temperatures from the late 1970's to the present, and a sharp temperature contrast occurred between the winter and summer extremes.

Since the late 1970's, the activity of El Nino has been greater than at any other time during the 20th century. This heightened El Nino activity and its interaction with other global circulation patterns has resulted in an increased frequency of storms bearing Gulf of Mexico moisture across the Devils Lake Basin, causing a higher frequency of wet years in the basin (fig. 5). Since the late 1970's, the movement of the mean jet stream position over time has resulted in warmer late winter and early spring temperatures. However, the annual average temperature for the region has decreased slightly since the mid-1980's, associated with greater cloud cover and precipitation. Since the early 1990's, unusually high precipitation amounts have occurred during May and June and again during the early fall.

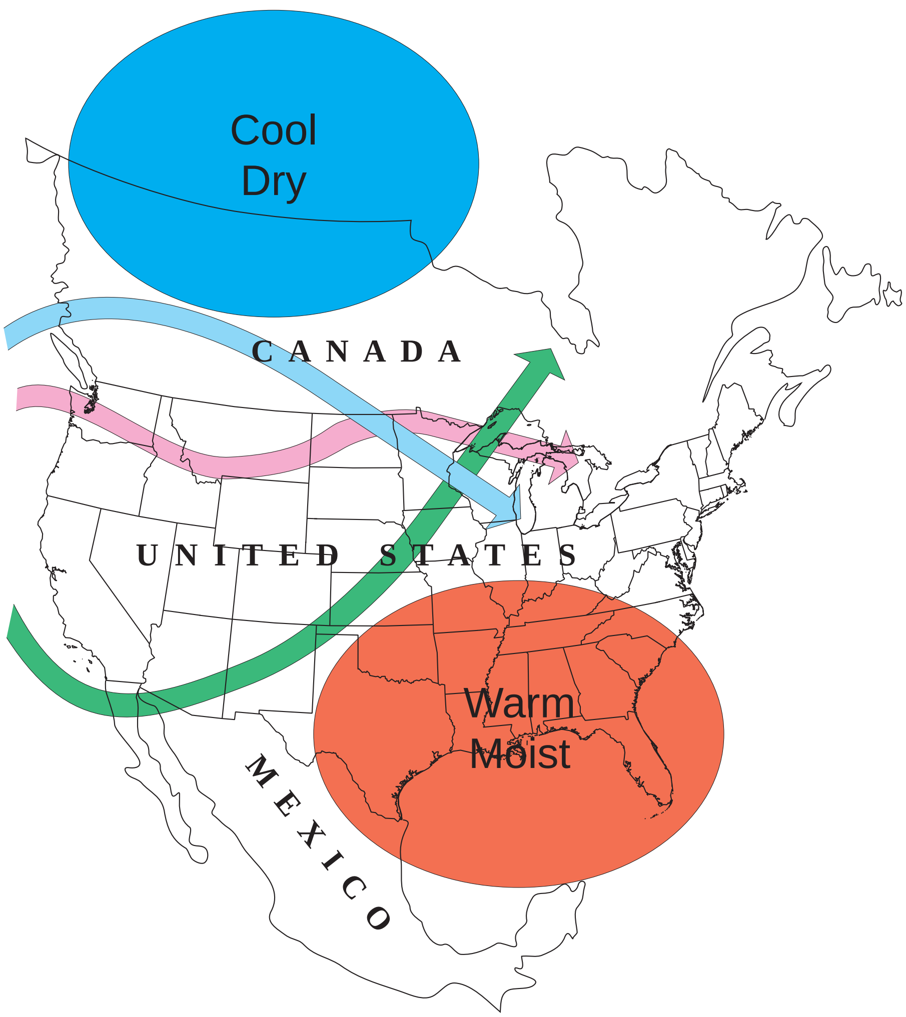

Figure 4. Extratropical storm tracks. (Blue arrow indicates Alberta Clipper storm track, green arrow indicates Colorado Low storm track, and pink arrow indicates zonal pattern.)

Future Atmospheric Weather Patterns

The duration of the recent wet conditions cannot be determined definitely because of the complex interactions between global weather factors. However, according to estimates by the Regional Weather Information Center, University of North Dakota, the present wet conditions are expected to continue beyond the first decade of the new century into 2015 (Osborne, 2000).

During this period, the recent tendency for a high frequency of wet years, punctuated by occasional dry years, probably will continue. Although La Nina conditions through the summer of 2000 could bring some periodic relief from the persistent, high precipitation of the past 8 years, long-range climate models indicate generally wet conditions during the coming fall and winter. Also, because the factors causing the recent wet conditions across the northern plains are global in scale, the transition from wet conditions to dry conditions may require years. Therefore, climatic conditions in the Devils Lake Basin during the next 15 years should be well represented by the historic conditions from the late 1970's to the present.

Hydrology of the Devils Lake Area

Lake Levels and Streamflow

As Devils Lake rose to about 1,425 ft asl in the early 1980's, the focus of various State and Federal projects was on the construction of a levee to protect the city of Devils Lake to a lake level of 1,440 ft asl and on completion of a feasibility report for flood control. The lake-level rise of the 1980's culminated when Devils Lake reached 1,428.8 ft asl (the highest level since the 1870's) in August 1987 as a result of a large snowmelt runoff during the spring of that year (fig. 3). A severe drought began late in the summer of 1987, and the lake level declined to 1,422.6 ft asl by February 1993. During the drought, the volume of water in Devils Lake decreased about 37 percent, from 884,000 acre-feet (acre-ft) in August 1987 to 558,400 acre-ft in February 1993.

The drought also caused lake-level declines on other lakes in the Devils Lake Basin, including the chain of small lakes north of Devils Lake (fig. 1). For example, Dry Lake was below the outlet elevation (1,445 ft asl) to Channel A during most of 1988-92. Crops were planted in the lakebed

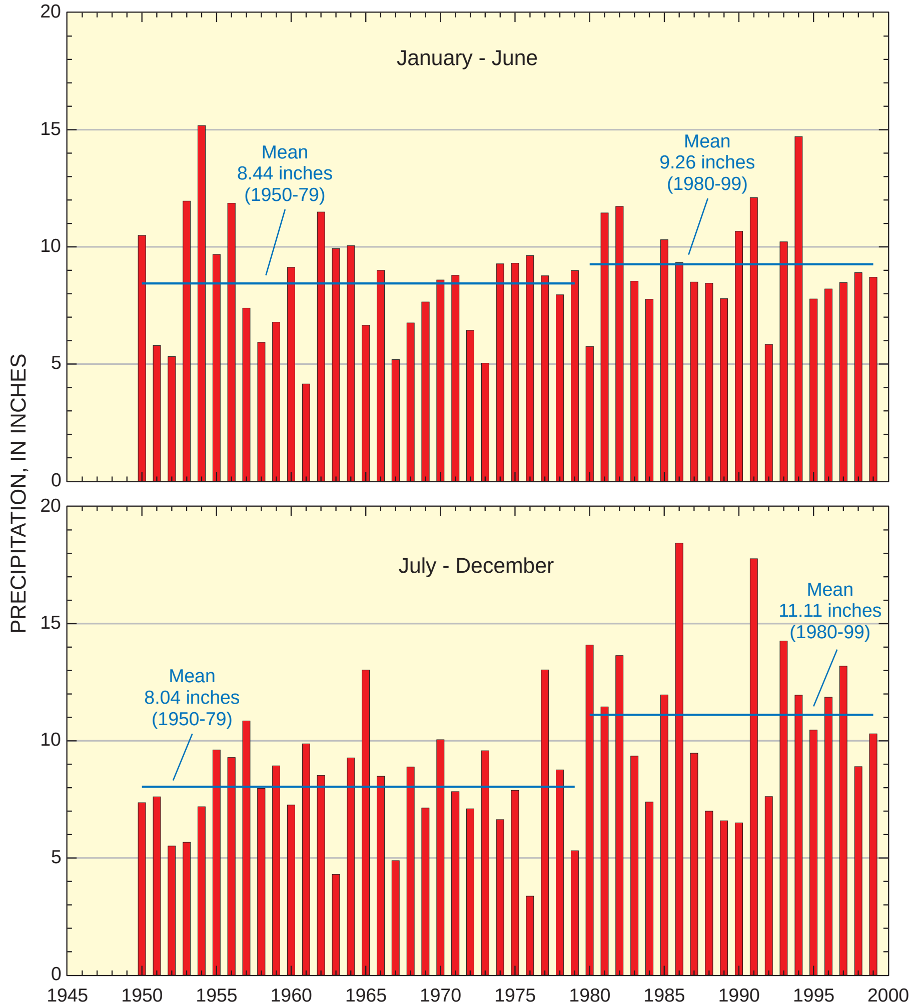

Figure 5. Devils Lake precipitation, 1950-99.

of Lake Irvine during part of the drought. During 1988-91, streamflow in tributaries to the chain of lakes ranged from only 3 percent of the long-term average at Mauvais Coulee near Cando (site 3, fig. 1) to 21 percent of the long-term average at Starkweather Coulee near Webster (site 2, fig. 1). Much-below-average streamflow into the chain of lakes and above-average evaporation from the lake surfaces during most of the drought resulted in little flow out of the chain of lakes into Devils Lake. The combined streamflow of Channel A (site 7, fig. 1) and Big Coulee (site 8, fig. 1) for 1988-92 was only 26,000 acre-ft.

From February 1993 to August 1999, the lake level of Devils Lake rose 24.5 ft. This lake-level rise corresponds to a 1,878,000-acre-ft increase in storage in Devils Lake. The estimated average annual inflow to Devils Lake for 1950-92 is 60,100 acre-ft. The estimated average annual inflow for 1993-99 is 328,200 acre-ft, and inflow for this 7-year period accounts for 47 percent of all inflow to Devils Lake for 1950-99.

The Devils Lake Basin contains many small lakes and wetlands and is typical of the prairie pothole region. The water levels in these lakes and wetlands have increased during the recent wet conditions. Analysis of a 1992 satellite image of about 3,000 mi^2 (80 percent) of the Devils Lake Basin indicates 42,629 acres of water, excluding Devils Lake, within the image area, and analysis of a 1997 image indicates 151,939 acres of water, excluding Devils Lake, within the same image area (Glenn Kelly, U.S. Geological Survey, written commun., 1998). The area of Devils Lake was 43,996 acres in 1992 and 100,655 acres in 1997. Therefore, during 1992-97, the area of land inundated by water in the upper basin increased 109,310 acres (256 percent), and the area of Devils Lake increased 56,659 acres (129 percent). By 1997, more than 10 percent of the entire basin area was water.

Sporadic lake-level measurements were made on Stump Lake from 1949 through 1979 and from 1993 through 1997. Before 1995, West Stump Lake ranged from about 1,394 ft asl in the dry years to about 1,400 ft asl in the wet years, and East Stump Lake ranged from about 1,382 ft asl in the dry years to about 1,385 ft asl in the wet years. No sustained, major lake-level changes occurred on Stump Lake from 1949 until 1993.

Although no streamflow gages exist in the Stump Lake drainage basin, quarterly lake-level measurements since 1993 and observations of local landowners, NDSWC personnel, and U.S. Fish and Wildlife Service (USFWS) personnel indicate West Stump Lake received a relatively large amount of tributary runoff late in the summer of 1993. By February 1994, the lake level was 1,395.8 ft asl. Runoff filled West Stump Lake and flowed into East Stump Lake during late 1993 and throughout 1994. By January 1995, West and East Stump Lakes were joined and the lake level was 1,398 ft asl. On July 16, 2000, Stump Lake reached 1,409.9 ft asl, the highest level in about 75 years (Swenson and Colby, 1955).

The natural outlet for Devils Lake is from the east end through the current West Stump Lake and Tolna Coulee to the Sheyenne River. The options presently being considered for constructing a Devils Lake outlet would discharge water from the west end of the lake to the Sheyenne River near Sheyenne. The long-term average annual streamflow of the Sheyenne River near Warwick (site 9, fig. 1) is 65.9 cubic feet per second (ft^3/s). Daily streamflows for 1990 and 1997 indicate the large variability between a dry year (1990) and a wet year (1997). During 1990, streamflow was less than 50 ft^3/s almost the entire year. However, in 1997, streamflow was greater than 500 ft^3/s for 39 days (from April 1 through May 9) and greater than 200 ft^3/s for 57 days.

Surface-Water Quality

Surface-water quality, especially dissolved-solids concentrations, in the Devils Lake area is affected by many factors, including, but not limited to, climate, topography, and geology. Climate affects surface-water quality through variations in precipitation and temperature. For example, warm, dry periods increase lake evaporation and, therefore, generally increase dissolved-solids concentrations. Wet periods generally increase streamflow and lake levels and, therefore, dilute dissolved-solids concentrations. Topography and geology affect surface-water quality by influencing the amount and rate of runoff and the degree of soil-water interaction (Lent and Zainhofsky, 1995).

Dissolved-solids concentrations in Morrison Lake, Sweetwater Lake, Dry Lake, Lake Alice, and Lake Irvine are similar. During 1960-99, average dissolved-solids concentrations ranged from 619 milligrams per liter (mg/L) in Sweetwater Lake (site 4; fig. 1) to 747 mg/L in Lake Alice (site 5; fig. 1). Sulfate concentrations averaged about 205 mg/L in all lakes in the chain of lakes.

Dissolved-solids concentrations in Channel A averaged 480 mg/L during 1993-99, and concentrations in Big Coulee averaged 455 mg/L. Sulfate concentrations in Channel A averaged 154 mg/L, and concentrations in Big Coulee averaged 130 mg/L. Before 1993, too few samples were collected to compute water-quality statistics for Big Coulee and Channel A.

Devils Lake consists of several bays that are, to some extent, isolated from each other at low lake levels and is characterized by large fluctuations in lake level and in concentrations of dissolved solids. Dissolved-solids concentrations vary both in space and time but generally increase from west to east in Devils Lake and East Devils Lake (fig. 2) as water enters the western part of the lake and becomes progressively more concentrated by evaporation as it moves eastward. Average concentrations during 1988-90 ranged from about 3,400 mg/L west of Highway 57 (fig. 1) to about 10,000 mg/L in East Devils Lake. Much-above-normal runoff into Devils Lake during 1993-99 caused decreases in both dissolved-solids and sulfate concentrations. In 1999, dissolved-solids concentrations in the western part of the lake ranged from 1,140 mg/L in West Bay to 1,350 mg/L in Main Bay, and sulfate concentrations ranged from about 480 mg/L in West Bay to 600 mg/L in Main Bay (fig. 2) (North Dakota Department of Health, written commun., 1999).

Dissolved-solids concentrations in Devils Lake generally fluctuate inversely with lake level. Concentrations decrease in the spring when water is diluted because of icemelt, surface-water inflow, and precipitation. Concentrations generally increase in the summer and fall when evaporation exceeds surface-water inflow and precipitation and in the winter when ions are concentrated because of ice formation.

Water-quality samples were collected from West and East Stump Lakes sporadically from 1949 through 1979 and from 1993 through 1999. In June 1949, the dissolved-solids concentration in West Stump Lake was 6,090 mg/L. During 1949-95, concentrations ranged from 2,430 mg/L in May 1995 to 108,000 mg/L in September 1963 during a drought. In comparison, the dissolved-solids concentration in seawater is about 35,000 mg/L. On February 16, 2000, the dissolved-solids concentration in West Stump Lake was 11,600 mg/L, and the sulfate concentration was 6,100 mg/L.

Dissolved-solids concentrations in East Stump Lake ranged from 10,300 mg/L in October 1999 to 241,000 mg/L in July 1961. On February 16, 2000, the dissolved-solids concentration in East Stump Lake was 11,600 mg/L, and the sulfate concentration was 6,100 mg/L. During 1993-94, the dissolved-solids concentrations in West and East Stump Lakes decreased dramatically because of dilution from the large amount of relatively fresh surface-water runoff. From 1995 through 1999, the dissolved-solids concentrations in East Stump Lake generally continued to decrease, but the concentrations in West Stump Lake began to increase. The increase started when the two lakes reached the same water level and the more-concentrated water from East Stump Lake started to mix with the less-concentrated water in West Stump Lake.

Average dissolved-solids concentrations for water samples collected from the Sheyenne River near Warwick are about the same as those for Big Coulee and Channel A, but the variability is less in the Sheyenne River. Dissolved-solids concentrations for 526 samples collected from 1951 through 1999 from the Sheyenne River near Warwick ranged from 150 to 1,010 mg/L and averaged 480 mg/L. For the same period, sulfate concentrations ranged from 28 to 230 mg/L and averaged 97 mg/L.

Outlet Simulation Model

Purpose and Description of Model

Devils Lake currently is a terminal lake, and the lake levels in any year are affected by the storage and, therefore, the lake levels in the previous year. In contrast, the elevation of a river in any year is not affected by the elevation in the previous year. Because of this difference, standard statistical tools used to calculate values such as the “one hundred year flood” for rivers cannot be used for Devils Lake, and a tool that accounts for previous conditions was needed to evaluate the effects of an outlet on Devils Lake. As a result, the USGS developed a simulation model for Devils Lake. This model, which is a modified version of the model described in Wiche and Vecchia (1996), uses historical climate conditions and the storage available in Devils Lake to generate 10,000 possible futures, called traces.

The simulation model for the Devils Lake outlet consists of three parts: (1) A statistical time-series model for generating future precipitation, evaporation, and inflow values for Devils Lake and Stump Lake and future discharges for the Sheyenne River; (2) a water and sulfate mass-balance model for generating future volumes and sulfate concentrations in Devils Lake and Stump Lake in response to future precipitation, evaporation, and inflow; and (3) a model for generating daily pumping volumes from Devils Lake to the Sheyenne River to meet downstream water-quantity and water-quality constraints. The water and sulfate mass-balance model is used to compute the change in volume and sulfate concentration in each of five major storage compartments--West Bay, Main Bay, East Bay, East Devils Lake, and Stump Lake (fig. 1)--in response to precipitation, evaporation, inflow, and outflow from each compartment. In addition to computing the flow-induced flux of sulfate into or out of each compartment, the model also computes the benthic flux of sulfate into or out of bottom sediments. The benthic flux of sulfate is an important component of the sulfate mass balance for Devils Lake. The sulfate concentrations of inflows to Devils Lake and Stump Lake and the sulfate concentrations of ambient (without an outlet) discharges for the Sheyenne River are computed on the basis of historical relations between flow and sulfate concentration for Big Coulee, Channel A, and the Sheyenne River near Warwick.

Assumptions Regarding Climatology

In the simulation model used by Wiche and Vecchia (1996), the time-series model for generating precipitation, evaporation, and inflow values was calibrated using data for 1950-93. The entire period of record was used because no statistical evidence was available at that time to indicate climatic conditions were not stationary.

The simulation model was updated in 1999 after 6 more years of data were recorded (1994-99). The record now available indicates a shift toward wet conditions occurred in the late 1970’s (fig. 5), particularly in the fall. The change appears to be rather abrupt, and the recent wet conditions do not appear to be statistically different than conditions during 1980-92. To better reflect the wet conditions, the time-series model for generating precipitation, evaporation, and inflow values for Devils Lake and future Sheyenne River discharges was recalibrated using data for 1980-99 (data for the late 1970’s were not included to avoid any possible transition period between the dry and wet conditions). As indicated previously, climatic conditions during 2000-15 are expected to be similar to conditions during 1980-99.

Assumptions Regarding Lake-Level Simulations

The simulation model was used to generate 10,000 traces that begin with the same initial conditions that existed on January 1, 2000 (a starting lake level for Devils Lake of 1,446.2 ft asl), and extend through 2015. For each trace, future precipitation, evaporation, and inflow values were generated at random from the time-series model using data for 1980-99 and given initial conditions in the basin. Each of the 10,000 traces was generated using the assumption that no west-end outlet is constructed. The model was run using a base elevation of 1,447 ft asl for the spill point between Devils Lake and Stump Lake. Since the model was run, 6 inches (in.) of sediment has been removed from the channel at that point, lowering the base elevation to about 1,446.5 ft asl. However, initial calculations indicate this change should have little effect on simulated lake levels for Devils Lake, especially for traces above 1,449 ft asl. Each of the 10,000 traces represents a realization of future lake levels that could happen if climate and basin characteristics during 2000-15 are the same as those during 1980-99. Statistics computed from the entire set of 10,000 traces can be used to determine the probability of future events. For example, 182 of the 10,000 traces exceed the natural (without a constructed outlet) spill elevation (1,459 ft asl) to the Sheyenne River between 2000 and 2015. Therefore, the estimated probability of a spill occurring sometime during the next 16 years is 182 divided by 10,000, or 1.8 percent.

Table 1. Hydrologic characteristics of 182 traces that spill to the Sheyenne River without a constructed outlet

Characteristic	Trace average	80-percent bounds[1]
For entire simulation period (2000-15)		
Mean annual precipitation, in inches[2]	21.7	20.4 to 22.9
Mean annual evaporation, in inches[2]	33.3	32.3 to 34.3
Mean annual net evaporation, in inches[2]	11.6	9.7 to 13.6
Mean annual inflow, in thousand acre-feet[2]	365	298 to 454
Maximum annual inflow, in thousand acre-feet[3]	1,478	945 to 2,185
Maximum 4-year total net evaporation, in inches[3]	62.8	52.1 to 75.6
First year to reach spill elevation	2009	2004 to 2014
Time above spill elevation, in years	5	2 to 8
Total Tolna Coulee discharge, in thousand acre-feet	610	66 to 1,425
Maximum annual Tolna Coulee discharge, in thousand acre-feet[3]	305	40 to 686
For 5-year period preceding first spill		
Mean annual precipitation, in inches[2]	22.4	20.8 to 25.2
Mean annual evaporation, in inches[2]	32.9	31.1 to 33.8
Mean annual net evaporation, in inches[2]	10.6	6.9 to 12.5
Mean annual inflow, in thousand acre-feet[2]	671	464 to 853

[1]80 percent of the traces (145 out of 182) were within the 80-percent bounds.
[2]Mean refers to the mean for the given time period.
[3]Maximum refers to the maximum single value for the given time period.

Water Balance Associated with Traces that Exceed Spill Elevation to the Sheyenne River

An analysis of the water balance associated with the 182 traces that exceed the natural spill elevation during 2000-15 provides a reference for comparison with the water balance for the Devils Lake Basin since 1993. The hydrologic characteristics of the 182 traces are summarized in table 1, and two of the traces are shown in figures 6 and 7. Although each trace is different, the traces shown in figures 6 and 7 illustrate typical features of the traces that exceed the spill elevation. For example, Devils Lake generally reaches 1,459 ft asl for the first time between 2004 and 2014 and remains above the spill elevation 2 to 8 years before subsiding (table 1). Trace 22 (fig. 6) reaches the spill elevation in 2011 and spills for 3 years, and trace 161 (fig. 7) reaches the spill elevation in 2006 and spills for 5 years. Maximum annual Tolna Coulee discharges resulting from the spills average 305,000 acre-ft and typically range from 40,000 to about 700,000 acre-ft (table 1). Annual inflows generally are highly variable; periods of normal (similar to 1980-99) inflow are accompanied by periods of very high inflow that last 3 to 6 years. For example, inflows for trace 22 are comparable to inflows during 1980-99 except for three extremely high inflows during 2009-11, and inflows for trace 161 are comparable to inflows during 1980-99 except for five extremely high inflows during 2003-09.

Maximum annual inflows during 2000-15 for the 182 traces that exceed the spill elevation average 1,478,000 acre-ft (table 1) and generally are between 1 and 2 million acre-ft. For example, trace 22 (fig. 6) has a maximum annual inflow of about 1,800,000 acre-ft in 2011, and trace 161 (fig. 7) has a maximum annual inflow of about 1,400,000 acre-ft in 2006. To consider these large inflows in a historical perspective requires an understanding of hydrologic conditions in the Devils Lake Basin. The chain of lakes upstream of Devils Lake, as well as many of the smaller lakes and wetlands in the upper Devils Lake Basin, have filled as a result of the recent wet conditions. Therefore, much of the Devils Lake Basin that did not contribute flow to Devils Lake during 1900-92 now contributes flow. For example, if the entire drainage area of the Devils Lake Basin (3,810 mi^2) contributed flow, 10 inches (in.) of runoff would produce about 2 million acre-ft of inflow to Devils Lake. That amount of runoff could be generated by a snowmelt runoff of 5 in. (comparable to the runoff per square mile during 1997 for eastern North Dakota) and a late spring-early summer precipitation runoff of 5 in. (comparable to the runoff per square mile during 1993 for parts of eastern North Dakota). The simulation model indicates the chances of at least one annual inflow during 2000-15 being higher than at any other time in recorded history are considerable unless the wet climatic conditions of the past 2 decades are reversed so that saturated conditions in the basin are reduced and flow paths and contributing drainage area from the upper basin to the lake revert to those existing between 1900 and 1992. For example, 618 (about 6 percent) of the 10,000 traces have at least one annual inflow during 2000-15 that exceeds 1 million acre-ft (almost twice as high as the highest recorded inflow of 528,000 acre-ft during 1997).

An understanding of the hydrologic conditions required to cause Devils Lake to spill to the Sheyenne River can be gained from table 1. For example, the mean annual precipitation for 2000-15 averaged 21.7 in. for the 182 traces that exceed the spill elevation and was between 20.4 and 22.9 in. for 80 percent of those traces. Thus, the mean annual precipitation for 2000-15 generally is slightly higher than for 1980-99 (20.4 in.). The mean annual net evaporation (evaporation minus precipitation) averaged 11.6 in. for the 182 traces that exceed the spill elevation and was between 9.7 and 13.6 in. for 80 percent of those traces. Thus, for most traces, the mean annual net evaporation for 2000-15 is lower than the mean annual net evaporation (13.2 in.) for 1980-99. The mean annual inflow averaged 365,000 acre-ft for the 182 traces that exceed the spill elevation and was between 298,000 and 454,000 acre-ft for 80 percent of those traces. These values are comparable to the mean annual inflow of 327,000 acre-ft for 1993-99.

The previous paragraph indicates climatic conditions during the next 15 years need to be slightly wetter, on average, than conditions during 1980-

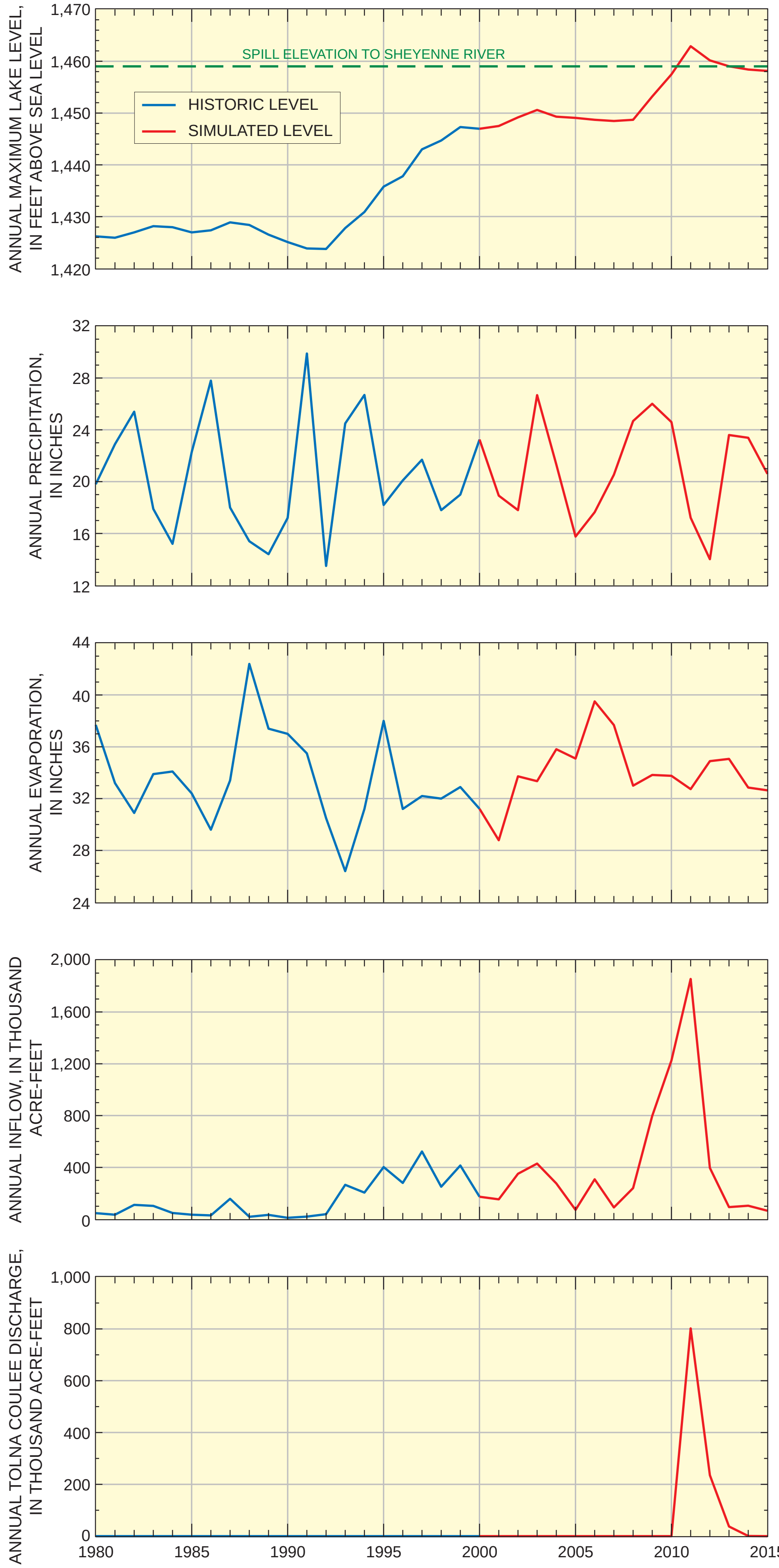

Figure 6. Generated data for trace 22.

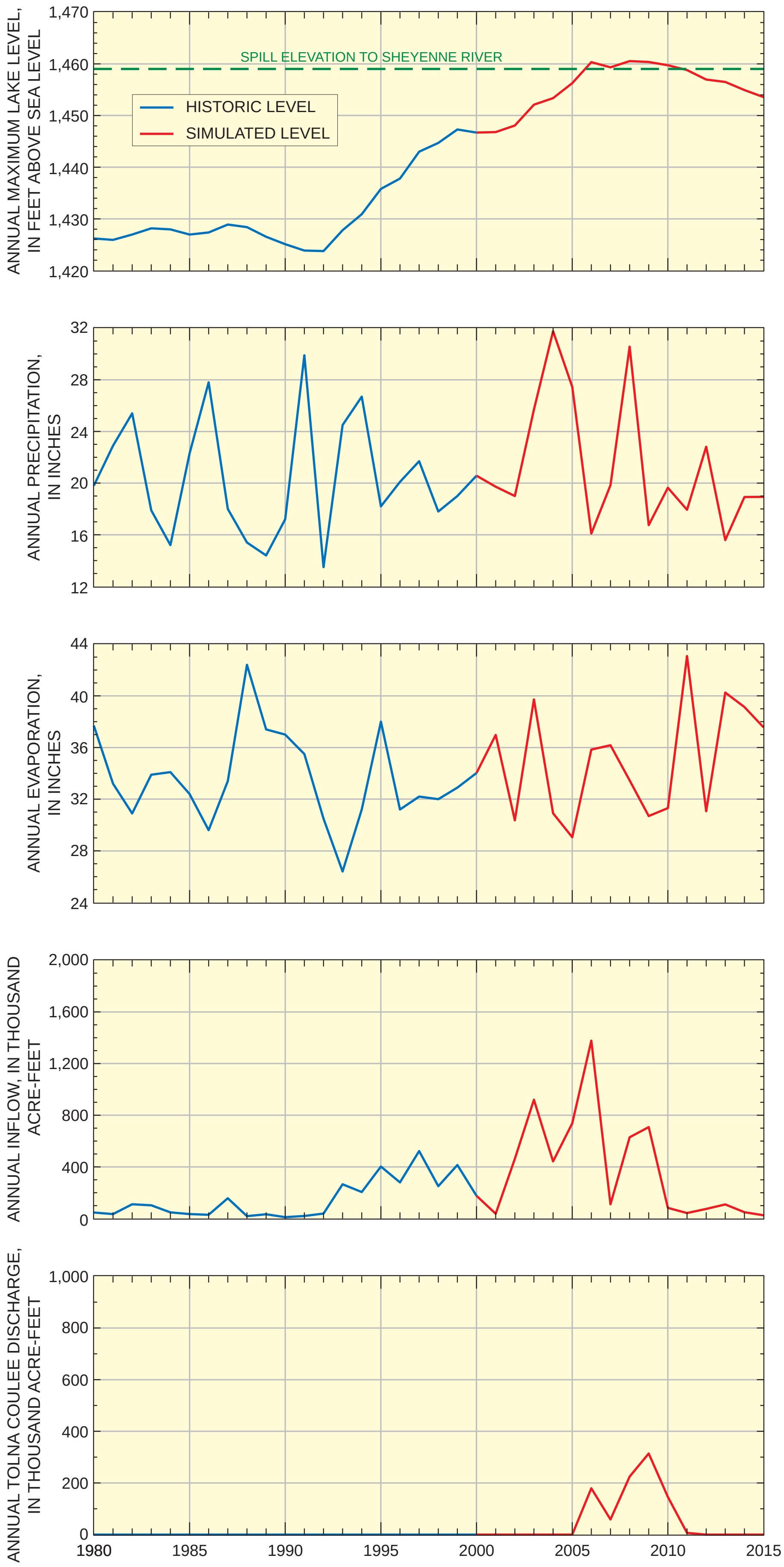

Figure 7. Generated data for trace 161.

99 to cause Devils Lake to spill to the Sheyenne River. However, traces that exceed the spill elevation generally have short time periods during which inflows to Devils Lake greatly exceed those recorded during the 1990's. These periods of high inflow generally are accompanied by periods of high precipitation and low net evaporation. For example, as indicated in table 1, for the 5-year period preceding the first year the lake spills, the mean annual precipitation for 80 percent of the traces was between 20.8 and 25.2 in., and the mean annual net evaporation was between 6.9 and 12.5 in. The 5-year periods of high precipitation and low net evaporation usually result from above normal (compared to 1980-99) fall and winter precipitation and cool, wet summer conditions, which have a dramatic effect on inflows. For 80 percent of the traces, the mean annual inflow for the 5-year period preceding the first spill was between 464,000 and 853,000 acre-ft, which is much higher than the average annual inflow (363,000 acre-ft) for the 5-year period from 1995-99.

Another characteristic of most traces that exceed the spill elevation during 2000-15 is the lack of a severe drought, comparable to the drought that occurred during 1987-90. A severe drought reduces high lake levels by increasing evaporative losses from the lake surface, increasing the available capacity of the lake for holding future inflows, and reducing surface runoff from the basin during and after the drought. Surface runoff from the Devils Lake Basin is particularly sensitive to drought because increased evaporative losses remove water from the soil profile, increasing the available storage capacity in the profile. Also, increased evaporative losses lower water levels in small lakes and wetlands, decreasing the number of small subbasins that compose the contributing drainage area.

The total net evaporation for Devils Lake during the 4-year period from 1987-90 was 85.2 in. As indicated in table 1, the maximum 4-year total net evaporation during 2000-15 averaged 62.8 in. for the 182 traces that exceed the spill elevation and was between 52.1 and 75.6 in. for 80 percent of those traces. For example, in trace 22 (fig. 6), the driest 4-year period occurred during 2005-08, during which total net evaporation was about 66 in. The combined surface area of Devils Lake and Stump Lake during this period was about 160,000 acres. Therefore, total net evaporative loss during 2005-08 was about 900,000 acre-ft. However, total inflow during this period was about 700,000 acre-ft, resulting in a total volume decrease of about 200,000 acre-ft. If the drought during 2005-08 would have been as severe as the drought during 1987-90, the evaporative loss would have been about 1,100,000 acre-ft and the total inflow probably would have been reduced to near zero, resulting in a total volume decrease of about 1,100,000 acre-ft. The more severe drought also would have increased available storage in wetlands, lakes, and soils in the upper basin and, thus, reduced inflows during 2009-11 as well. For example, a 5-in. reduction in runoff during 2009-11 would reduce inflows by about 1 million acre-ft. Therefore, with the severe drought, the volume of the lake in 2011 would have been 1,900,000 acre-ft lower than the actual volume for trace 22 (900,000 acre-ft more volume decrease during 2005-08 and 1 million acre-ft less inflow during 2009-11).

The previous example shows that the volume of Devils Lake 2 or 3 years after a severe drought may be reduced by about 2 million acre-ft compared to a moderate drought. The reduction in volume could be much larger depending on the timing and severity of the drought. The large increase in available storage greatly decreases the chance of a subsequent spill for many years after the drought. Thus, most of the traces that include a severe drought do not exceed the spill elevation by 2015.

Simulation of an Emergency Outlet

To evaluate the potential effects of an outlet, each of the 10,000 model traces also was generated using an assumed emergency outlet configuration proposed by the NDSWC. In the simulation, the outlet is assumed to be operational May 1, 2001. The pump intake is from the southern part of West Bay, and the pumps may operate from May 1 to November 30 of each year. The downstream channel-capacity constraint for the Sheyenne River is 600 ft^3/s, and the downstream sulfate standard for the Sheyenne River is 450 mg/L (North Dakota State Department of Health and Consolidated Laboratories, 1991). Two options were considered for outlet capacity. In option 1, the NDSWC plan, outlet capacity is 300 ft^3/s (six 50-ft^3/s pumps), and in option 2 (presented for comparison with option 1), outlet capacity is 450 ft^3/s (nine 50-ft^3/s pumps). Therefore, on any given day when the pumps are operating, as much as 300 ft^3/s (option 1) or 450 ft^3/s (option 2) of water can be discharged to the Sheyenne River provided the combined outlet discharge and ambient Sheyenne River streamflow is less than 600 ft^3/s and the combined sulfate concentration is less than 450 mg/L. If either constraint is reached, outlet discharge is reduced as required to return to levels below the constraints.

The potential effects of an outlet on the probabilities of future lake levels for Devils Lake are shown in figure 8. Without an outlet, the chance (probability) that Devils Lake will exceed 1,450 ft asl sometime between 2001 and 2015 is about 33 percent. If the lake level exceeds 1,450 ft asl, major infrastructure damage will occur, especially to several major highways, and Devils Lake will overflow and fill Stump Lake. With the 300-ft^3/s-outlet option, the chance that the lake level will exceed 1,450 ft asl by 2015 is about 20 percent, and with the 450-ft^3/s-outlet option, the chance is about 16 percent. Although the reduction in risk from 33 percent to either 20 or 16 percent is significant, the effectiveness of the outlet in preventing the lake from reaching 1,450 ft asl is limited because many of the traces reach that level early in the simulation period before the outlet can be effective in drawing the lake

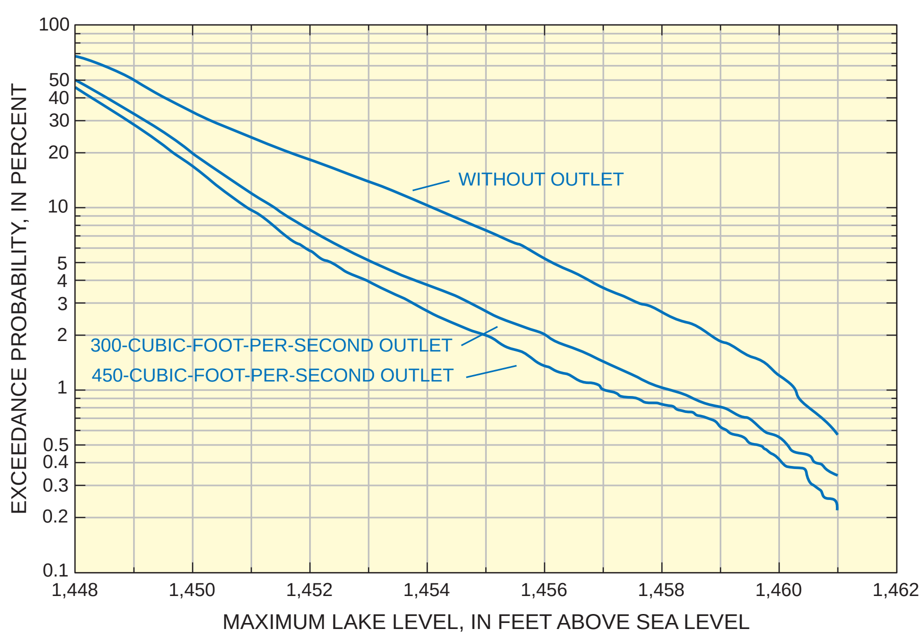

Figure 8. Estimated exceedance probabilities computed from 10,000 model traces for Devils Lake for 2000-15.

down. For example, between 2000 and 2005, 1,570 traces reach 1,450 ft asl without an outlet. The 300-ft^3/s-outlet option prevents 430 of those traces from reaching that level, and the 450-ft^3/s-outlet option prevents 536 from reaching that level. However, between 2006 and 2015, 1,760 traces reach 1,450 ft asl without an outlet. The 300-ft^3/s-outlet option prevents 930 of those traces from reaching that level, and the 450-ft^3/s-outlet option prevents 1,130 from reaching that level.

As indicated in figure 8, the outlet would be effective in reducing extremely high lake levels. For example, 1,030 of the traces reach 1,454 ft asl by 2015 without an outlet, but only 372 of those traces reach that level with the 300-ft^3/s-outlet option and 269 reach that level with the 450-ft^3/s-outlet option. Similarly, 182 (1.8 percent) of the traces reach 1,459 ft asl (spill elevation) without an outlet, but only 81 of those traces reach that level with the 300-ft^3/s-outlet option and 63 reach that level with the 450-ft^3/s-outlet option.

The exceedance probabilities cannot be used directly to evaluate the effects of the outlet on a trace-by-trace basis. The effectiveness of the outlet in reducing flood damages on a trace-by-trace basis can be measured by the reduction in peak lake level. This reduction is defined as the difference between the maximum lake level without an outlet and the maximum lake level with an outlet. For example, if a trace peaks at 1,456 ft asl in 2010 without an outlet and the same trace peaks at 1,452 ft asl in 2006 with an outlet, the reduction in peak lake level for that trace is 4 ft. The reductions in peak lake levels for the 300- and 450-ft^3/s-outlet options are shown in figure 9. The curves in figure 9 were obtained by averaging the reductions over all traces that peak near a given elevation (without an outlet). For example, the average reduction in peak lake level for all traces that reach 1,456 ft asl without an outlet is 3.3 ft for the 300-ft^3/s-outlet option and 4.2 ft for the 450-ft^3/s-outlet option. Although some traces will be above these values and some below, the average is a reasonable estimate of the expected reduction in peak lake level.

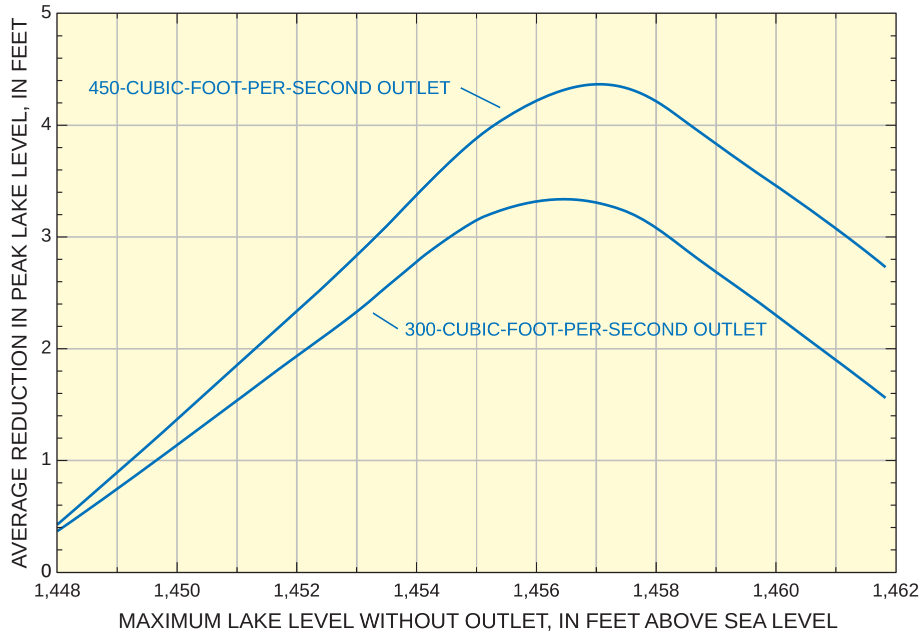

Figure 9. Average reductions in peak lake levels of Devils Lake for 2000-15 for 300- and 450-cubic-foot-per-second-outlet options.

For both outlet options, the outlet is most effective in reducing levels of the peaks for those traces that peak between 1,454 and 1,459 ft asl. Traces in this range generally peak long after the outlet is operational, and the lake generally remains relatively fresh; therefore, the sulfate standard does not greatly constrain pump output. The effectiveness of the outlet is reduced for peak lake levels below 1,454 ft asl because many of those traces either peak early or have increased sulfate concentrations that result in reduced pumping. The effectiveness also is reduced for peak lake levels above 1,459 ft asl because of the extremely high inflows necessary to raise the lake above that level. The high inflows often exceed combined pumping volumes and evaporative losses although, for many traces, the pumps are operating at full capacity.

The effectiveness of an outlet on a trace-by-trace basis also can be measured by drawdown. Drawdown is defined in this report as the difference between the lake level without an outlet and the lake level with an outlet in a given year. For example, if the lake level in 2015 for a certain trace is 1,452 ft without an outlet and 1,445 ft with an outlet, the drawdown is 7 ft. The benefits of drawdown are twofold--previously flooded land around the lake can be reclaimed sooner and subsequent flood damages occurring after the simulation period can be reduced because of more available storage.

The average drawdowns for the two outlet options are shown in figure 10. The curves shown were obtained by averaging over all traces in a manner similar to that used for figure 9. The outlet is much more effective in drawing the lake down in the long term (2015) than in the short term (2005). The 300- and 450-ft^3/s-outlet options provide about 2 and 3 ft of drawdown, respectively, in 2005 for traces that have lake levels between 1,450 and 1,456 ft asl. However, by 2015, the 300- and 450-ft^3/s-outlet options

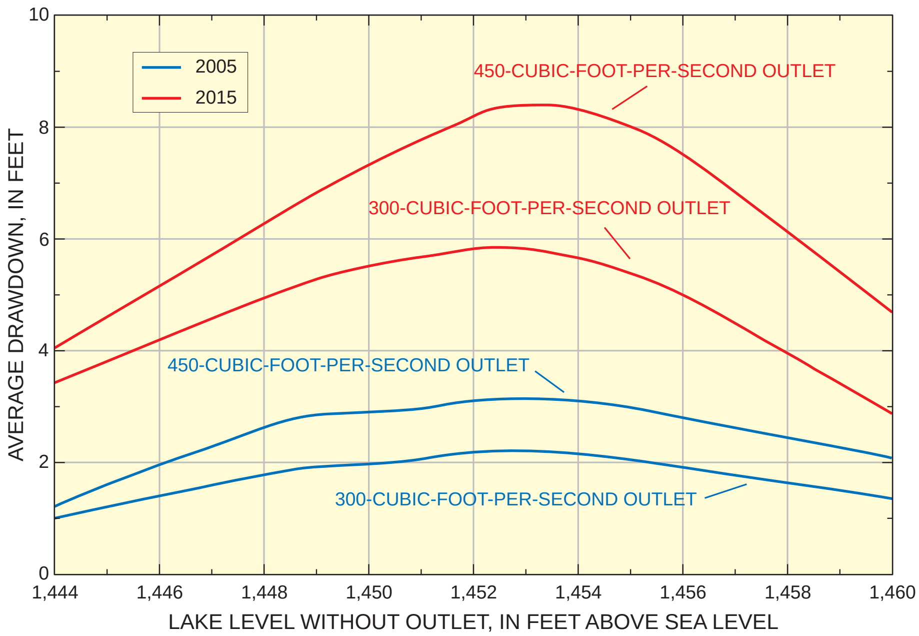

Figure 10. Average drawdown of Devils Lake for 2005 and 2015 for 300- and 450-cubic-foot-per-second-outlet options.

provide about 5.5 and 8.0 ft of drawdown, respectively, for traces in that range. Drawdown is smaller for lake levels below 1,450 ft asl because of the sulfate standard for the Sheyenne River and for lake levels above 1,456 ft asl because much more volume is required to draw the lake down at those levels.

The quantity and quality of water discharged from an outlet is an important consideration to downstream interests. The sulfate concentration in the southern part of West Bay (near the proposed outlet intake) was about 480 mg/L in the fall of 1999 (fig. 2). This concentration is greater than the 450-mg/L standard for the Sheyenne River. Therefore, without significant dilution from Sheyenne River streamflow, the amount of water discharged from the outlet may be less than the 300- or 450-ft^3/s pump capacity. The in-lake sulfate concentration of each trace generated from the model varies depending on future climatic conditions. Wet conditions (and increasing lake levels) generally produce low sulfate concentrations, and dry conditions (stable or decreasing lake levels) generally produce high sulfate concentrations.

The potential effects of an outlet on Sheyenne River streamflow are shown in figure 11. The maximum mean monthly streamflow occurs in April when the outlet is not operating. However, the mean monthly streamflow (563 ft^3/s) for April for traces that have maximum lake levels above 1,450 ft asl is about twice as large as the streamflow (296 ft^3/s) for traces that have maximum lake levels below 1,450 ft asl because wet conditions in the Devils Lake Basin generally correspond to wet conditions in the Sheyenne River Basin. Most of the streamflow in the Sheyenne River from May through November, when the outlet is operating, is water discharged from the outlet.

For maximum lake levels below 1,450 ft asl (fig. 11), the amount of water discharged with the 450-ft^3/s-outlet option is only slightly larger than the amount discharged with the 300-ft^3/s-outlet option. For both outlet options, the mean monthly outlet discharge ranges from about 125 ft^3/s in May to about 80 ft^3/s in October and November. However, outlet discharge is much higher for lake levels above 1,450 ft asl than for lake levels below 1,450 ft asl because in-lake sulfate concentrations generally are lower and ambient Sheyenne River streamflow generally is higher for levels above 1,450 ft asl. For both outlet options, the lowest mean monthly outlet discharge occurs in May (about 200 ft^3/s for the 300-ft^3/s-outlet option and 250 ft^3/s for the 450-ft^3/s-outlet option) when the channel-capacity constraint results in reduced pumping for many traces. In June-November, mean monthly outlet discharge remains nearly constant at about 210 ft^3/s for the 300-ft^3/s-outlet option and 280 ft^3/s for the 450-ft^3/s-outlet option.

The potential effects of an outlet on sulfate concentrations in the Sheyenne River also are shown in figure 11. For maximum lake levels below 1,450 ft asl and both outlet options, sulfate concentrations in the Sheyenne River are about 380 mg/L during May-November. The sulfate concentrations are less than the 450-mg/L standard because the pumps operate in 50-ft^3/s increments and, therefore, outlet discharge cannot be altered continuously to reach the standard. For maximum lake levels above 1,450 ft asl and both outlet options, sulfate concentrations in the Sheyenne River are about 340 mg/L during May-November. For many traces, especially those that reach 1,454 ft asl or higher, the in-lake sulfate concentrations are below 450 mg/L for substantial time intervals.

The potential for a catastrophic spill from the natural outlet to the Sheyenne River poses a threat for downstream interests. If Devils Lake reaches the spill elevation (1,459 ft asl), the contributing drainage area of the Sheyenne River near Cooperstown will quadruple (from 1,270 mi^2 to 5,070 mi^2) because the entire Devils Lake Basin then would contribute flow to the Sheyenne River. Although the large size of Devils Lake results in substantial evaporative losses of water and attenuation of outflows, potential still exists for major downstream flooding as a result of a natural spill. The water in Stump Lake (which becomes

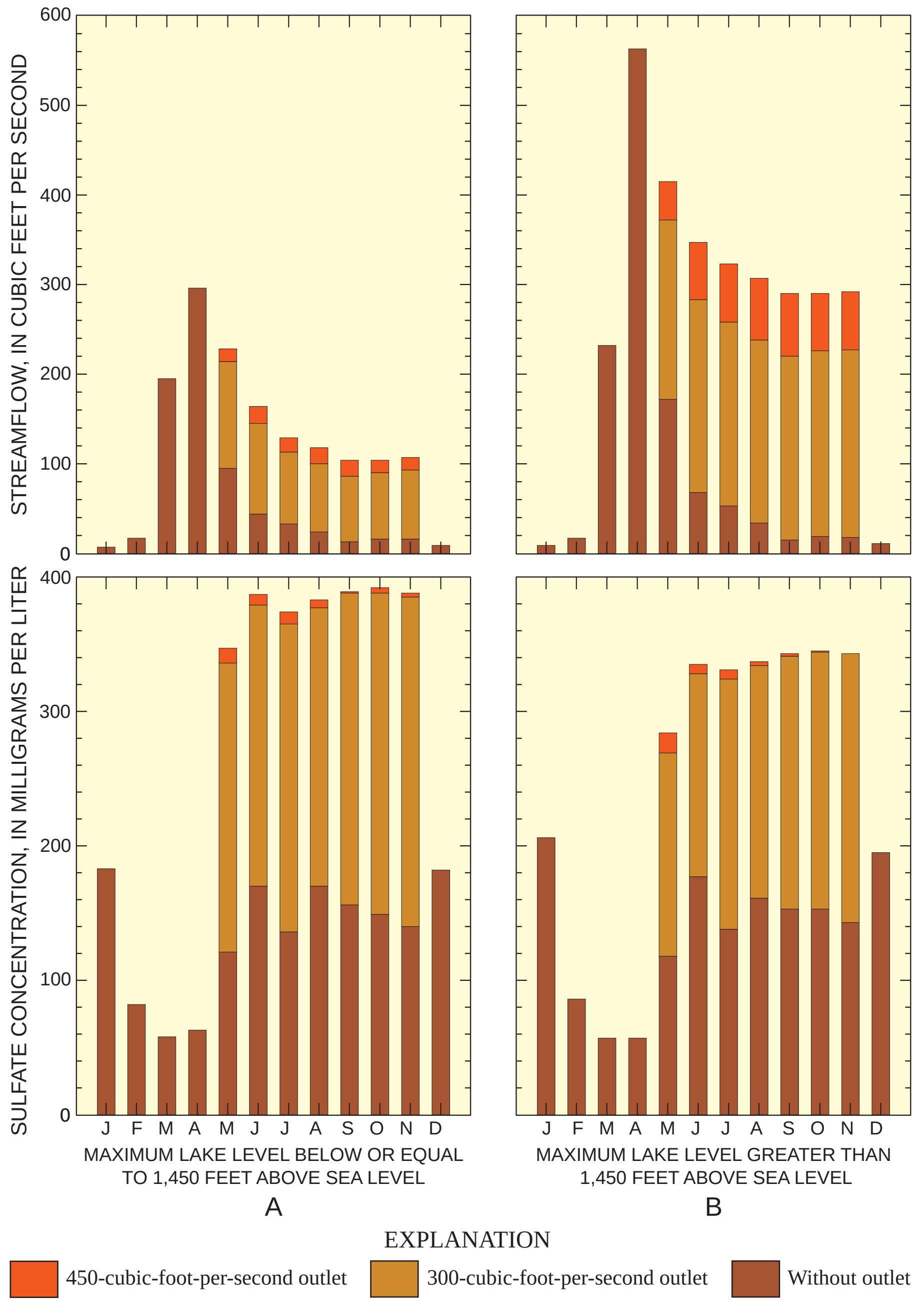

Figure 11. Modeled mean monthly streamflow and sulfate concentrations for the Sheyenne River near Warwick, North Dakota, for 2001-15. (A--Average of all traces that have maximum lake levels below or equal to 1,450 feet above sea level; B--average of all traces that have maximum lake levels greater than 1,450 feet above sea level.)

part of Devils Lake at an elevation of about 1,447 ft asl) also is of much poorer quality than water in western Devils Lake, and substantial volumes of water spilling from the natural outlet could cause serious downstream water-quality degradation.

Modeled discharges of spills from Devils Lake through Tolna Coulee to the Sheyenne River and the associated sulfate concentrations are shown in figure 12. The amount of water that spills from Devils Lake is controlled by the geometry of the spill channel. Devils Lake can rise to an elevation several feet above 1,459 ft asl, and the magnitude of the spill will increase as the lake rises. Therefore, the 182 traces that exceed the spill elevation were separated into two groups--the 50 highest-elevation traces, for which Devils Lake exceeded 1,460.8 ft asl, and the remaining 132 traces, for which Devils Lake peaked between 1,459 and 1,460.8 ft asl.

The top graph in figure 12 shows daily discharges and sulfate concentrations averaged over 50 traces that exceed 1,460.8 ft asl without an outlet. The 2 years shown are the year in which the lake peaks and the year after the lake peaks. Without an outlet, discharge is about 2,100 ft^3/s in late June, above 2,000 ft^3/s for more than 1 month, above 1,000 ft^3/s for more than 4 months, and above 400 ft^3/s for more than 1 year. In terms of volume and duration, the spills would overwhelm ambient Sheyenne River streamflow. For example, in 1997, a wet year, discharge for the Sheyenne River near Warwick peaked at 3,900 ft^3/s, was above 2,000 ft^3/s for 12 days, above 1,000 ft^3/s for 20 days, and above 400 ft^3/s for 42 days. The water quality of the spills also would be very poor. Sulfate concentrations are several times the 450-mg/L standard, and dissolved-solids concentrations are more than twice as large as sulfate concentrations. Although neither outlet option would eliminate the effects of the potentially catastrophic spills, the spill volumes and durations would be reduced substantially.

The bottom graph in figure 12 shows daily discharges and sulfate concentrations averaged over 132 traces that are between 1,459 and 1,460.8 ft asl without an outlet. Without an outlet, discharge is about 430 ft^3/s in July, above 200 ft^3/s for more than 4 months, and above 100 ft^3/s for more than 1 year. Although these discharges are not large enough to cause major flooding of the Sheyenne River, the duration and high sulfate concentrations (more than 2,000 mg/L) of the spills would cause substantial water-quality degradation downstream. The effects of the spills would be reduced greatly (or entirely eliminated) with either outlet option. The 300-ft^3/s-outlet option completely eliminated the spills in 98 of the 132 traces and greatly reduced spill volumes in the remaining traces. The 450-ft^3/s-outlet option completely eliminated the spills in 111 of the 132 traces and greatly reduced spill volumes in the remaining traces.

Potential Erosion of Natural Outlet Channel

The simulation results presented earlier were based on the assumption that the natural outlet channel connecting West Stump Lake and the Sheyenne River remains unchanged throughout the simulation period. However, preliminary analyses conducted by the NDSWC and summarized in this section indicate significant erosion of the channel is possible during the course of a natural spill. If such erosion occurs, the spill volumes would be larger than indicated in the model simulations. Further hydraulic analysis is required to accurately model channel-erosion processes. However, this section qualitatively describes potential erosion problems that may arise in the event of a natural spill.

Stump Lake is connected to Tolna Coulee and, therefore, to the Sheyenne River by a channel about 600 feet wide and 4,000 feet long. The controlling channel-bottom elevation is about 1,459 ft asl. A flat region that has slightly elevated dike-like soil structures at each end separates the eastward slope into West Stump Lake and the westward slope to Tolna Coulee. The origin of the structures at each end of this region is unknown; however, the structures likely would be eroded quickly during a discharge event because of potentially erosive velocities. If the structures erode, the controlling channel-bottom elevation will decrease to about 1,458 ft asl, which is the elevation of the bottom of the long, flat region between the structures. The rating curves before and after erosion are shown in figure 13. If the lake rises to 1,461 ft asl, the structures probably will erode and flow

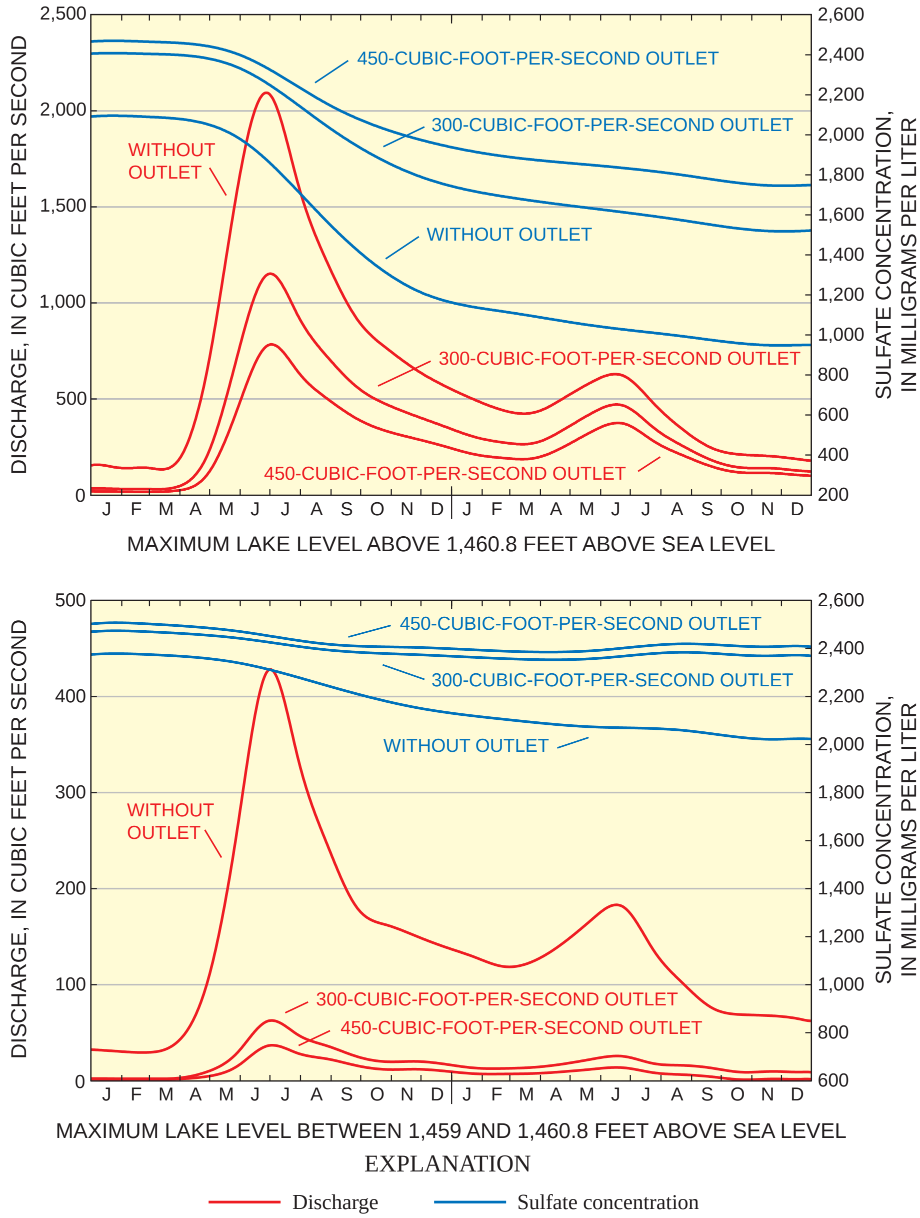

Figure 12. Modeled discharges and sulfate concentrations of spills through Tolna Coulee to the Sheyenne River. (Top--average of 50 traces that peak above 1,460.8 feet above sea level; bottom--average of 132 traces that peak between 1,459 and 1,460.8 feet above sea level.)

will increase to about 1,400 ft^3/s under the eroded condition. At higher elevations, erosion of the structures will increase the flow for a given stage by as much as 2,000 ft^3/s.

The Devils Lake-Stump Lake system contains about 900,000 acre-ft of water between 1,458 and 1,461 ft asl. If 1,400 ft^3/s is the maximum discharge and 700 ft^3/s is the average, about 21 months are needed to reduce the lake level to 1,458 ft asl. With this prolonged continuous discharge, erosion probably will continue below 1,458 ft asl.

The ultimate development of the erosion channel would depend upon the rate of erosion and the supply of water. If the rate of erosion is large, the shifting of the rating curve could be sufficient to maintain high rates of flow even if the lake level decreases. The erosion could continue down to about 1,446.5 ft asl. At that level,

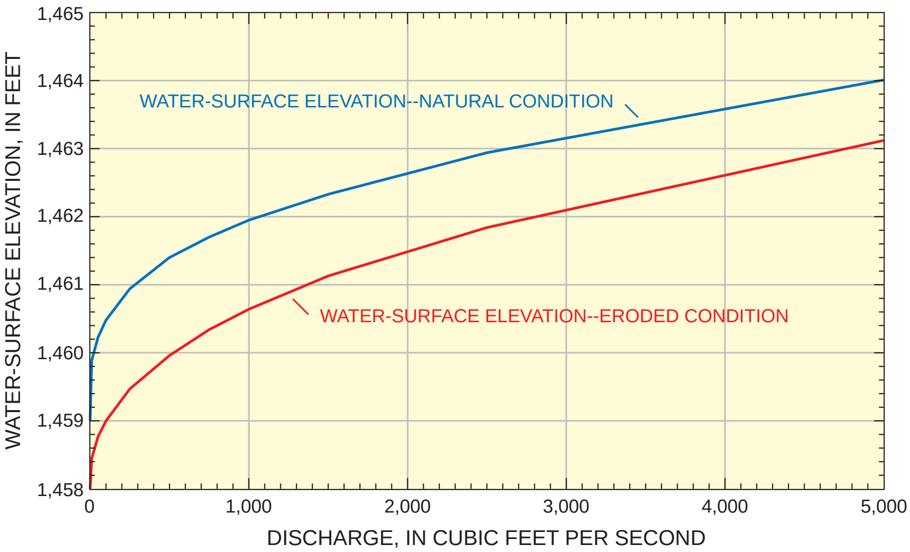

Figure 13. Discharge rating curves for Tolna Coulee under natural and eroded conditions.

Devils Lake separates from Stump Lake. (Corresponding erosion at the Devils Lake-Stump Lake connection is unlikely because of the much longer channel and much flatter slopes in that area.) Soil profiles in the Tolna Coulee outlet (Murphy and others, 1997) indicate no erosion-resistant materials within the 20-ft sampling depth; therefore, the down-cutting erosion probably would not encounter any natural barrier.

Given that the estimated probability of a spill occurring during the next 16 years is 1.8 percent, NDSWC engineers conducted an assessment of erosion-prevention measures near the Tolna Coulee outlet (Bruce Engelhardt, North Dakota State Water Commission, oral commun., 2000). The engineers concluded measures such as armoring the controlling dikes or paving would not be sufficient to control erosion. The engineers also concluded that construction of a dam to prevent a spill through Tolna Coulee is not practical.

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