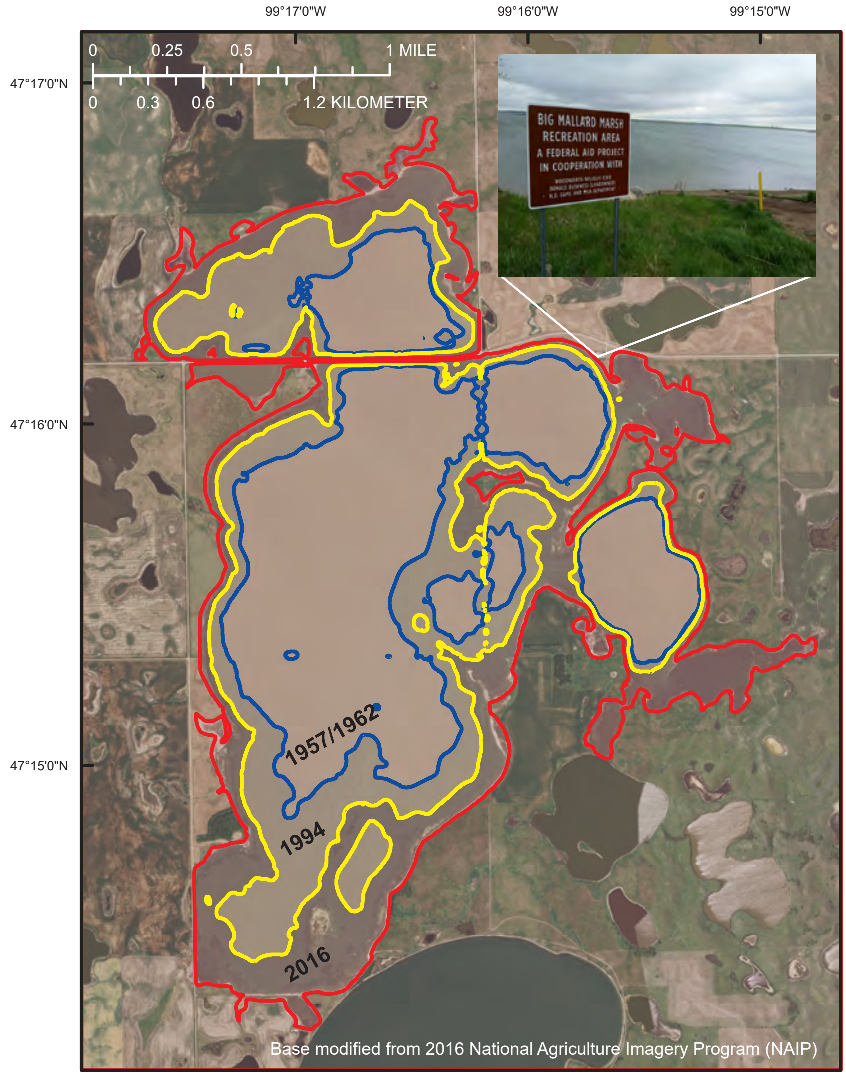
Prepared in cooperation with the North Dakota Game and Fish Department

Water-Balance Modeling of Selected Lakes for Evaluating Viability as Long-Term Fisheries in Kidder, Logan, and Stutsman Counties, North Dakota



Scientific Investigations Report 2019–5007

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

Cover: Aerial extent of Big Mallard Marsh and Big Mallard Marsh Recreation Area, May 17, 2017 (photograph in upper right by Robert Lundgren, U.S. Geological Survey). Located in the North Dakota Missouri Coteau. Colored shaded regions are the extent of lake levels for 1957/1962 (multiyear mosaiced image), 1994, and 2016 (2016, National Agriculture Imagery Program).

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Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
	Area	
acre	4,047	square meter (m^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)

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

$$1°C = (°F – 32) / 1.8.$$

Datum

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).

Abbreviations

ET	evapotranspiration
GIS	geographic information system
GNSS	Global Navigation Satellite System
HPRCC	High Plains Regional Climate Center
NCDC	National Climatic Data Center
NDAWN	North Dakota Agricultural Weather Network
NDGF	North Dakota Game and Fish
NGS	National Geodetic Survey
PET	potential evapotranspiration
RTN	real-time network
SMD	soil moisture deficit
USGS	U.S. Geological Survey
VRS	virtual reference station

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Abstract

Water levels in lakes and wetlands in the central North Dakota Missouri Coteau region that were either dry or only sporadically held water since before the 1930s have been rising since the early 1990s in response to an extended wet period. The lakes have remained full since the mid-1990s, which has provided benefits to migratory waterfowl, fisheries, and wildlife. A small shift in climate conditions, either to drier or wetter conditions, can have a large effect on the lake levels of these water bodies. The North Dakota Game and Fish Department identified five lakes as candidates for sustaining long-term fisheries. The lakes are in Kidder, Stutsman, and Logan Counties, and some lakes might receive inflow from mostly freshwater aquifers, such as the Central Dakota and Streeter aquifers, and were mostly dry during the early 1990s. After about 1995, the lakes had filled up and were deep enough to sustain populations of game fish such as walleye, perch, and northern pike. Before investing in development of permanent fisheries and associated infrastructure, such as campgrounds and boat ramps, fisheries biologists needed to know if the lake levels are likely to remain high in coming decades.

The U.S. Geological Survey, in cooperation with the North Dakota Game and Fish Department, developed a water-balance model to determine the effects of precipitation, evapotranspiration, and groundwater interaction on lake volumes. The model was developed using climate input data and lake volumes for the calibration period 1992 through 2016, during which historical lake volumes could be estimated using land surface elevation data and Landsat images. Long-term (1940–2018) climate input data were used with the water-balance model to reconstruct historical lake volumes prior to the calibration period, and block-bootstrapping was used to simulate potential future climate input data and lake volumes for 2017 through 2067. The simulated future lake volumes were used to estimate the likelihood of annual lake volumes remaining consistent, increasing, or decreasing through the year 2067.

Of the five lakes, Sibley Lake was the most likely to sustain a long-term fishery for a period longer than 50 years. The simulated lake volumes for Alkaline Lake, Big Mallard Marsh, and Remmick Lake indicated the lakes have a 50-percent chance to fall below 75 percent of their 2016 volume by about 2030, 2067, and 2025, respectively. Simulation results for Marvin Miller Lake were substantially different compared to the other four lakes and indicated the lake has a 50-percent chance to fall below 75 percent of its 2016 volume prior to 2025.

Introduction

Lake water levels, hereinafter referred to as “lake levels,” in eastern and central North Dakota have been rising since the early 1990s in response to an extended wet period and generally above-normal precipitation in much of North Dakota, Minnesota, and southern Manitoba (Vecchia, 2011). Thousands of lakes and wetlands in the central North Dakota Missouri Coteau region (fig. 1) that were either dry or only sporadically held water since before the 1930s have remained full since the mid-1990s, providing benefits to migratory waterfowl, fisheries, and wildlife. Lake levels in these water bodies are driven primarily by precipitation and evapotranspiration (ET), and a somewhat small shift in climate conditions can have a large effect on the lake levels. If the climate in the study area shifts towards drier conditions, lake levels likely will decline; however, the magnitude of effect on the fisheries and lake levels depends on the influence of surface and groundwater inflow to the lakes. Some lakes might receive inflow from mostly freshwater aquifers, such as the Central Dakota and Streeter aquifers (fig. 1; North Dakota State Water Commission, 2018), and the water levels in these aquifers might remain high at or near the land surface long after drier conditions return, providing a buffer for maintaining high lake levels and good water quality necessary for sustaining long-term fisheries. Because of the higher lake levels in the North Dakota Missouri Coteau region and other areas in the State, the North Dakota Game and Fish (NDGF)

Department stocked fish in various lakes. Before developing long-term fisheries and establishing permanent fisheries and associated infrastructure, such as campgrounds and boat ramps, fisheries biologists need to know the likelihood of the lakes remaining high in coming decades. The U.S. Geological Survey (USGS), in cooperation with the NDGF, developed a model that describes the viability of establishing and maintaining long-term fisheries in five lakes identified by NDGF as promising candidates for sustaining fish populations. The five lakes were Alkaline Lake, Big Mallard Marsh, Marvin Miller Lake, Remmick Lake, and Sibley Lake in Kidder, Logan, and Stutsman Counties, North Dakota (fig. 1; table 1). The model will help improve understanding of the climate interactions with lake levels in the Missouri Coteau region, and the model (code available in appendix 1) could be applied to other lakes in the region.

A water-balance model was developed and used to determine the effects of precipitation, ET, and potential groundwater interaction on lake water volumes and levels. The model was developed using climate data and lake water volumes (hereinafter referred to as "lake volumes") for a 25-year calibration period (1992 through 2016). This calibration period included the rise in lake levels, during which historical lake levels and volumes could be estimated from Landsat images. Long-term (1940–2018) climate data were used as inputs to the water-balance model to reconstruct historical lake volumes prior to the calibration period, and block-bootstrapping (Davison and Hinkley, 1997; Cantry and Ripley, 2017) was used to simulate potential future climate conditions and lake volumes for 2017–67. The simulated lake volumes were used to assess the effect of historical and potential future climatic shifts on lake volumes and to estimate the likelihood of the lakes sustaining viable long-term fisheries in the coming decades.

Purpose and Scope

The purpose of this report is to describe data and methods used for the development of a water-balance model to simulate potential future climate conditions and lake volumes and subsequently assess the viability of Alkaline Lake, Big Mallard Marsh, Marvin Miller Lake, Remmick Lake, and Sibley Lake as long-term fisheries in North Dakota using the simulated data for future conditions. The water-balance model was developed using lake water-level data, Landsat imagery, area-capacity information derived from bathymetry data, and climate data. The water-balance model was developed to simulate potential future climate conditions and lake volumes for the selected lakes, and the model was used to simulate the likelihood of maintaining lake levels necessary for sustaining fisheries in the lakes for the next several decades.

Data Resources

The data resources used to develop the water-balance model were either measured directly at field sites associated with each of the five lakes during 2016 and 2017, retrieved from available online databases, or estimated from existing data. Data included lake water-surface elevations, estimates of lake surface-water area and volumes, and climate data.

Water-Surface Elevations

Lake water-surface elevations were collected seven times during the months of May through October in 2016 and 2017, and from the same temporary boat access points at each lake using survey-grade Global Navigation Satellite System (GNSS) methods described in Rydlund and Densmore (2012). The data provided measured elevations that were used as a reference and verification for comparison to elevations derived from Landsat imagery (see "Lake Water-Surface Area and Water Volume" section).

A check-in and checkout method using a National Geodetic Survey (NGS) vertical control marker in the local area was used to correct elevation positional accuracy (Rydlund and Densmore, 2012; National Geodetic Survey, 2012). Using this method, a receiver is connected to a base station such as real-time network (RTN) and corrections are provided by a virtual reference station (VRS) system (Rydlund and Densmore, 2012). A VRS network covers a local, regional, or statewide area of reference stations using cellular communication. The reference station network continuously streams data correcting the receiver (using local-area network, Internet, or radio links) to a central location (server) in real time to derive position and elevation of an objective point (Rydlund and Densmore, 2012).

Using a VRS network, an RTN survey was completed across five lakes in the study area. Accuracy of RTN surveying depends on many factors including the reference station distances, equipment and settings, survey procedures, and the survey environment (Rydlund and Densmore, 2012). Generally, this accuracy is in the range of traditional surveying methods. Several factors affect the vertical accuracy of these GNSS surveys, including movement from wind at observed point locations, current satellite geometry, and various obstruction factors (for example, multipath errors and signal degradation) interfering with the base communication. The RTN approach was used during each survey, and NGS marker elevation (National Geodetic Survey, 2012) was used for verification shots during the start and end of each survey with the NGS marker being the baseline benchmark. The position and elevation data were collected at the five lakes during each survey visit.

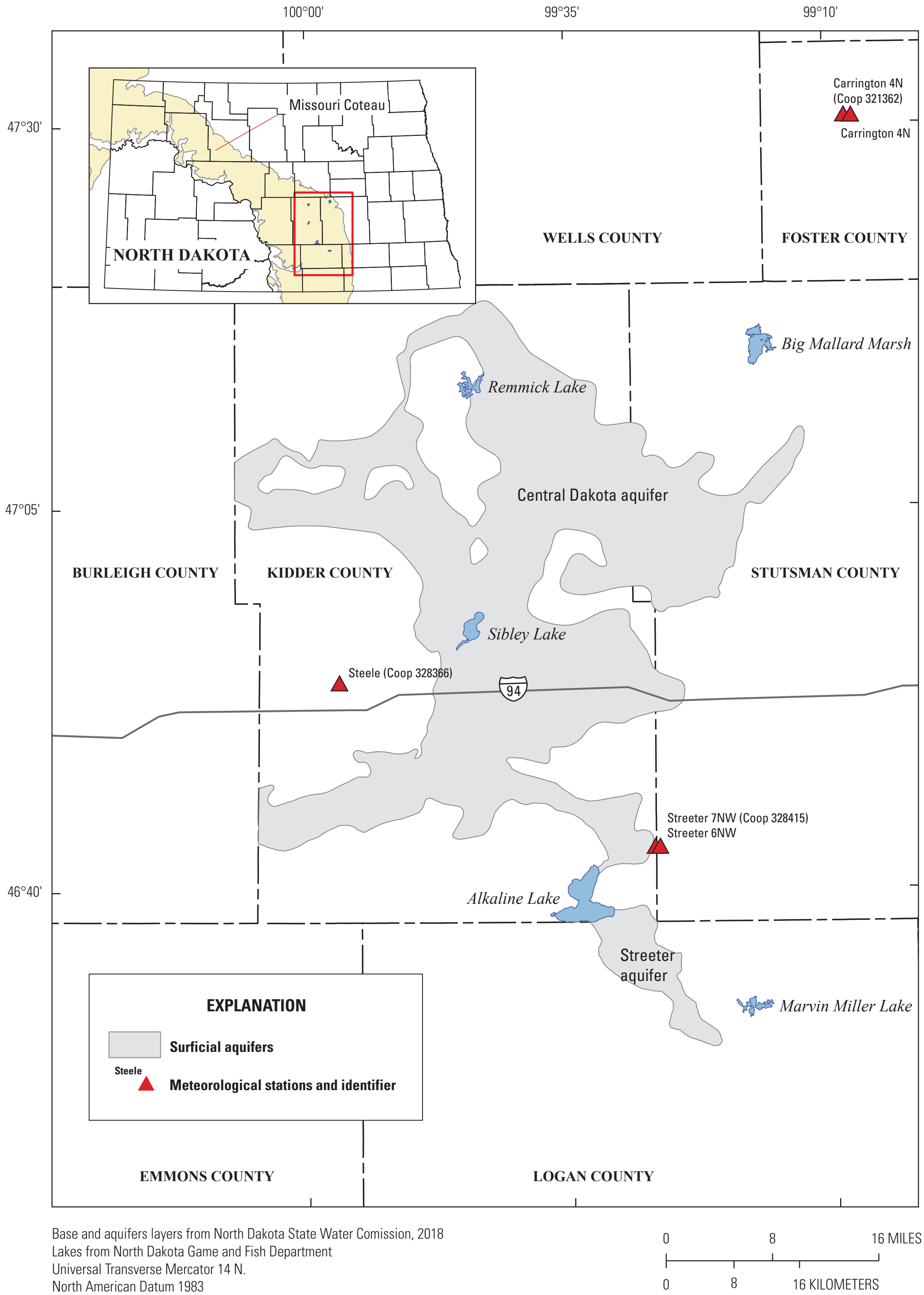

Figure 1. Location of study area including selected lakes, meteorological stations, and surficial aquifers in Kidder, Logan, and Stutsman Counties, North Dakota.

Table 1. Site information for lakes sites in study area.

Lake name (fig. 1)	County	Temporary boat access coordinates, in decimal degrees		Maximum area, in acres	Maximum depth, in feet[1]	Recent (2016) volume, in acre-feet[1]	50-percent lake volume, in acre-feet[1]	75-percent lake volume, in acre-feet[1]
		Latitude	Longitude					
Alkaline Lake	Kidder	46.6340	−99.6014	5,313	19	83,028	41,514	62,271
Big Mallard Marsh	Stutsman	47.2692	−99.2621	2,230	13	15,843	7,921	11,882
Marvin Miller Lake	Logan	46.5367	−99.3095	680	16	6,630	3,315	4,972
Remmick Lake	Kidder	47.2221	−99.7207	660	15	7,167	3,584	5,375
Sibley Lake	Kidder	46.9695	−99.7210	1,200	25	20,388	10,194	15,291

[1]Data from lake bathymetry provided by North Dakota Game and Fish (2018).

Lake Water-Surface Area and Water Volume

Changes in lake area and volume were determined using a combination of remote-sensing data and bathymetry data. Landsat Enhanced Thematic Mapper Plus and Operational Land Imager imagery was retrieved for each lake and used to determine the area and calculate the volume (U.S. Geological Survey, 2017). Images were retrieved for the period of about 1990 through 2016, and earlier if possible. The images selected were from seasonal periods during the highest lake level in the spring (about May) and the lowest lake level in the fall (about October). The images also encompassed various hydrological periods that included drought in 1992, a rising and wet period from 1992 through 1995, and a somewhat stable period from 1997 through 2016.

The surface area of each lake was determined using georeferenced Landsat imagery and geographic information system (GIS) software. The shoreline of each lake was digitized to determine the annual extent of the lake surface-water area from imagery taken in the spring (about May) and fall (about October) each year. The Landsat imagery retrieved has a spatial resolution of 30 meters and all the digitizing was done manually in GIS and required some interpretation of the shorelines because of the spatial resolution of the imagery.

The surface-water area and the shoreline of each lake were used in combination with bathymetry data collected by NDGF (North Dakota Game and Fish, 2018) to determine annual lake volumes. The bathymetry data of the lakes were contained in a GIS shapefile and had contour intervals of 3 feet. Bathymetry data with 3-foot contour intervals that were collected by the NDGF were converted to contour data with 1-foot intervals. This conversion was done in Esri ArcMap by using the 3-foot contour interval shapefile as the input in the “Create TIN” tool in 3D-Analyst. The resulting triangular irregular networks were converted to a raster using the “TIN to Raster” tool in 3D-Analyst. The new 1-foot contour interval shapefiles were then generated from the raster using the “Contour” tool in 3D-Analyst (Esri, 2017). The values associated with each contour interval for the generated 1-foot contour interval shapefile were used as input in the “Surface Volume” tool in 3D-Analyst (Esri, 2017). The output was the volume of the bathymetry raster below the value of the contour interval for each lake. Digitized annual fall-season shoreline elevations were then matched to the closest bathymetric contour. The bathymetry raster volume for the respective 1-foot contour line elevation was then associated with the annual fall-season shoreline, which produced an annual (fall season) volume for each lake from about 1990 through 2016. Big Mallard Marsh was selected as an example to show the surface-water area changes for three periods in comparison to surface-water area in 2016 (fig. 2).

Climate Data

Climate data were selected from climate stations that had data available for the period of record and were nearest to the respective lakes for accurate representation of precipitation and evaporation. The precipitation and evaporation data were used for the climate inputs in the model.

Climate data that included precipitation and evaporation were obtained from the High Plains Regional Climate Center (HPRCC; High Plains Regional Climate Center, 2018), and North Dakota Agricultural Weather Network (NDAWN) for the period from January 1991 through December 2016 (North Dakota Agricultural Weather Network, 2018). Climate data also were retrieved from the National Climatic Data Center (NCDC) from 1940 through 2015 (National Climatic Data Center, 2018). The HPRCC provided precipitation data that were downloaded from the Carrington 4N (Coop 321362), Steele (Coop 328366), and Streeter 7NW (Coop 328415) climate stations (fig. 1, table 2). The three stations had daily precipitation data that consisted of rainfall and liquid equivalent of snowfall (melted snowfall) for the entire study period. The HPRCC Carrington 4N station precipitation data were applied to Big Mallard Marsh. The HPRCC Steele station precipitation data were applied to Sibley and Remmick Lakes. The HPRCC Streeter 7NW station precipitation data were applied to Alkaline and Marvin Miller Lakes.

Daily potential evapotranspiration (PET, computed using the Penman method; Penman and Keen, 1948) data were downloaded from the Carrington 4N and Streeter 6NW NDAWN stations for the period from January 1991 through December 2016 (table 2). Daily PET data were used and summed to calculate monthly PET values for the study area.

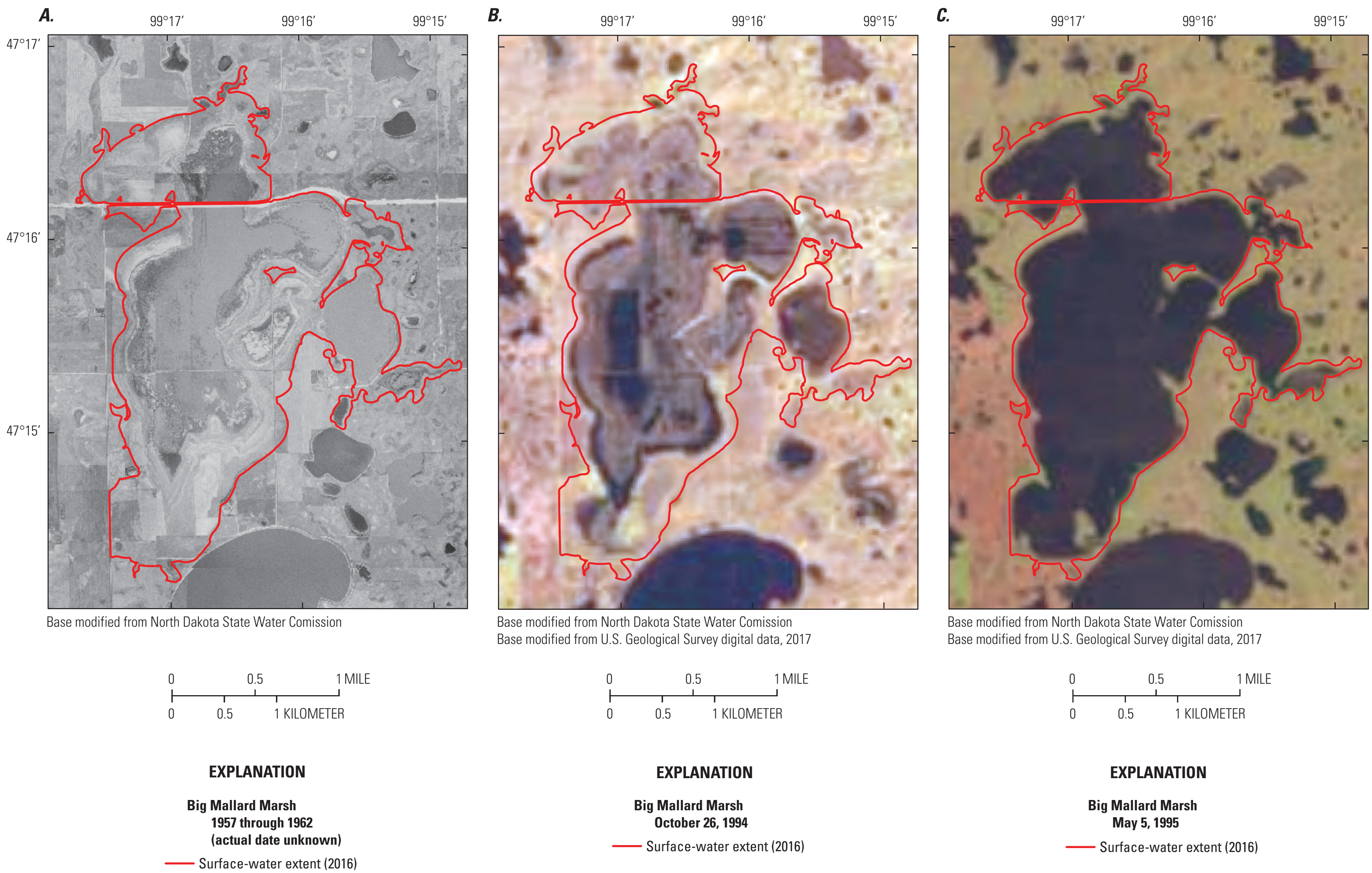

Figure 2. Lake water-surface areas of Big Mallard Marsh, 1957–2016. *A*, image taken between 1957 and 1962 (actual date unknown); *B*, image on October 26, 1994; and *C*, image on May 5, 1995.

The NCDC data consisted of monthly precipitation and temperature for climate division 5 (Central) in North Dakota that encompasses the study area (National Climatic Data Center, 2018). The NCDC climate division data were used to develop long-term (1940–2018) historical time series of monthly total precipitation and PET for the lakes, extending the somewhat short record available from HPRCC and NDAWN stations. The extended record was used to simulate future climate data required for estimating the probabilities of future lake levels.

Because the NCDC data did not include PET, monthly mean temperatures were used to estimate PET for each month using the Thornthwaite method, which requires only monthly mean temperature (Thornthwaite, 1948). Although the Thornthwaite method has been widely used and provides a reasonable approximation to PET, it underestimates PET compared to other methods, such as the Penman method (Rosenberry and others, 2004; Penman and Keen, 1948), which was the method used for the model calibration period. Therefore, monthly PET estimated using the Thornthwaite method was adjusted by comparing the Penman PET data and the Thornthwaite PET data for the calibration period and increasing the Thornthwaite PET values so that the monthly means for the two methods were identical. The same monthly corrections were applied to the Thornthwaite PET values for the pre-calibration period from 1940 through 2016. A similar procedure was used to adjust the monthly precipitation data. Whereas monthly precipitation data acquired from climate stations represented local conditions, precipitation data associated with climate divisions represent regional averages. Although there were high correlations between the monthly precipitation values for the climate division and individual stations, small adjustments were made to climate division data so that the monthly precipitation values from both sources had the same means for the calibration period.

Water-Balance Model Development

A water-balance model was developed and used to estimate the effects of precipitation, ET, surface inflow and outflow, and groundwater interaction, and to subsequently simulate future lake volumes for the five lakes. The model was developed using climate data and lake volumes for a 25-year calibration period from 1992 through 2016, during which historical lake levels and volumes could be estimated from Landsat images. Long-term (1940–2018) climate data were used along with the water-balance model to reconstruct historical lake volumes prior to the calibration period, and block-bootstrapping (Davison and Hinkley, 1997; Cantry and Ripley, 2017) was used to simulate potential future climate data and annual lake volumes for 2017 through 2067. The simulated future lake volumes were used to estimate the likelihood of the lakes retaining water in the coming decades (after 2018).

The water-balance model was developed using R, a programming and software environment for statistical computing (R Development Core Team, 2018). The water-balance model R code and supporting climate dataset are linked in appendix 1. Parameters of the model were calibrated for each of the lakes to reflect the unique characteristics of geography and hydrology of the lakes and surrounding watersheds. Input datasets for the water-balance model included monthly precipitation, PET, and estimated annual lake water-surface elevations and volumes from 1992 through 2016. The water-balance model operates on a quarterly (3-month) time step and was based on water years (October 1–September 30). The four quarters correspond to October–December (quarter 1), January–March (quarter 2), April–June (quarter 3), and July–September (quarter 4). Input data were temporally aggregated to the quarterly time step to be consistent with the temporal resolution of the water-balance model. The model was calibrated to lake volumes estimated to represent the end of each water year (August through November).

Table 2. Location information for climate data used for study, 1991–2016.

[HPRCC, High Plains Regional Climate Center; NDAWN, North Dakota Agricultural Weather Network]

Data source	Station name (fig. 1)	County	Latitude	Longitude	Data type	Lake where data were used	Period that data were used
HPRCC	Carrington 4N (Coop 321362)	Foster	47.5089	−99.1211	Precipitation (rainfall and liquid equivalent of snowfall)	Big Mallard Marsh	01/01/1991–12/31/2016
HPRCC	Steele (Coop 328366)	Kidder	46.8947	−99.9483	Precipitation (rainfall and liquid equivalent of snowfall)	Sibley and Remmick	01/01/1991–12/31/2016
HPRCC	Streeter 7NW (Coop 328415)	Stutsman	46.7153	−99.4475	Precipitation (rainfall and liquid equivalent of snowfall)	Alkaline and Marvin Miller	01/01/1991–12/31/2016
NDAWN	Carrington 4N	Foster	47.5090	−99.1320	Penman evapotranspiration	Averaged for all lakes	01/01/1991–12/31/2016
NDAWN	Streeter 6NW	Stutsman	46.7151	−99.4504	Penman evapotranspiration	Averaged for all lakes	01/01/1991–12/31/2016

Each lake is assumed to be in a watershed, or basin, that can contribute surface or groundwater inflow to the lake. The basins consist of the surface of the lake itself, a buffer area surrounding the lake that accounts for precipitation and ET from vegetation immediately surrounding the lake, and the remainder of the basin that includes soils and vegetation that are not part of the lake or surrounding buffer area. The lake/buffer area is defined as the area that would be inundated by the lake at an elevation that is 5 feet higher than the water-surface elevation at the end of the quarter. The water-balance model is used to estimate the lake volume at the end of each quarter as a function of the following components: precipitation on and evaporation from the lake water surface and surrounding lake buffer area, precipitation on the surrounding catchment, frozen precipitation storage and melt, soil moisture storage and ET, surface-water inflow, groundwater storage, leakage of groundwater storage to the lake, groundwater leakage from the lake, and surface outflow from the lake (eq. 1). A schematic of the model is given in figure 3 and the various model components are described in the following paragraphs.

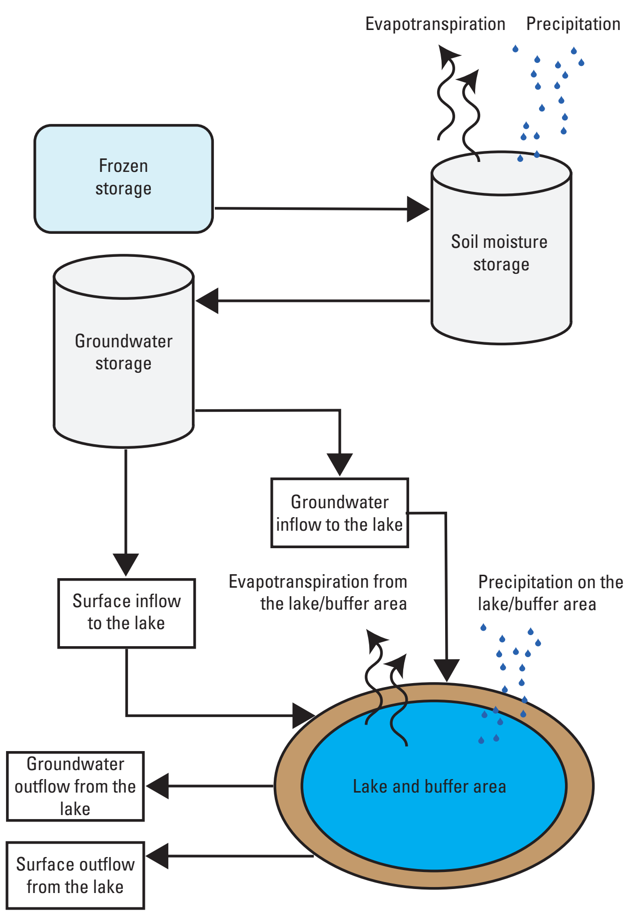

Figure 3. Water-balance model applied to five selected lakes in North Dakota, 1992–2016.

Lake volume at the end of each quarter estimated with the following equation:

$$V_1 = V_0 + PRLAKE - EVLAKE + QIN + GWGAIN - GWLOSS - QOUT \quad (1)$$

where

- V_1 is the lake volume at the end of the current quarter, in acre-feet;
- V_0 is the lake volume at the end of the previous quarter, in acre-feet;
- $PRLAKE$ is precipitation on the lake/buffer area, in acre-feet;
- $EVLAKE$ is evaporation from the lake/buffer area, in acre-feet;
- QIN is surface inflow to the lake, in acre-feet;
- $GWGAIN$ is groundwater inflow to the lake, in acre-feet;
- $GWLOSS$ is groundwater outflow from the lake, in acre-feet; and
- $QOUT$ is surface outflow from the lake, in acre-feet.

The equations used to compute each of the variables in equation 1 are given in table 3. The first part of table 3 provides equations for computing variables related to the water balance for the drainage basin contributing to the lake. Each lake is assumed to be in a watershed, or basin, with area *barea* (in acres) that can contribute inflow to the lake. Precipitation on the soils and vegetation of the basin (P, table 3) is a constant multiple of precipitation from the climate station closest to the lake (P_M). Precipitation for quarter 4 is equal to P_M. Precipitation for the remaining quarters is from 10 to 20 percent higher than P_M to adjust for the tendency for undercatch of precipitation during snowy and windy months (Vecchia, 2008). Evaporation (E, table 3) from the soils and vegetation is a constant value ranging from 0 to 1 and is multiplied by PET calculated at each respective climate station. Values of evaporation are typical of values expected for this region, as defined by previous work (Saxton and McGuinness, 1982). Precipitation for quarter 1 is used to satisfy moisture demand, represented by evaporation, and replenish the soil moisture deficit (SMD) from the previous quarter, with excess precipitation (XP) held in frozen storage. The SMD from the previous quarter (quarter 4 of the previous year) is either eliminated (if excess precipitation is greater than 0), reduced (if excess precipitation is equal to 0 and P is greater than evaporation), or increased (if excess precipitation is equal to 0 and P is less than evaporation) up to a maximum of 3.5 inches. For quarter 2, evaporation is set to zero and there is no change in SMD from quarter 1, and excess precipitation, which consists of frozen storage carried over from quarter 1 plus precipitation for quarter 2, is held in frozen storage. For quarter 3, frozen storage carried over from quarter 2 (which is assumed to melt by the end of quarter 3) is combined with precipitation for quarter 3 and the total is used to satisfy moisture demand (E) and any remaining SMD from the end of the previous quarter, and SMD is updated in a similar manner to quarter 1. Frozen storage for the end of quarters 3 and 4 is zero. After computing excess precipitation, it is used to compute the total volume of surplus water (SW, in acre-feet) for each quarter, which is used as described later for the remaining water-balance calculations. SW is zero for quarters 1 and 2 (when all available water is in frozen storage), and for quarters 3 and 4, SW is computed as the product of excess precipitation (in feet) and the area of the contributing basin (*barea*) minus the area of the lake itself, including the buffer area, for the end of the previous quarter (A_0).

The remaining water-balance equations are given in the second part of table 3. PRLAKE is the product of (P) and A_0. For quarter 2 and 4, EVLAKE is the product of evaporation from the basin (E) and $A_{0,}$ but E for quarter 2 is assumed to be zero for the winter months. For quarters 1 and 3, E was increased by 50 percent before multiplying by A_0 because lake evaporation for those quarters tends to exceed evaporation from the soils and vegetation of the contributing basin. Computation of groundwater inflow to the lake (GWGAIN) and surface inflow (QIN) depends on the volume of groundwater storage (GWS). The maximum value for GWS is designated by *maxgwstor*. If *maxgwstor* is 0, there is no groundwater storage (GWS equals 0) and no groundwater inflow to the lake (GWGAIN equals 0), and surplus water (SW) is assumed to flow directly into the lake as surface inflow (QIN equals SW). If *maxgwstor* is greater than 0, some or all of SW is held in groundwater storage before reaching the lake. For quarters 1 and 2, GWGAIN is the product of a specified coefficient (*cgain*) times the amount of groundwater storage from the end of the previous quarter (GWS_0), multiplied by a damping factor that reduces the rate of groundwater inflow if GWS_0 is less than *maxgwstor*. For quarters 3 and 4, SW is combined with GWS_0, and GWGAIN is computed in a similar manner to the previous quarters except that GWGAIN is capped at the maximum allowable value (*cgain* times *maxgwstor*) if the sum of GWS_0+SW exceeds *maxgwstor*. If the sum of GWS_0+SW exceeds *maxgwstor* (which can only happen during quarters 3 and 4), the surplus becomes surface inflow (QIN). After computing GWGAIN and QIN, and updating GWS, groundwater outflow from the lake (GWLOSS) and surface-water outflow from the lake (QOUT) can be determined. GWLOSS depends on a specified coefficient (*closs*). If *closs* is 0, there is no groundwater loss, and if *closs* is greater than 0, there is groundwater loss when the lake exceeds a specified volume (*vgwloss*). In that case, GWLOSS is the product of *closs* and the excess lake volume. Unlike GWLOSS, which can occur during any quarter, surface outflow (QOUT) can occur only during quarters 3 and 4 and only if the lake volume (after accounting for all other sources of inflow and outflow) is above the lake volume at the spill elevation (*vspill*). For quarter 3, QOUT equals one-half of the excess lake volume above *vspill* and the lake can remain above *vspill* at the end of the quarter. For quarter 4, QOUT equals the entire excess volume above *vspill* and the lake must be at or below *vspill* at the end of the quarter.

The lake-specific water-balance model coefficients, basin area, and volumes that needed to be specified for each lake (*barea*, *cgain, closs*, *maxgwstor*, and *vloss*) along with the spill elevation (*espill*), spill area (*aspill*), and spill volume (*vspill*) of each lake are shown in table 4. The modeled lake volumes (quarterly time step) and observed lake volumes (annual time step) during the calibration period (1992 through 2016) for each lake are shown in figure 4. For each lake, the initial values for the soil moisture deficit (SMD) and groundwater storage (GWS) for quarter 1 of 1992 were 3.5 inches and 0, respectively, because of the period of extended drought during 1988–92. The basin area (*barea*), model coefficients (*cgain* and *closs*), and specified volumes (*maxgwstor* and *vloss)* were selected through a combination of manual calibration and nonlinear least squares regression. An effort was made to maximize the correlation coefficient (Spearman's Rho, hereafter referred to as "rho") (Helsel and Hirsch, 2002) between modeled and observed annual lake volumes, subject to the constraint that the model was approximately unbiased (the average difference between observed and modeled lake volumes was close to zero). For the first pass, it was assumed there was no groundwater storage or loss (*maxgwstor*. *cgain*, and *closs* were set to 0), and *barea* (the only unknown parameter in that case) was estimated using nonlinear least squares regression. For two of the lakes (Alkaline and Sibley Lakes), the resulting model fit was deemed adequate and the one-parameter model was selected. For the remaining lakes, the predicted lake volumes using the one-parameter model rose too quickly during the mid- to late 1990s, thus groundwater storage parameters (*maxgwstor* and *cgain*) were included along with *barea*. The values for the groundwater storage parameters were manually varied to obtain the best agreement between modeled and observed lake volumes. For Remmick Lake, the three-parameter model was deemed adequate. For Marvin Miller Lake (which did not exceed the spill volume during the calibration period), the three-parameter model provided lake volumes that were too high after 2005. The only way to match the later volumes was to increase *maxgwstor* to a very large value, in which case the modeled lake volumes prior to 2005 were much too low. Therefore, the groundwater loss parameters (*closs* and *vloss*) were included. For Big Mallard Marsh, unlike Marvin Miller Lake, the lake volume was above the spill volume for years after about 2000, and there was considerable surface outflow during some years; however, surface outflows for the three-parameter model were too high during years after 2000 and the modeled lake volumes were at (for quarter 4) or well above (for quarter 3) the spill volume every year after 2000. Inclusion of the groundwater loss parameters provided a considerable improvement to the three-parameter model.

Overall, the modeled lake volumes provided a good fit to the observed lake volumes for all five lakes (fig. 4, table 4). The correlation coefficient (rho) between observed and modeled annual lake volume changes for the end of each water year ranged from about 0.41 for Big Mallard Marsh to about 0.76 for Sibley Lake. The root-mean-square error between the modeled and observed volume, as a percent of the observed volume, was less than 10 percent for Sibley and Alkaline Lakes, between 10 and 20 percent for Big Mallard Marsh and Remmick Lake, and about 24 percent for Marvin Miller Lake.

Table 3. Computations used in the water-balance model for five selected lakes in North Dakota, 1992–2016.

[P_M, precipitation in inches from the climate station nearest to the lake; PET_M, potential evapotranspiration, in inches, from the climate station nearest to the lake; SMD_0, soil moisture deficit from the end of the previous quarter; >, greater than; min, minimum value; <, less than; barea, total basin area contributing to the lake in acres; A_0, area of the lake (including buffer) in acres at the end of the previous quarter; PRLAKE, precipitation on the lake/buffer area; EVLAKE, evaporation from the lake/buffer area; GWGAIN, groundwater inflow to the lake; QIN, surface inflow to the lake; GWLOSS, groundwater outflow from the lake; QOUT, surface outflow from the lake; cgain, fraction of groundwater storage that leaks into the lake per quarter (dimensionless); GWS_0, groundwater storage from the end of the previous quarter; exp, base of the natural logarithm and equal to approximately 2.718; maxgwstor, maximum volume of groundwater storage, in acre-feet; closs, fraction of lake volume above vgwloss that is lost per quarter (dimensionless); V_0, lake volume, in acre-feet, at the end of the previous quarter; vgwloss, lake volume, in acre-feet, above which groundwater outflow occurs; vspill, lake volume in acre-feet above which surface outflow occurs]

Quarter	Precipitation (P), in inches	Evaporation (E), in inches	Excess precipitation (XP), in inches	Soil moisture deficit (SMD), in inches	Frozen storage (FS), in inches	Surplus water (SW), in acre-feet
1 (Oct.–Dec.)	$1.1P_M$	$0.4\ PET_M$	$P–E–SMD_0$, if $P–E>SMD_0$; 0, otherwise	0, if $XP>0$; $SMD_0–(P–E)$, if $XP=0$ and $(P–E)>0$; $\min(SMD_0+(E–P), 3.5)$, if $XP<0$ and $(E–P)>0$	XP	0
2 (Jan.–Mar.)	$1.2P_M$	0	FS+P	$SMD=SMD_0$	XP	0
3 (Apr–June)	$1.1P_M$	$0.3\ PET_M$	$FS+P–E–SMD_0$, if $FS+P–E>SMD_0$; 0, otherwise	0, if $XP>0$; $SMD_0–(FS+P–E)$, if $XP=0$ and $(P–E)>0$; $\min(SMD_0+(E–P–FS), 3.5)$, if $XP<0$ and $(E–P–FS)>0$	0	$(barea–A_0)\ XP/12$
4 (July–Sept.)	P_M	$0.8\ PET_M$	$P–E–SMD_0$, if $P–E>SMD_0$; 0, otherwise	Same as quarter 1	0	$(barea–A_0)\ XP/12$

Quarter	PRLAKE, in acre-feet	EVLAKE, in acre-feet	GWGAIN, in acre-feet	QIN, in acre-feet	Groundwater storage (GWS), in acre-feet	GWLOSS, in acre-feet	QOUT, in acre-feet
1 (Oct.–Dec.)	$A_0\ P$	$1.5\ A_0\ E$	$cgain(GWS_0)\ \exp\{–2(1–GWS_0/maxgwstor)\}$, if $GWS_0<maxgwstor$	0	$GWS_0–GWGAIN$	$closs(V_0–vgwloss)$, if $V_0>vgwloss$; 0, otherwise	0
2 (Jan.–Mar.)	$A_0\ P$	0	Same as quarter 1	0	Same as quarter 1	Same as quarter 1	0
3 (Apr.–June)	$A_0\ P$	$1.5\ A_0\ E$	$cgain(maxgwstor)$, if $GWS_0+SW>maxgwstor$; $cgain(GWS_0+SW)\ \exp\{–2(1–[GWS_0+SW]/maxgwstor)\}$, if $GWS_0<maxgwstor$	$GWS_0+SW–maxgwstor$, if $(GWS_0+SW)>maxgwstor$; 0, otherwise	$GWS_0+SW–QIN–GWGAIN$	Same as quarter 1	$0.5(V_0+PRLAKE–EVLAKE+GWGAIN+QIN–GWLOSS–vspill)$, if greater than 0; 0, otherwise
4 (July–Sept.)	$A_0\ P$	$A_0\ E$	Same as quarter 3	Same as quarter 3	Same as quarter 3	Same as quarter 1	$V_0+PRLAKE–EVLAKE+GWGAIN+QIN–GWLOSS–vspill$, if greater than 0; 0, otherwise

Table 4. Calibration coefficients used in the water-balance model for five selected lakes in North Dakota, 1992–2016.

Lake name (fig. 1)	Basin area (barea), in acres	Groundwater storage (maxgwstor), in acre-feet	Calibration coefficient (cgain), dimensionless	Calibration coefficient (closs), dimensionless	Volume loss (vloss), in acre-feet
Alkaline Lake	54,850	0	0.0	0	0
Big Mallard Marsh	13,250	9,180	0.1	0.1	17,220
Marvin Miller Lake	4,800	4,130	0.1	0.4	6,200
Remmick Lake	4,860	6,890	0.05	0	0
Sibley Lake	8,700	0	0.0	0	0

Lake name (fig. 1)	Spill elevation (espill), in feet above North American Vertical Datum of 1988)	Spill volume (vspill), in acre-feet	Spill area (aspill), in acres	Correlation coefficient (Spearman's rho), dimensionless	Root-mean-square error as a percent of observed volume
Alkaline Lake	1,864	84,000	7,490	0.668	9.3
Big Mallard Marsh	1,835	16,870	2,180	0.415	13.7
Marvin Miller Lake	1,861	11,620	900	0.744	24.1
Remmick Lake	1,811	7,460	960	0.551	19.0
Sibley Lake	1,732	21,210	1,600	0.757	7.1

As discussed previously in this section, for Alkaline and Sibley Lakes, there was no delayed groundwater storage (*maxgwstor*=0, *cgain*=0, *closs*=0) and no groundwater loss from the lake (*closs*=0) (table 4). Thus, for those lakes the only calibration parameter was the estimated basin area (*barea*). For Alkaline Lake, the largest of the five lakes, *barea* was about 55,000 acres and the area of the lake at the spill elevation (*aspill*) was about 7,500 acres. For Sibley Lake, *barea* was about 8,700 acres and *aspill* was about 1,600 acres. The ratio of *barea* to *aspill* for Alkaline Lake (7.3) was similar to the ratio for Sibley Lake (5.5)

For Big Mallard Marsh, there was delayed groundwater storage. The maximum groundwater storage (*maxgwstor*) was 9,180 acre-feet, or about 54 percent of the spill volume (*vspill*), which was about 16,870 acre-feet, and *cgain* was equal to 0.1. The lake lost groundwater outflow (GWLOSS) at a volume (*vloss*) of 17,220 acre-feet during the calibration period, which is about equal to the spill volume, and *closs* was equal to 0.1. The basin area (*barea*) for Big Mallard Marsh was 13,250 acres compared to area at the spill elevation (*aspill*) of 2,180 acres. The ratio of *barea* to *aspill* for Big Mallard Marsh (6.1) was similar to the ratio for Alkaline Lake (7.3) and Sibley Lake (5.5).

For Marvin Miller Lake, there also was delayed groundwater storage (*maxgwstor*) of 4,130 acre-feet, or about 35 percent of spill volume (*vspill*) of 11,620 acre-feet, and *cgain* was equal to 0.1. The lake lost groundwater at a volume (*vloss*) of 6,200 acre-feet during the calibration period, and *closs* was equal to 0.4. Compared to Big Mallard Marsh, Marvin Miller Lake lost groundwater at a lower lake volume (in relation to *vspill*) and had a higher outflow rate (*closs*=0.4 versus 0.1). The basin area (*barea*) for Marvin Miller Lake was 4,800 acres and the spill area (*aspill*) was 900 acres.

For Remmick Lake, there also was delayed groundwater storage (*maxgwstor*) of 6,890 acre-feet, or about 92 percent of spill volume (*vspill*) of 7,460 acre-feet, and cgain was equal to 0.05. There was no groundwater outflow (*closs*) from the lake. The basin area (*barea*) for Remmick Lake was 4,860 acres and the spill area (*aspill*) was 960 acres

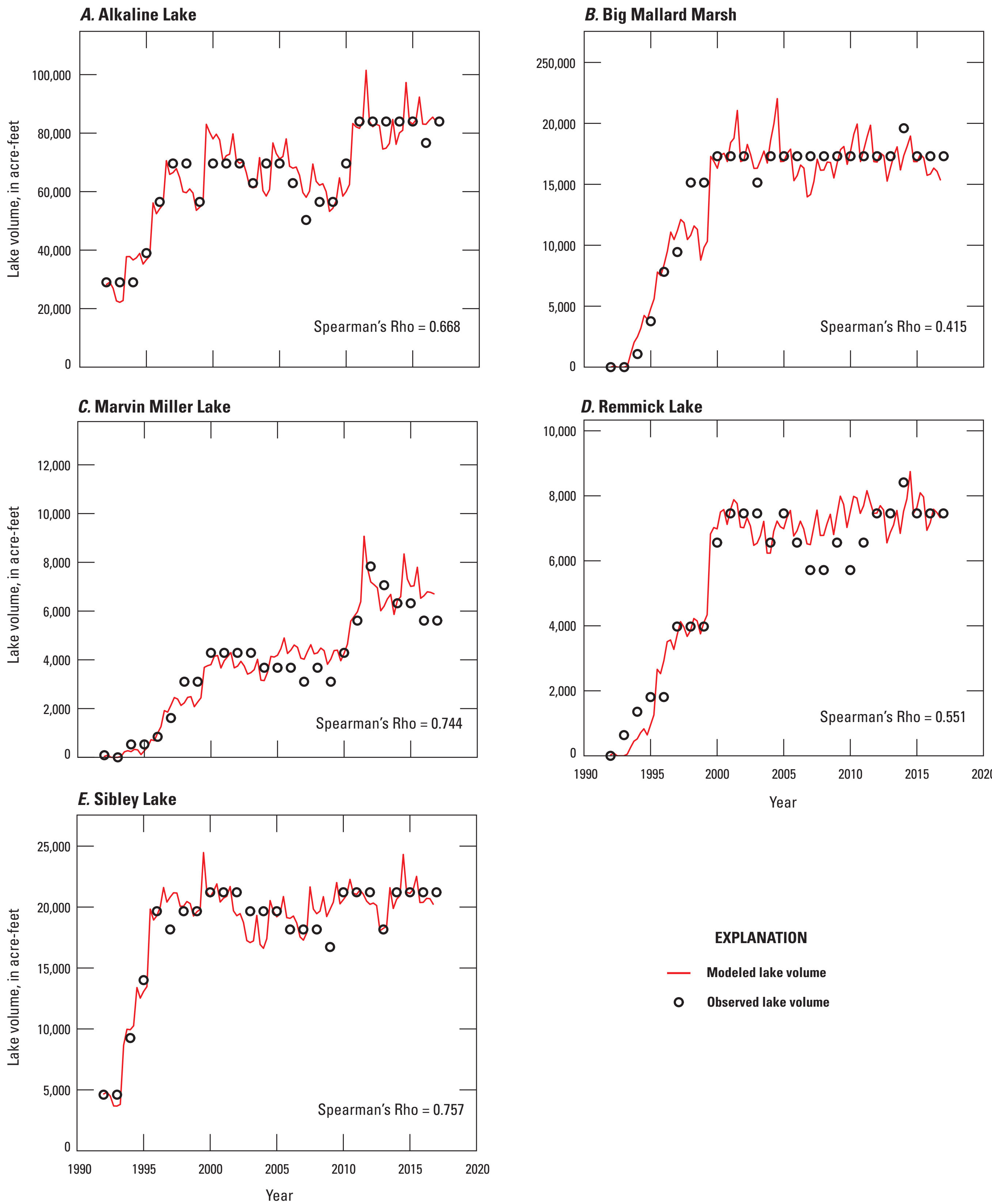

Figure 4. Modeled and observed lake volume for five selected lakes in North Dakota, 1992–2016.

Water-Balance Model Simulations

The water-balance model was developed to simulate potential future lake volumes for five selected lakes in Kidder, Logan, and Stutsman Counties, N. Dak. (fig. 1). The model uses long-term historical NCDC data for North Dakota climate division 5 (National Climatic Data Center, 2018) to back-extend the short-term (1992–2016) period of record for precipitation and PET used to calibrate the water-balance model, resulting in a long-term (1940–2018) extended climate dataset. In addition to simulating future lake volumes, the long-term climate dataset was used to reconstruct historical lake volumes for 1940 through 2018 for comparison to the observed, calibrated, and simulated future lake volumes. The reconstructed historical lake volumes provided an additional verification of the calibrated water-balance model by ensuring that the reconstructed lake levels were in close agreement with the observed lake levels for the calibration period.

Comparison of the reconstructed long-term lake volumes for each lake from 1940 through 2018 (computed using the adjusted NCDC data) and the estimated lake volumes from the water-balance model for the calibration period from 1992 through 2016, indicates close agreement for each lake. An example of the comparison is shown for Sibley Lake in figure 5. The reconstructed Sibley Lake volume in 1940 (at the end of the 1930s drought) was similar to the lake volume at the beginning of the calibration period (1992), and the estimated lake volumes for the calibration period were in close agreement with the reconstructed lake volumes (fig. 5). Although the reconstructed lake levels did not rise quite as quickly during 1995 through 2000 compared to the lake levels from the calibrated model, the reconstructed lake volumes were in overall good agreement with the calibration results. For Sibley Lake (and each of the other lakes), the reconstructed lake volumes during 1940 through 1990 were lower than the lake volumes during 1995 through 2016, which agrees with evidence from larger lakes in eastern North Dakota (such as Devils Lake), for which lake volumes during recent decades are known to be higher than lake volumes dating back to at least the late 1880s (Wiche and Vecchia, 1995).

A method known as block-bootstrapping (Davison and Hinkley, 1997; Cantry and Ripley, 2017) was used to simulate 50 years of potential future time series of the climate data inputs after the end of the calibration period (2016) that were resampled from the long-term historical record and that contained virtually every reasonable climate outcome (duration and sequence of wet and dry periods) that could be expected. To generate a 50-year sequence of potential future climatic variables, a block length (*b*) is first selected at random such that *b* is equally likely to take any value from 1 to 50 years. Then, a historical starting year is selected at random from among 1940 through 2018. For example, suppose the *b* is 25 and the starting year 1961; in that case, the historical climatic inputs for 1961 through 1985 consist of the first 25 years of the simulated data. To generate the remaining 25 years, another starting year is selected at random and 25 years of historical data starting with that year are used. If the end year extends past the end of the historical record, values from the beginning of the record are used to fill out the sequence. For example, if the starting year is 2000 and the block length is 25 years, the first 19 years would consist of 2000 through 2018 and the remaining 6 years would consist of 1940 through 1945. The same process is repeated to obtain another bootstrap replicate. For example, for the second replicate, the initial block length (*b*) might be 10 years (starting year selected at random) and the remaining block length would be 40 (50–10) years with the starting year again selected at random. This process was repeated 1,000 times to simulate 1,000 potential future sequences of the climate data, each one equally likely. Each sequence was fed into the water-balance model starting with the same initial conditions at the end of the calibration period (2016) and continuing for another 50 years with the simulated climate input data. Thus, for each of the future 200 quarters (50 years of quarterly data), there were 1,000 simulated lake levels, each equally likely. These were used to compute the 50-, 75-, and 90-percent exceedance levels for each quarter, and the quarterly exceedance levels were smoothed using supsmu, Friedman's SuperSmoother (R Development Core Team, 2018), to remove seasonality and noise, resulting in a smooth exceedance curve.

Block-bootstrapping was used to randomly resample the long-term historical record and obtain simulated future climate data for the next 50 years (2017–67). A total of 1,000 bootstrapped replicates of future climate data and lake volumes were generated for each lake. The replicates were used to determine exceedance levels for the next 50 years (lake volumes that are exceeded with specified probabilities of 50 percent, 75 percent, and 90 percent). For a given future year, the lake has an "equal chance" (50-percent chance) of being above or below the 50-percent exceedance level, a "good" chance (75-percent chance) of being above the 75-percent exceedance level, a "small" chance (90-percent chance) of being below the 90-percent exceedance level.

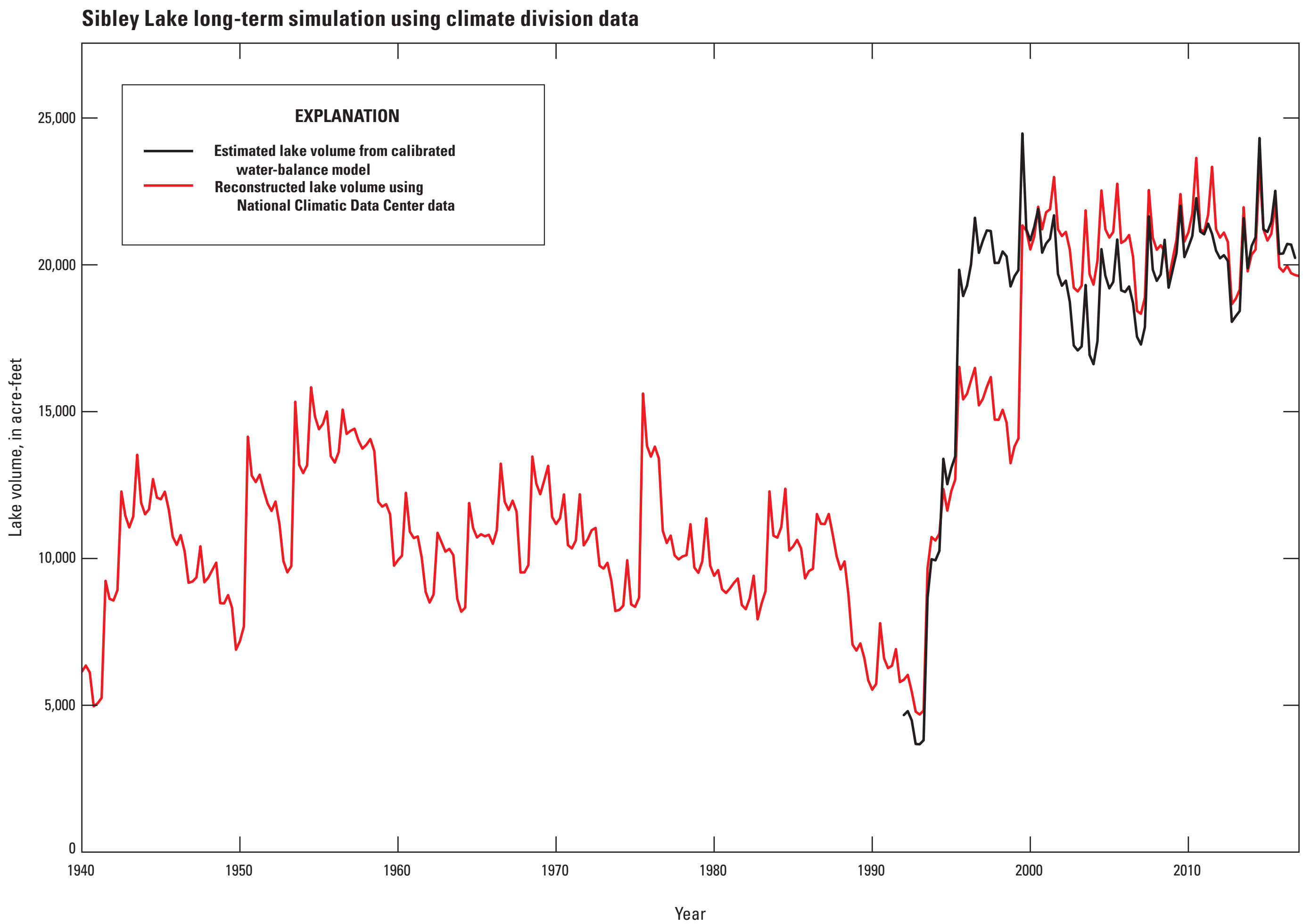

Figure 5. Simulated and reconstructed lake water volume for Sibley Lake, 1940–2018.

Simulated Future Lake Volumes

Future lake volumes were simulated for each of the five lakes for the period of 2017 through 2067 (figs. 6–10). For comparison, reconstructed lake volumes from 1940 through 2016, which include reconstructed volumes from the reconstructed period of 1940 through 1991 and the calibration period of 1992 through 2016, are displayed with the future simulation period of 2017 through 2067 (figs. 6–10). Four (out of 1,000) random replicates of simulated future lake volumes are shown for comparison to the historical record. The probabilities of future lake conditions from the simulations are summarized using the 50-, 75-, and 90-percent exceedance levels. For discussion purposes, the lake volume in a future year will be described as having an “equal chance” of being above the 50-percent exceedance level and a “good” chance of being above the 75-percent exceedance level. Conversely, for low lake volumes, the lake volume will be described as having a small chance of being below the 90-percent exceedance level. For assessing effects on fisheries, two reference volumes, the 50- and 75-percent lake volume, are shown on each plot. These reference volumes were selected in consultation with NDGF fisheries biologists (Scott Gangl, North Dakota Game and Fish Department, written commun., 2018). Because the depth of each lake is different and effects might vary among the lakes at different depths, the NGDF determined the 75-percent lake volume with respect to the recent (2016) lake volume would be most appropriate as a conservative volume above which the fisheries could remain sustainable (Scott Gangl, North Dakota Game and Fish Department, written commun., 2018). If the lake volume is between 50 and 75 percent of the recent volume, there might not be complete fish kills but productivity would be diminished, and if the lake volume is below 50 percent of the recent volume, the fishery would likely be unsustainable.

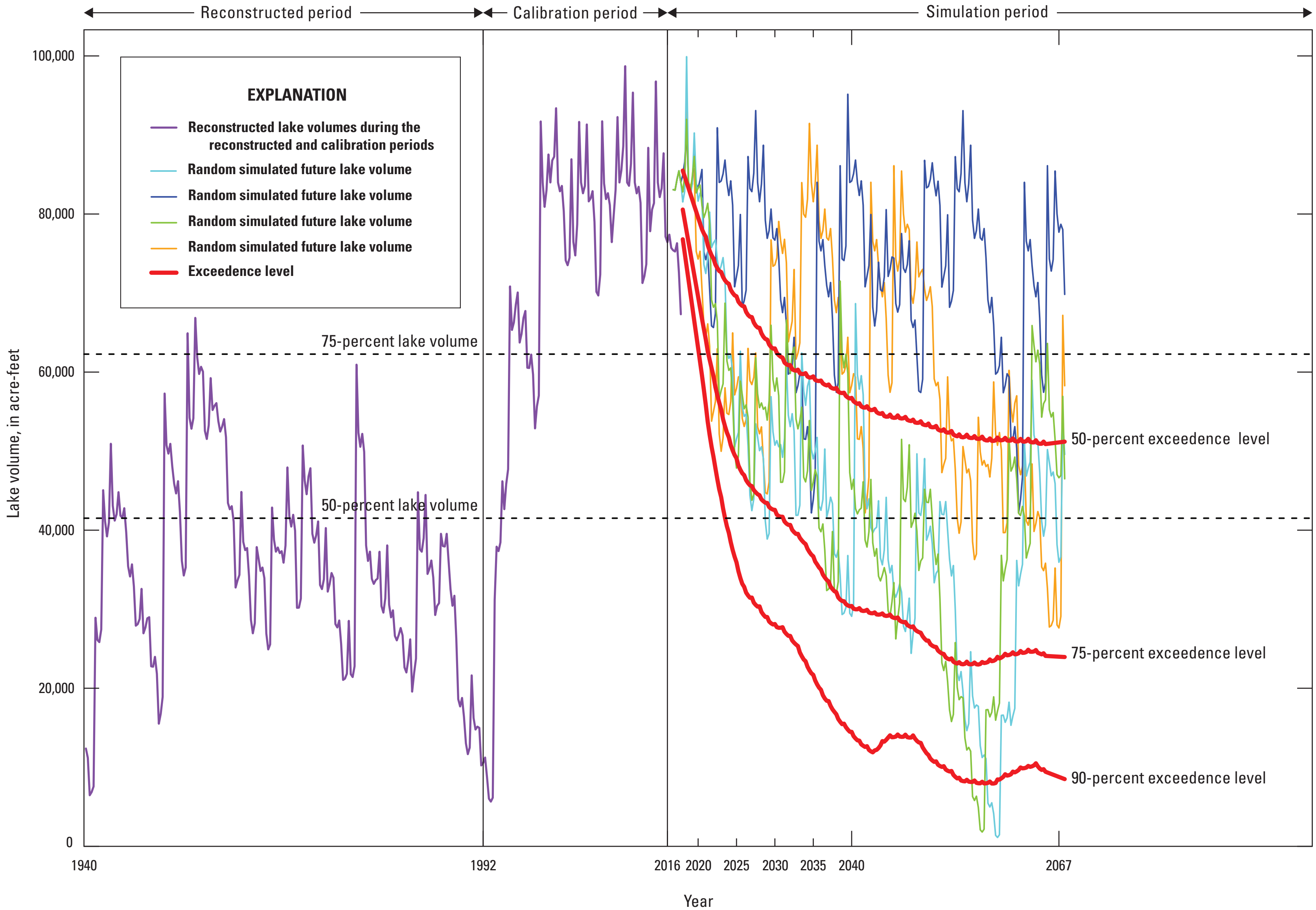

Figure 6. Simulated lake volumes and exceedance levels for Alkaline Lake, 1940–2067.

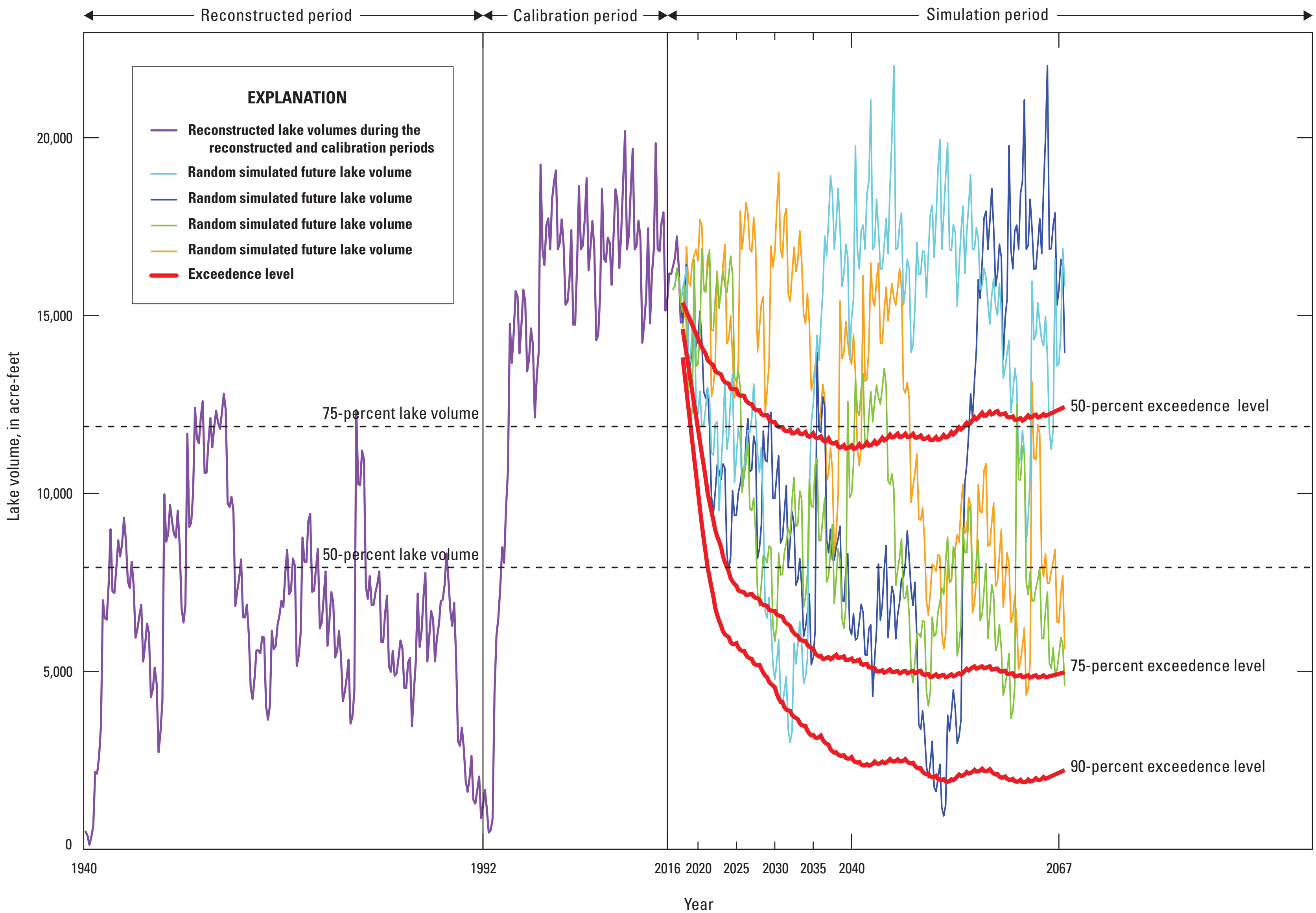

Figure 7. Simulated lake volumes and exceedance levels for Big Mallard Marsh, 1940–2067.

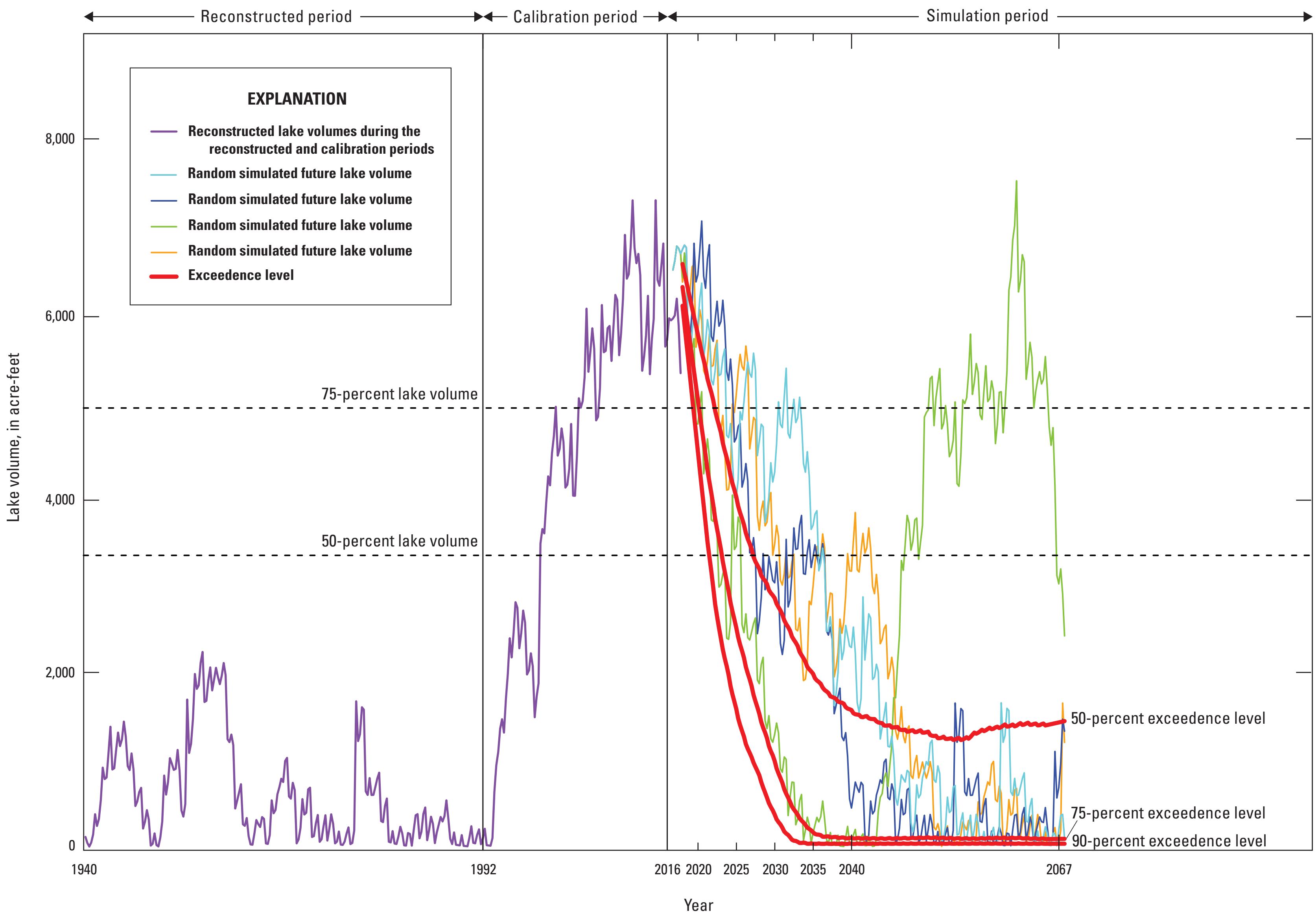

Figure 8. Simulated lake volumes and exceedance levels for Marvin Miller Lake, 1940–2067.

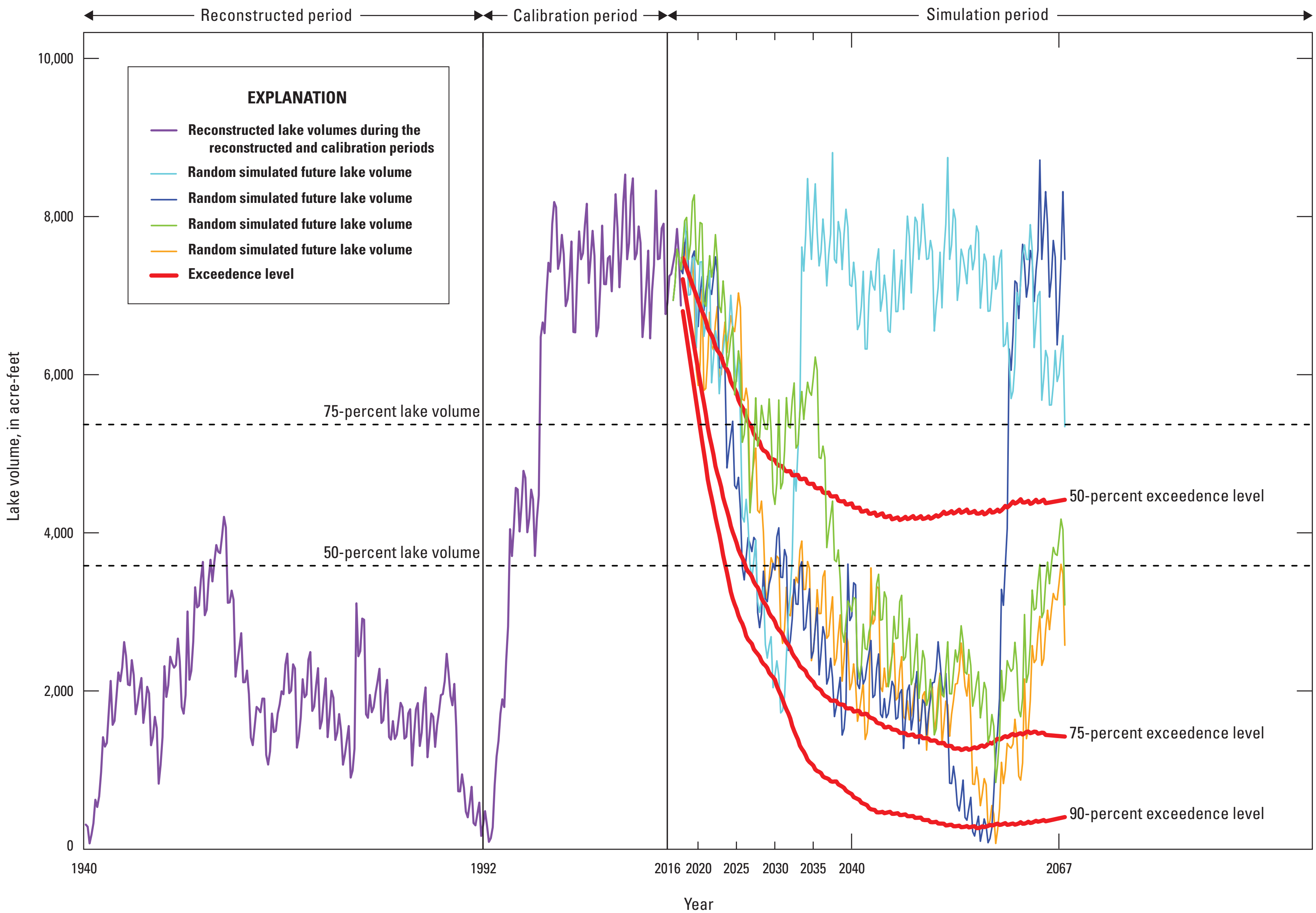

Figure 9. Simulated lake volumes and exceedance levels for Remmick Lake, 1940–2067.

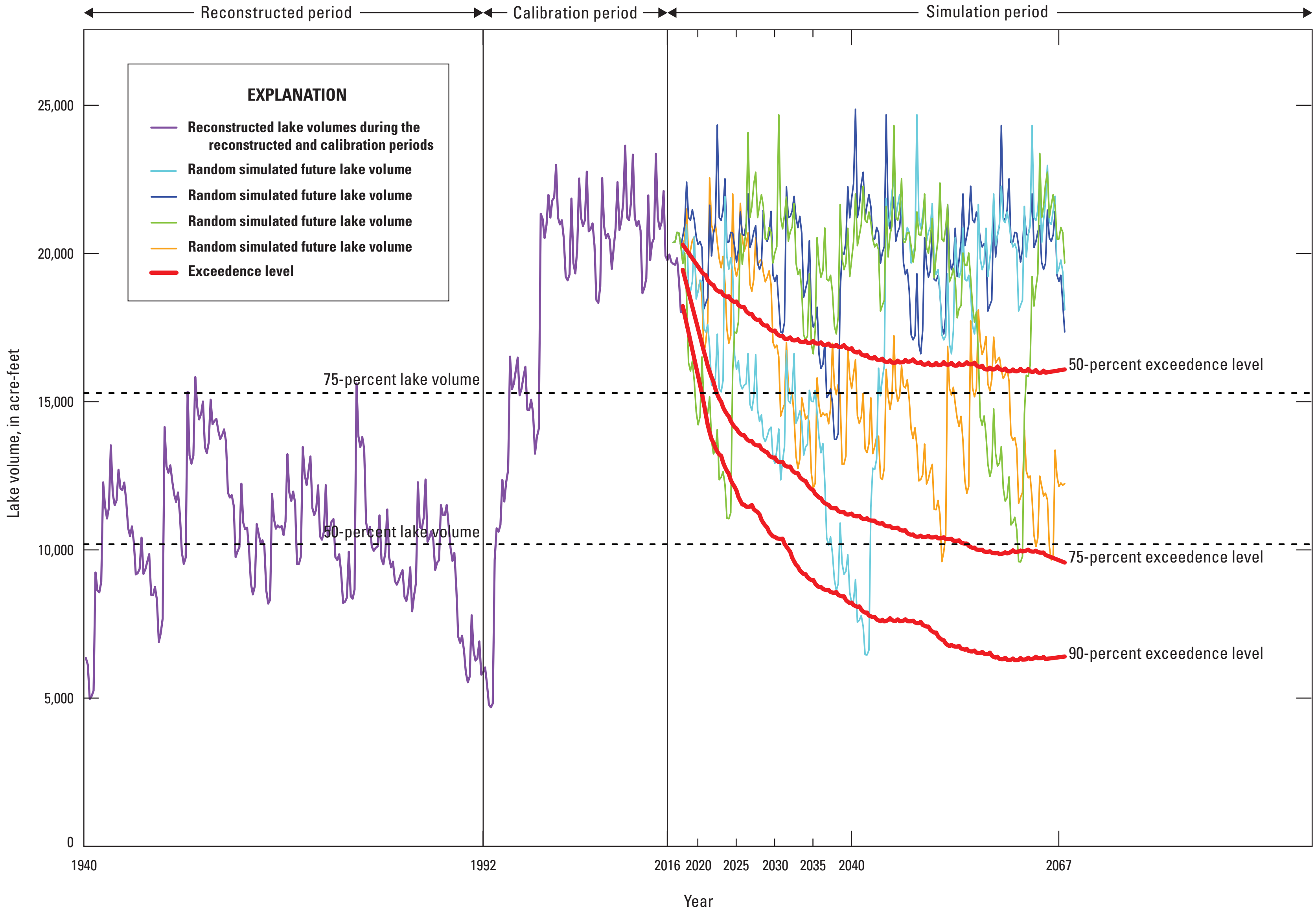

Figure 10. Simulated lake volumes and exceedance levels for Sibley Lake, 1940–2067.

Alkaline Lake

Alkaline Lake was nearly dry in the early 1990s and quickly rose to a volume of about 83,000 acre-feet during the mid- to late 1990s (table 1; fig. 6). The reconstructed historical lake volumes for 1940 through 1992 fluctuated between nearly dry (less than 10,000 acre-feet) and about 75 percent of its 2016 volume (62,271 acre-feet). The simulated lake volumes for 2017 through 2067 indicated that the lake has an equal (50 percent) chance to remain above 75 percent of its 2016 volume until about 2030, and a good (75 percent) chance to remain above 50 percent of its 2016 volume until about 2030. There is a small (10 percent) chance that the lake will fall below the 50-percent volume by about 2025.

Big Mallard Marsh

Big Mallard Marsh also was nearly dry in the early 1990s (fig. 2), and during the reconstructed period for 1940 through 1992 the historical lake volumes fluctuated between about 0 acre-feet and about 12,000 acre-feet (fig. 7). During the calibration period, the lake quickly rose to its 2016 volume of about 15,800 acre-feet (table 1). The simulated lake volumes for 2017 through 2067 indicated that the lake has an equal (50 percent) chance of remaining near 75 percent of its 2016 volume until 2067, and a good (75 percent) chance to remain above 50 percent of its 2016 volume until about 2025. There is a small (10 percent) chance that the lake will fall below 50 percent of its 2016 volume by about 2025.

Marvin Miller Lake

Marvin Miller Lake was periodically dry during much of the reconstructed period from 1940 through 1992, and the historical lake volumes fluctuated between about 0 acre-feet and about 2,000 acre-feet (fig. 8). During the calibration period from 1992 through 2016, the lake rose to its 2016 volume of about 6,630 acre-feet (table 1) much more gradually than the other four lakes. Simulation results for Marvin Miller Lake were substantially different than the other four lakes. The simulated lake volumes for 2017 through 2067 indicated that the lake has an equal (50 percent) chance to fall below 75 percent of its 2016 volume prior to 2025, and a good (75 percent) chance to fall below 50 percent of its 2016 volume prior to 2025.

Remmick Lake

Remmick Lake also was nearly dry in the early 1990s, and during the reconstructed period from 1940 through 1992, the historical lake volumes fluctuated between about 0 acre-feet and about 4,000 acre-feet (fig. 9). During the calibration period from 1992 through 2016, the lake quickly rose to its 2016 volume of about 7,200 acre-feet (table 1). The simulated lake volumes for 2017 through 2067 indicated that the lake has an equal (50 percent) chance to remain above 75 percent of its 2016 volume until 2025 and a good (75 percent) chance to remain above 50 percent of its 2016 volume until about 2025. There is a small (10 percent) chance that the lake will fall below 50 percent of its 2016 volume by about 2025.

Sibley Lake

Of the five lakes, Sibley Lake was the most likely to sustain a long-term fishery (fig. 10). During most of the reconstructed period from 1940 through 1992, the historical lake volume remained above about 5,000 acre-feet. During the calibration period from 1992 through 2016, the lake quickly rose to its 2016 volume of about 20,400 acre-feet (table 1). The simulated lake volumes for 2017 through 2067 indicated that the lake has an equal (50 percent) chance to remain above 75 percent of its 2016 volume for a period longer than 50 years, and a good (75 percent) chance to remain above 50 percent of its 2016 volume until about 2055. There is a small (10 percent) chance that the lake will fall below the 50-percent volume by about 2030.

Summary

Water levels in lakes and wetlands in the central North Dakota Missouri Coteau region that were either dry or only sporadically held water since before the 1930s have been rising since the early 1990s in response to an extended wet period. The lakes have remained full since the mid-1990s, which has provided benefits to migratory waterfowl, fisheries, and wildlife. A small shift in climate conditions can have a large impact on the lake water levels of these water bodies. The North Dakota Game and Fish Department identified five lakes as promising candidates for sustaining long-term fisheries. The lakes are in Kidder, Stutsman, and Logan Counties and were mostly dry during the early 1990s. After about 1995, the lakes had filled up and were deep enough to sustain populations of game fish such as walleye, perch, and northern pike.

The U.S. Geological Survey, in cooperation with the North Dakota Game and Fish Department, developed a water-balance model to determine the effects of precipitation, evapotranspiration, surface inflow and outflow, and groundwater interaction to simulate future lake volumes for the five lakes. The model was calibrated using climate data and lake volumes for a 25-year calibration period from 1992 through 2016, during which historical lake water levels and volumes could be estimated from Landsat images. The water-balance model was used to estimate the lake volume at the end of each 3-month (quarterly) time step on the basis of the following components: precipitation on and evaporation from the lake surface and surrounding lake buffer area, precipitation on the surrounding catchment, frozen precipitation storage and melt, soil moisture storage and evapotranspiration, surface-water inflow, groundwater storage, leakage of groundwater storage to the lake, groundwater leakage from the lake, and surface outflow from the lake. The simulation model was developed to simulate potential future lake volumes and uses long-term historical National Climatic Data Center data to back-extend the short-term (1992–2016) period of record for precipitation and potential evapotranspiration used to calibrate the water-balance model, resulting in a long-term (1940–2018) extended climate dataset. In addition to simulating future lake volumes, the long-term climate dataset was used to reconstruct historical lake volumes for 1940 through 2018 for comparison to the observed, calibrated, and simulated future lake volumes.

Block-bootstrapping was used to simulate 50 years of potential future time series of the climate data after the end of the calibration period (2016). The simulated future climate data inputs were used along with the water-balance model to simulate future lake volumes. Future lake volumes were simulated for each of the five lakes for the period of 2017 through 2067. The probabilities of future conditions from the simulations are summarized using the 50-, 75-, and 90-percent exceedance levels. For assessing effects on fisheries, two reference volumes, the 75- and 50-percent lake volume, were selected in consultation with North Dakota Game and Fish Department fisheries biologists.

Alkaline Lake was nearly dry in the early 1990s and quickly rose to its 2016 volume (about 83,000 acre-feet) during the mid- to late 1990s. The simulated lake volumes for 2017 through 2067 indicated that the lake has a 50-percent chance to remain above 75 percent of its 2016 volume until about 2030, and a 75-percent chance to remain above 50 percent of its 2016 volume until about 2030. There is a 10-percent chance that the lake will fall below the 50-percent volume by about 2025.

Big Mallard Marsh also was nearly dry in the early 1990s and during the reconstructed period for 1940 through 1992, the historical lake volumes fluctuated between about 0 acre-feet and about 12,000 acre-feet. During the calibration period, the lake quickly rose to its 2016 volume of about 15,800 acre-feet. The simulated lake volumes for 2017 through 2067 indicated that the lake has a 50-percent chance of remaining near 75 percent of its recent volume until 2067, and a 75-percent chance to remain above 50 percent of its 2016 volume until about 2025. There is a 10-percent chance that the lake will fall below the 50-percent volume by about 2025.

Marvin Miller Lake was periodically dry during much of the reconstructed period from 1940 through 1992, and the historical lake volumes fluctuated between about 0 acre-feet and about 2,000 acre-feet. During the calibration period from 1992 through 2016, the lake rose to its recent 2016 volume of about 6,630 acre-feet much more gradually than the other four lakes. Simulation results for Marvin Miller Lake were substantially different compared to the other four lakes. The simulated lake volumes for 2017 through 2067 indicated that the lake has a 50-percent chance to fall below 75 percent of its 2016 volume prior to 2025, and a 75-percent chance to fall below 50 percent of its 2016 volume prior to 2025.

Remmick Lake also was nearly dry in the early 1990s, and during the reconstructed period from 1940 through 1992, the historical lake volumes fluctuated between about 0 acre-feet and about 4,000 acre-feet. During the calibration period from 1992 through 2016, the lake quickly rose to its 2016 volume of about 7,200 acre-feet. The simulated lake volumes for 2017 through 2067 indicated that the lake has a 50-percent chance to remain above 75 percent of its 2016 volume until 2025, and a 75-percent chance to remain above 50 percent of its 2016 volume until about 2025. There is a 10-percent chance that the lake will fall below the 50-percent volume by about 2025.

Of the five lakes, Sibley lake was the most likely to sustain a long-term fishery. During most of the reconstructed period from 1940 through 1992, the historical lake volume remained above about 5,000 acre-feet. During the calibration period from 1992 through 2016, the lake quickly rose to its 2016 volume of about 20,400 acre-feet. The simulated lake volumes for 2017 through 2067 indicated that the lake has a 50-percent chance to remain above 75 percent of its 2016 volume for a period longer than 50 years and a 75-percent chance to remain above 50 percent of its 2016 volume until about 2055.

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Appendix 1. Water-Balance Modeling R Documentation and Supporting Dataset

The appendix contains a link to a zipped folder, NDGF_Project_R-Code, that has the following water-balance model R code scripts and R Workspace data file. The folder can be downloaded and there is a separate Rscript file for each lake's water-balance model, and another Rscript (compute_monthly_pet) that produces the long-term potential evapotranspiration outputs. All necessary input data for the scripts are contained in the R Workspace.

Five lake Rscripts and one long-term potential evapotranspiration Rscript:

- Alkaline Lake – AlkalineWaterBal.R
- Big Mallard Marsh – BigMallardWaterBal.R
- Marvin Miller Lake – MarvinMillerWaterBal.R
- Remmick Lake – RemmickWaterBal.R
- Sibley Lake – SibleyWaterBal.R
- Long-term potential evapotranspiration data – compute_monthly_pet.R

R Workspace data file:

- WaterBalWorkspace.RData

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