Prepared in cooperation with the U.S. Fish and Wildlife Service and the Joint Water Commission

Evaluation of Restoration Alternatives Using Water-Budget Tools for the Wapato Lake National Wildlife Refuge, Northwestern Oregon

Scientific Investigations Report 2020–5013

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

Cover: Pumphouse structures at northern end of Wapato Lake (background, right) where water is discharged to Wapato Creek (foreground), northwestern Oregon. Photograph by Stewart Rounds, U.S. Geological Survey, March 17, 2016.

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

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

$$°F = (1.8 \times °C) + 32.$$

Datums

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).

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

Abbreviations

AET	actual evapotranspiration
DEM	digital elevation model
FOGO	Forest Grove AgriMet station
GIS	geographic information system
JWC	Joint Water Commission
lidar	light detection and ranging
NWR	National Wildlife Refuge
PET	potential evapotranspiration
RK	river kilometer
RM	river mile
SMT	Shoreline Management Tool
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WID	Wapato Improvement District
WMST	Water Management Scenario Tool
WTP	water treatment plant

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By Stewart A. Rounds[1], T. Zach Freed[2], Daniel T. Snyder[1], Cassandra D. Smith[1], Micelis C. Doyle[1], Erin Holmes[3], Curt Mykut[3], Tim Mayer[3], Erin Stockenberg[3], and Stephen L. Pilson[3]

Abstract

The lakebed in Wapato Lake National Wildlife Refuge (NWR) in northwestern Oregon was farmed for decades prior to the establishment of the refuge in 2013. Planning for restoration of these lands required extensive data collection and construction of a water budget and tools to design and evaluate potential restoration strategies. The U.S. Geological Survey (USGS) and U.S. Fish and Wildlife Service worked together to monitor streamflow and water levels in and around Wapato Lake NWR, apply the USGS Shoreline Management Tool (SMT), then construct and apply a water-budget-based Water Management Scenario Tool (WMST). The SMT was used to determine the spatial availability of different water depths (as potential habitat for different species) as a function of water level and other factors, based on topographic data. The WMST uses a water-budget approach to predict daily water levels, inflows, outflows, and areas of specific categories of water depth in the refuge over the course of a water year in response to a range of hydrologic and meteorological conditions and potential water-management strategies. In this study, two hypothetical water-management strategies were simulated to predict their effect on water levels and areas with specific water depths as an indicator of potential habitat. In the first scenario, several tributaries that had been diverted around the lakebed since the 1930s were reconnected to the lake, and an outflow weir was used to control lake level and to create a lake and seasonal wetlands of specific depths. In the second scenario, an outflow weir was combined with pumps to help meet target lake levels. Results showed that reconnecting the largest three tributaries to Wapato Lake would provide sufficient water to create a range of aquatic conditions in most years. For a median water year, rainfall and tributary flows in these scenarios provided 99 percent of total inputs to the lake, whereas pumping, weir outflows, and open-water evaporation accounted for 95–97 percent of losses. Management of lake levels could be accomplished with a variable-elevation outflow weir or a combination of a weir and pumps. The lake would take longer to fill to a higher seasonal target level during a dry year. Without an outflow weir or other means of allowing water to flow out of the lake, the largest of two existing pumps would need to be used during late spring or early summer to attain a lower seasonal target water level in summer. High-water conditions downstream of Wapato Lake may prevent the use of a simple outflow weir, as historical downstream water levels in winter and spring sometimes were higher than the target water levels used in these scenarios. Water-budget-based methods applied in this study have proven to be valuable for the design and evaluation of potential restoration strategies at Wapato Lake NWR.

Introduction

The Wapato Lake National Wildlife Refuge (NWR) is located in the upper Tualatin River Basin near the city of Gaston in northwestern Oregon and was established in December 2013 as the 562nd refuge in the National Wildlife Refuge System operated by the U.S. Fish and Wildlife Service (USFWS). Wapato Lake NWR contains important wetland and riparian areas that USFWS plans to enhance through restoration and water management. Restored habitats may support various fish species, including salmonids listed as threatened or endangered under the Endangered Species Act of 1973 (Public Law 93–205, 87 Stat. 884, as amended) as well as wildlife and migratory birds including breeding landbirds, wading birds, shorebirds, and wintering waterfowl. Historically, Wapato Lake was one of the most important waterfowl sites in northwestern Oregon (U.S. Fish and Wildlife Service, 2007). The motivation for establishing Wapato Lake as a national wildlife refuge was the area's high potential for restoration of stream, wetland, and riparian systems.

[1]U.S. Geological Survey

[2]The Nature Conservancy

[3]U.S. Fish and Wildlife Service

Prior to western settlement, Wapato Lake was influenced by precipitation, seasonal floodwaters from the Tualatin River, and water flowing from several tributary streams. Alterations to Wapato Lake began in the late 19th century when settlers changed the surrounding topography and hydrology of the lake to enable farming of the lakebed during the summer dry season. In the 1930s, levees were built around the perimeter of the lakebed, with canals on the outside of the levees to capture and divert tributary streams that originally fed the lake. Cut off from the surrounding rivers, a lake still formed in winter from seasonal rains, but the levees allowed the lake to be pumped out in spring to enable farming on the lakebed during summer. Conversion from a predominantly wet environment to dry farmland caused subsidence through aerobic decay of exposed peat soils; the land surface elevation of the lakebed has decreased substantially from its pre-settlement level (Christy, 2015). Converting the lakebed to agricultural use removed the native plants, and areas not actively farmed became overgrown with invasive vegetation. Although changes to the lake disrupted its natural hydrologic processes and altered the associated habitat, the area likely can be restored to a mixture of riparian forest, seasonal scrub-shrub wetlands, and herbaceous wetlands with diverse land-cover types to support a wide range of fish and wildlife (U.S. Fish and Wildlife Service, 2007).

In 2011, USFWS needed to quantitatively assess the water resources available to Wapato Lake NWR to define the type of restoration scenarios that might be possible, and to begin to determine how water resources might be managed under those scenarios. Evaluation of restoration alternatives is a complex balance between the optimization of available habitat for fish, birds, and wildlife and the appropriate management of river and lake hydrology and water quality. USFWS and U.S. Geological Survey (USGS) staff monitored streamflows and water levels in the Wapato Lake area from October 2011 to April 2013. Those data then were used to develop a daily water budget to determine water fluxes throughout the system. USFWS collected high-resolution light detection and ranging (lidar) data and used those data to create a digital elevation model (DEM) of the Wapato Lake area. Using that DEM, the USGS Shoreline Management Tool (SMT; Snyder and others, 2013) was applied to Wapato Lake to assess the relations between surface-water stage and water depth, inundated area, and water volume in the lake and surrounding area. Combining information from the water budget, the SMT, and the DEM, a spreadsheet-based Water Management Scenario Tool (WMST) was created to allow water-resource managers to design potential restoration and water-management strategies and to evaluate their effects on the hydrology and habitat characteristics of Wapato Lake under a range of conditions.

Purpose and Scope

The objectives of this study were to (1) construct a water budget for Wapato Lake, (2) develop and apply the WMST for Wapato Lake, (3) and describe and document how the WMST, in conjunction with the SMT, could be used to assist restoration and water management planning for Wapato Lake NWR. The water budget was developed using estimated and measured water fluxes for October 2011 through March 2014—the time period with the most available data. The WMST then was constructed using estimated and measured water fluxes for water years 1992–2014. Both the water budget and WMST focused on the lakebed area constrained by surrounding levees, which constitutes the spatial extent of modern Wapato Lake. This report describes the water budget and technical development of the WMST, then describes and discusses two hypothetical water-management scenarios in which the WMST was used to evaluate resulting lake levels and water depths that are critical for determining the quantity of potential habitat for target species.

Study Site

Wapato Lake NWR is located between the Coast Range and the Chehalem Mountains near river kilometer (RK) 100 (river mile [RM] 62) of the Tualatin River near the city of Gaston in northwestern Oregon (figs. 1–2). The Tualatin River flows east out of the Coast Range, then turns north on the valley floor near Wapato Lake to skirt the northern edge of the Chehalem Mountains before continuing eastward toward its confluence with the Willamette River. Water discharged from the Wapato Lake area flows northward in Wapato Creek, exiting the low-lying areas of the lakebed at Gaston Road and joining the Tualatin River about 3 km (1.9 mi) downstream near the river's confluence with Scoggins Creek (fig. 2). Summertime streamflow in the Tualatin River is augmented from two upstream reservoirs—Henry Hagg Lake on Scoggins Creek and Barney Reservoir in the adjacent Trask River Basin (through an interbasin diversion). Wapato Lake is located upstream of an important municipal water intake at RK 90.3 (RM 56.1); the drinking-water treatment plant operated by Joint Water Commission serves more than 300,000 people in the basin.

Near-surface alluvium sediments of the Tualatin River Basin are underlain with Missoula Flood deposits of the Willamette Silt formation, composed of micaceous clay and sand materials in the area near Wapato Lake (Wilson, 1998). The bed of Wapato Lake consists of poorly drained soils of high organic content in the Labish soil series, described as 0.3–0.6 m (1–2 ft) of black, mucky clay interspersed with lenses of organic material and underlain by thick peat deposits below about 1 m (3 ft) (Green, 1982). Peat deposits in the Labish and Semiahmoo soils of this area were reported in the 1930s to be as thick as 3.5 m (11.5 ft) (Dachnowski-Stokes, 1936; Christy, 2015).

Figure 1. Wapato Lake when the lake was refilling with rainwater, northwestern Oregon, winter 2015. Photograph by Stewart Rounds, U.S. Geological Survey, January 27, 2015.

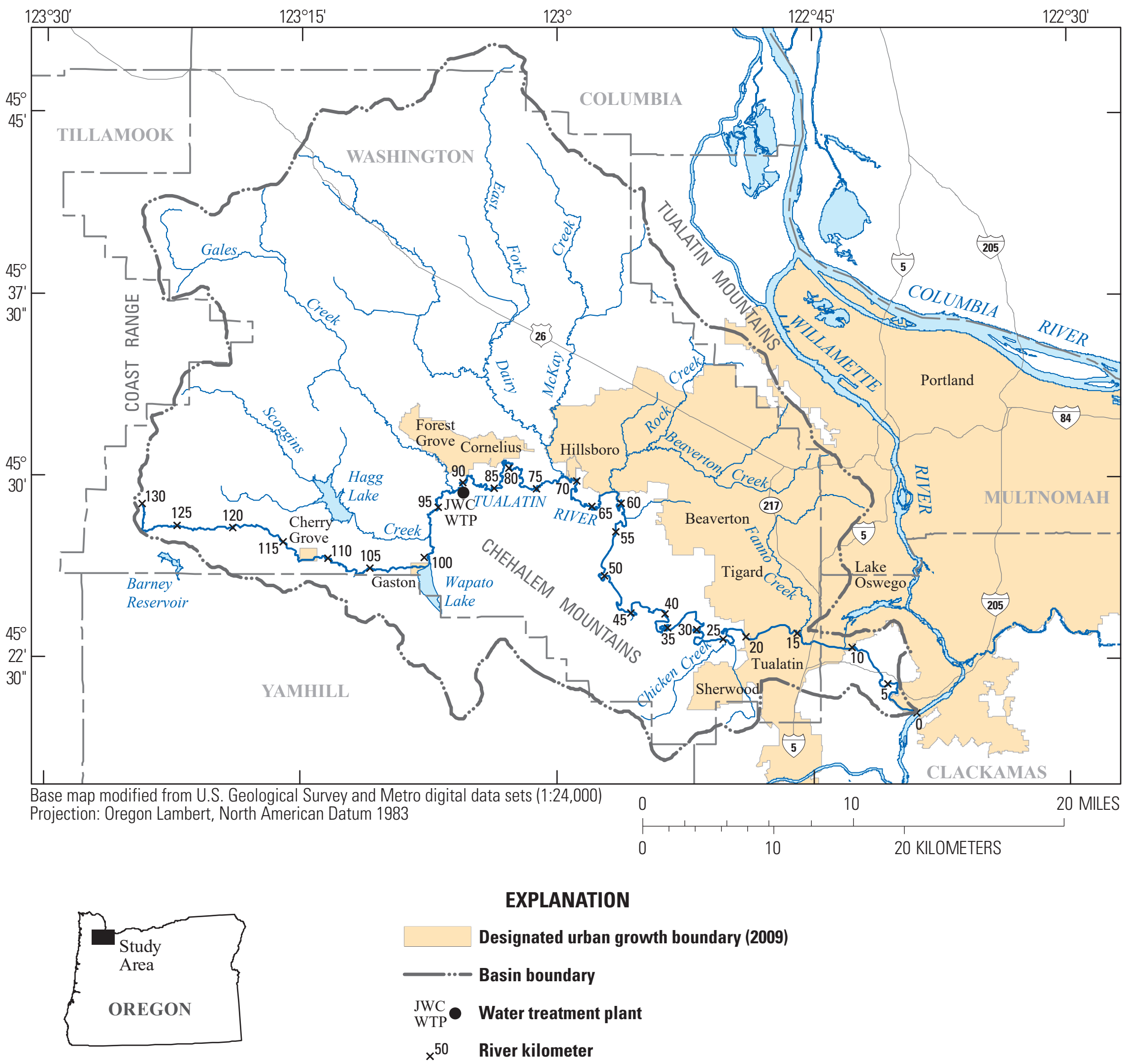
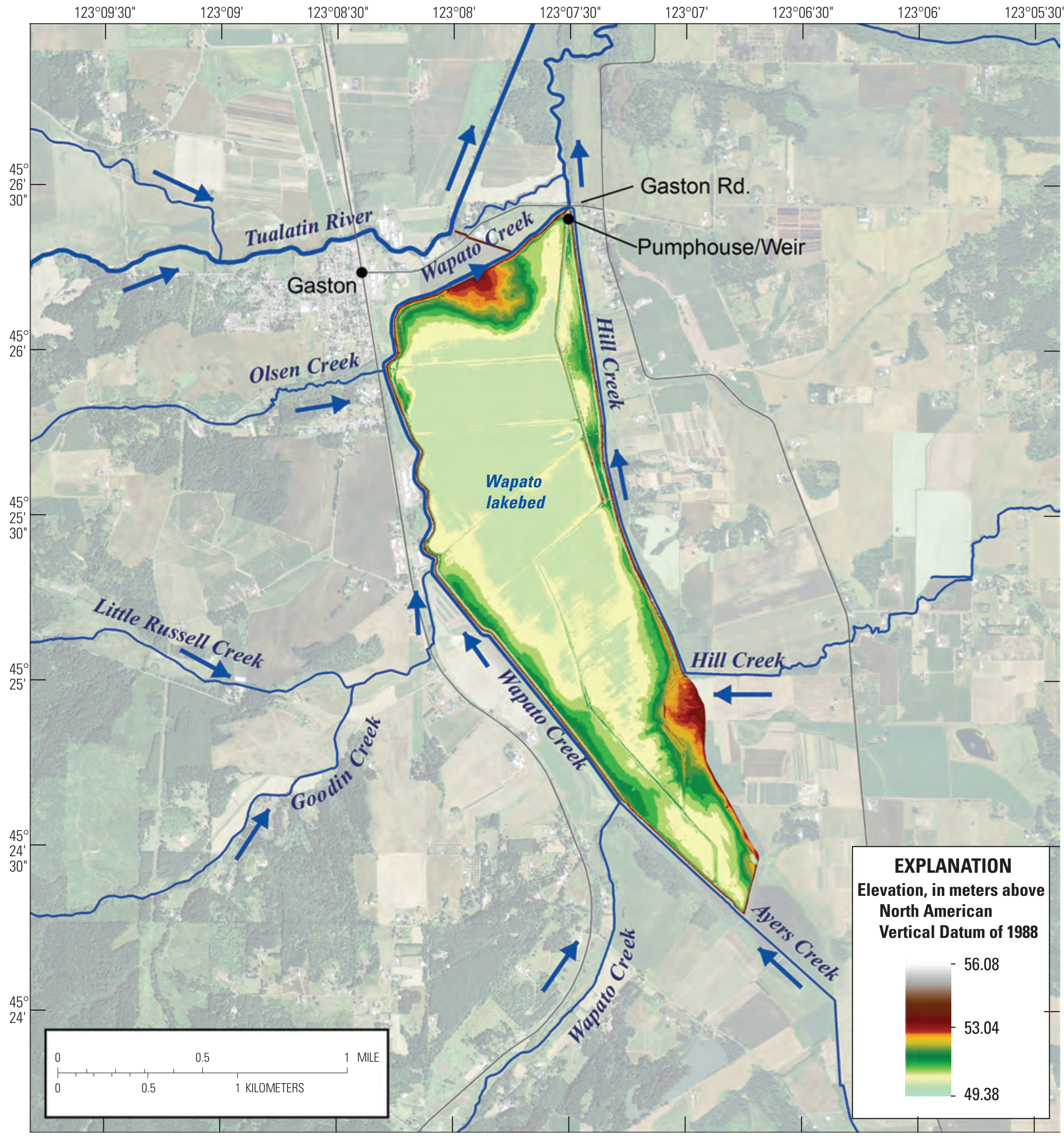


Figure 2. Tualatin River Basin, including Wapato Lake in southwestern part of the basin, near Gaston, and Joint Water Commission (JWC) water treatment plant (WTP) downstream of Wapato Lake, northwestern Oregon.

Wapato Lake was the only large natural lake in the Tualatin River Basin (Hart and Newcomb, 1965). In 1882, the Tualatin River was channelized between Gaston and the river's confluence with Scoggins Creek, bypassing the section of river that flowed closer to the outlet of Wapato Lake (Washington County, 1883), thus weakening the strong winter high-water connection between the lake and river and making it feasible to drain the lake for farming. By 1895, Wapato Lake had been drained by the installation of canals (Cass and Miner, 1993). The Wapato Improvement District (WID), a state-sponsored irrigation and drainage district, was formed in the 1930s to manage the lake. The WID installed 8.9 km



Base map coyright from Esri, 2019. Coordinate system: Universal Transverse Mercator, Zone 10 North. Horizontal datum is North American Datum of 1983.

Figure 3. Wapato lakebed and study area for the water budget inside the levees of the lake, colored by land-surface elevation, southeast of Gaston, northwestern Oregon. Water flow direction is indicated by arrows along the creeks and rivers. Diversion canal from the Tualatin River to the canal outside the levees at the north end of the lake is indicated by a brown line. Rd, Road.

(5.5 mi) of levees and exterior canals around the lake, a lift pump station at the northern end of the lake, and interior ditches to facilitate drainage of the lake to the pumphouse (fig. 3). Creeks that historically flowed into the lake (Ayers, Goodin, Hill, Olsen, and Wapato Creeks) were diverted around the lake outside the levees to allow pumps to more easily empty the lake in spring so that the lakebed could be farmed in summer. Prior to channelization of the river and construction of levees, seasonal high water flowed into Wapato Lake from the Tualatin River, providing additional storage of flood waters and causing the lake to expand and contract in response to river conditions.

For many years, the canals outside the levees were used in summer to deliver water for irrigation. In 1975, the WID entered into agreement with the Tualatin Valley Irrigation District and the Bureau of Reclamation to allow the use of these canals for water delivery to customers on the periphery of the lake. In spring 2012 after USFWS had agreements to purchase most of the lakebed within the levees, the WID voted to disband and donate its assets to USFWS. A diversion canal from the Tualatin River at RK 99.6 (RM 61.9) to the Wapato canal system (fig. 3) was still used in 2014 to deliver water to irrigation district customers outside the lakebed as well as to any farmed areas within the lakebed.

Despite the construction of levees, channelization of the Tualatin River, and diversion of tributary streams, Wapato Lake forms and inundates the lakebed each winter through a combination of precipitation and subsurface seepage. USFWS has continued to manage the system by dewatering the lakebed in winter and spring and working with farmers to cultivate grain crops over most of the lakebed, an activity that minimizes the intrusion of invasive vegetation and provides additional forage for waterfowl. Drainage of the lake is accomplished with two pumps that lift water from the lakebed and discharge it to Wapato Creek near Gaston Road on the north end of the lake.

Restoration Scenarios

USFWS and its partners are working to restore Wapato Lake to create a year-round shallow lake surrounded by a seasonally inundated herbaceous wetland (U.S. Fish and Wildlife Service, 2019). USFWS and USGS evaluated a combination of potential actions, including reconnection of tributary streams to Wapato Lake, and using pumps and an adjustable-height outlet weir to manage lake levels. A scenario that includes an open lake outlet connecting Wapato Lake with Wapato Creek and the Tualatin River downstream was documented elsewhere by Rounds and others (2020). The intent of these scenarios was to maximize year-round shallow-water habitat for aquatic plants and animals as well as surrounding seasonal wetland areas to provide additional diversity of habitat for uses such as waterbird nesting. USFWS and USGS used the WMST to quantify the effects of these restoration scenarios on a daily basis throughout the water year, focusing on the extent and duration of lake inundation, depth/area/volume of the lake, and associated areas of specific water depths that relate to potential habitat for species such as waterbirds.

Reconnection of several tributary streams to Wapato Lake for part of the year would provide substantial additional water (and additional management flexibility) to fill the lake and to create a range of water depths. Without tributary inflows, rainfall and subsurface seepage might not be sufficient to create and maintain specific (higher) water levels during a dry year. Continuous inflows and outflows caused by tributary reconnection also could be useful in avoiding poor water-quality conditions that might result from long residence times and stagnation of water in the lake. However, tributary reconnection without an active means of exporting water from the lake might create deep-water conditions that have less habitat value for many waterbirds, and could create a flooding threat to adjacent homes and agricultural fields.

Restored lake levels could be controlled in a number of ways—through (1) an open-outlet connection with Wapato Creek and the Tualatin River downstream, (2) continued use of levees and pumps, or (3) installation of a variable-height weir at the lake outlet, to list just a few. During conditions of high water in the Tualatin River, water might back up through Wapato Creek and enter the lake if not prevented from doing so by levees and sufficiently high outlet structures. Allowing floodwaters from the Tualatin River to inundate the lake could be beneficial in some ways, but may result in deeper water in winter than desired for target species; therefore, an open connection between Wapato Lake and downstream reaches of Wapato Creek requires critical evaluation, despite its seeming simplicity.

Evaluation of future restoration and management alternatives for Wapato Lake NWR must consider local habitat conditions as well as implications for the broader Tualatin River watershed. The Tualatin River provides aquatic and riparian habitat for many fish and wildlife species and serves as a water supply for extensive agricultural and municipal areas. Management of Wapato Lake NWR must avoid flooding of adjacent private farmlands when possible. Permanent inundation throughout the season might lead to increased mosquito activity and water-quality problems in the lake. Discharges from Wapato Lake also can affect water quality downstream, with important ramifications for municipal water treatment and recreation. For example, a levee failure at Wapato Lake in December of 2007 led to deeper-than-normal water in the lake in winter that could not be pumped out until June and July of 2008; typically, the lake was pumped out by the end of April each year. An algal bloom in the lake and high concentrations of dissolved organic matter and phosphorus, in combination with pumping to evacuate the lake in June and July of 2008, caused municipal water-treatment problems as well as instream water-quality problems about 70-100 km (44-62 mi) downstream in the Tualatin River (Bonn, 2008; Rounds and others, 2015). The Tualatin River has Total Maximum Daily Load programs in place for parameters such as phos-phorus and ammonia that could be affected by Wapato Lake discharges. Downstream effects on river hydrology and water quality from refuge water management must be considered in any restoration alternatives.

Methods

Three tools were used in this study to assess potential water-management strategies for Wapato Lake NWR and to evaluate water-depth areas created by those strategies over a range of hydrologic conditions. The USGS Shoreline

Management Tool (SMT) was applied to Wapato Lake to assess the topography of the lakebed and to quantify the types and amounts of potential habitat for target species produced under a range of lake levels. A water budget for Wapato Lake was constructed to quantify the inputs and losses of water to and from the lakebed and to estimate the rates of several unmeasured seepage inputs. Using information from the SMT and the water budget, a Water Management Scenario Tool (WMST) was developed to predict daily lake levels throughout the year in response to different water-management strategies and climatic conditions, with ties to the amount and type of habitat associated with the predicted water levels.

Shoreline Management Tool and Topographic Data

The USGS SMT is a geographic information system (GIS) software program that runs in ArcMap™ and is designed to quantify the results of water-management strategies for areas subject to periodic inundation such as wetlands and seasonal lakes (Snyder and others, 2013). Using land-surface topographic data, the tool allows resource managers to calculate water quantity, water depth, area of inundation, and area of dry land based on surface-water levels. Such information can be useful to balance competing management priorities and needs, including water supply, water quality, aquatic and terrestrial habitat for plants and animals, and human use of water and land areas. In addition to quantifying water depths and the areas and volumes of inundation, the SMT allows the user to define habitat criteria such as water depth, land-surface slope and aspect, or other factors, and then determines the quantity and location of areas meeting those criteria. Documentation and the GIS program are available in Snyder and others (2013).

USFWS collected high-resolution lidar data for the Wapato Lake area to define the elevation of the lakebed and surrounding area with centimeter accuracy. These data were collected in May 2012 when the lake was empty and vegetation on levees and other areas of interest had not fully leafed out. After independent quality-assurance reviews were completed and the data were tied to multiple surveyed benchmark locations, the lidar data were converted to a DEM in GIS. This DEM became the basis for the analysis of potential habitat areas for the target species in the SMT, and were used to generate stage/area and stage/volume tables for Wapato Lake.

Water-Budget Construction

Evaluation of hypothetical restoration and water-management strategies for Wapato Lake NWR requires a knowledge of the lake water budget to predict the water levels and areas of water depths that might result. As part of the development of such a predictive tool, data were collected and a water budget was constructed for Wapato Lake for October 2011 through March 2014. Several streamflow and water-level (stage) gages were operated in and around the lake for the 18 months from October 2011 to March 2013. To augment flow and water-level measurements, data were obtained for meteorological parameters as well as for pumping duration and frequency. The DEM derived from lidar data was used to create relations between stage, area, and volume so that the surface area and volume of the lake could be estimated from its water level.

The water budget for the lake comprises inputs, losses, and storage. Water is added to the system as precipitation, seepage through levees, groundwater discharge, and leakage through the pumphouse (fig. 4). Water typically leaves the system through open-water evaporation, evapotranspiration, groundwater recharge, and pumping. No data were available to quantify any summertime irrigation-water inputs; such inputs were not included in the water budget because the lake was dry in summer for the period of interest and the resulting water table was at or below the lakebed. In the future, tributaries could be reconnected to the lake to provide additional inputs, and outflow weirs or other mechanisms could be added to control or manage outflows. Within the area bounded by levees, water is stored in the lake as well as in the subsurface soil and groundwater system (fig. 5). Combining all known and measured components of the water budget, the residuals of a comparison between modeled and measured data for October 2011 through March 2014 were used to estimate the unmeasured components of the water budget, such as groundwater discharge and seepage of water through the levees. The following sections describe each water-budget component in more detail.

Stage/Area and Stage/Volume Tables

Python scripts developed for use with the SMT (Snyder and others, 2013) were used to analyze the land-surface topography in the DEM and to create tables relating lake water level to lake area and lake volume—also known as stage/area and stage/volume tables. The analysis is similar to that of filling a bathtub (or lakebed) and determining the surface area and volume of the resulting waterbody for each incremental increase in water-level elevation. Tables of surface area and lake volume that correspond to each water level then can be used to predict lake areas and volumes for use in the water-budget calculations.

Precipitation

Precipitation data were obtained from the Forest Grove AgriMet station (FOGO) in Verboort, Oregon, about 13 km north-northeast of Wapato Lake. The FOGO data were multiplied by 1.06 to account for the predicted difference between annual mean precipitation at FOGO and at Wapato Lake as estimated by the PRISM model (Daly and others, 1994), which predicts spatial variations in precipitation based on measured rainfall and topographic features. When data

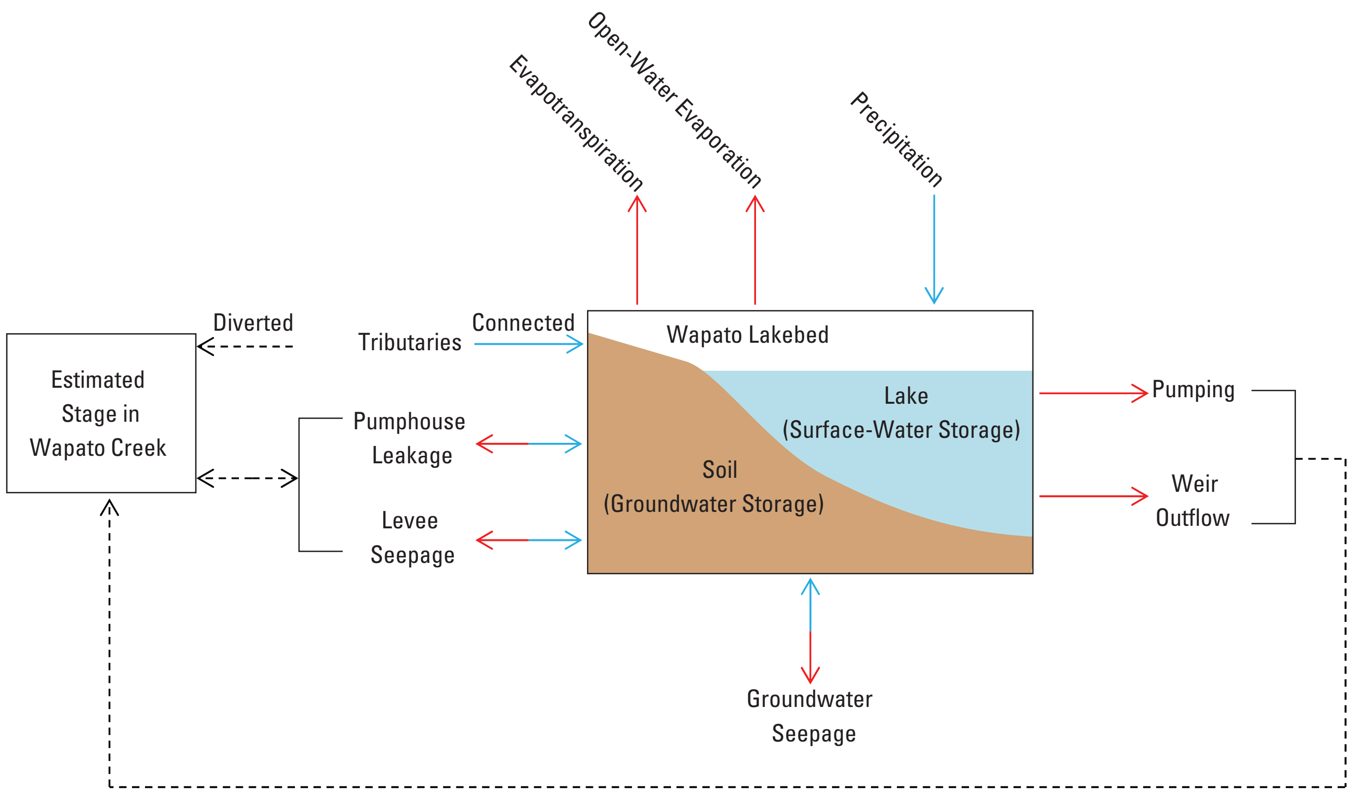


Figure 4. Potential input and loss components considered in the water budget of Wapato Lake, northwestern Oregon. Blue arrows indicate inputs, red arrows indicate losses, and dashed lines indicate feedback processes in the calculations.

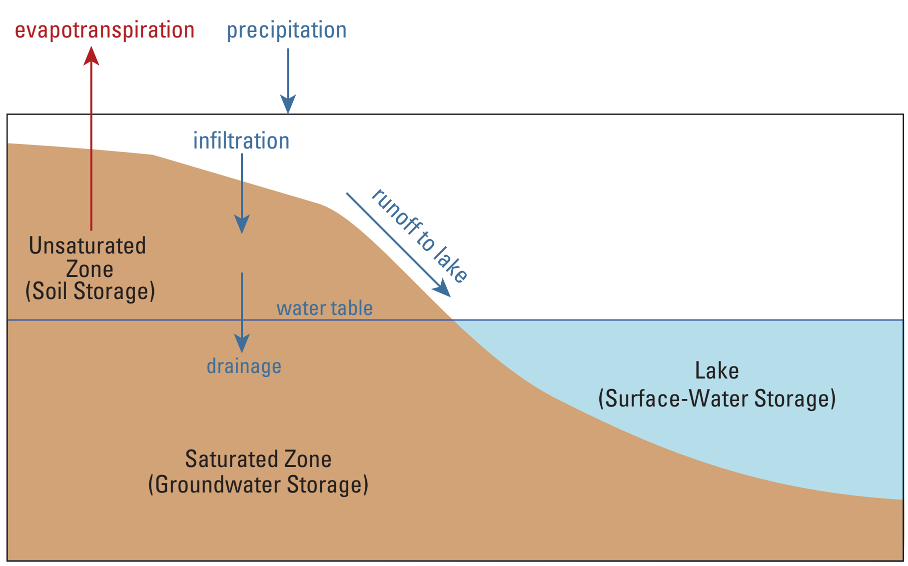


Figure 5. Processes moving water into and through the unsaturated zone and included in the water budget of Wapato Lake, northwestern Oregon. Blue arrows indicate inputs of water to the lake system and red arrow indicates a loss.

from FOGO were not available, uncorrected precipitation values from the nearby Dilley 1S National Weather Service cooperative precipitation station (site 352325) were used; no correction was needed because of the proximity of this site to Wapato Lake. Percentiles of daily precipitation (median, 10th, 25th, 75th, 90th) were computed for later use by calculating the daily cumulative rainfall rate for each water year from 1992 to 2014, then computing the percentile for each day.

Evaporation from Open Water

Evaporation can be estimated with various methods and typically depends on the vapor pressure of water, relative humidity, and wind speed, among other factors (Finch and Calver, 2008). In the absence of water-temperature data from the lake, however, an alternate approach was needed. Open-water evaporation from Wapato Lake was estimated using methods developed by Linacre (1993), who simplified the Penman evaporation equation to create a relation that relies only on air temperature, dew-point temperature, wind speed, solar radiation, and site elevation data:

$$\mathrm{E} = (0.015 + 0.00042\,\mathrm{T} + 10^{-6} z) \times [0.8\,R_s - 40 + 2.5\,(1.0 - 8.7\times10^{-5} z)\,\mathrm{u}\,(T - T_d)], \quad (1)$$

where

E is the estimated evaporation rate in millimeters per day,

T is the daily mean air temperature in degrees Celsius,

z is the site elevation (50.3 meters),

R_s is the solar irradiance in Watts per square meter,

u is wind speed in meters per second at 2 meters height, and

T_d is dew-point temperature in degrees Celsius.

Like the precipitation data, air temperature, solar radiation, wind speed, and dew-point temperature data were obtained from the nearby AgriMet station (FOGO) in Verboort, Oregon. The total loss of water from the lake due to open-water evaporation was computed by applying this rate over the calculated surface area of the lake on any particular day. Percentiles of the daily open-water evaporation rates (median, 10th, 25th, 75th, 90th) were computed for later use by calculating the daily cumulative open-water evaporation rate for each water year from 1992 to 2014, then computing the percentile for each day.

Evapotranspiration from Land Surface

Evapotranspiration is the combined loss of water to the atmosphere through evaporation from soil and land surfaces and through transpiration of water via the stomata of vegetation. Potential evapotranspiration (PET) is the quantity of water that could be lost through evapotranspiration, typically calculated for a particular crop type and assuming that adequate water is available in the soil. For this study, daily PET data were obtained from the FOGO AgriMet station. When adequate supplies of water are available to soils, the actual evapotranspiration (AET) is assumed to equal the PET; otherwise, it is common to adjust the AET estimate by multiplying PET by some factor to account for the scarcity of moisture. For the region near Wapato Lake, a factor of 0.7 was derived from information provided by Thompson and others (2012). When the daily precipitation rate exceeded the daily PET, AET was set to PET; otherwise, AET was estimated by applying the 0.7 factor to PET. These loss rates were applied to the area of the Wapato lakebed that was not occupied by open water each day.

Pumping

Two pumps were located at the pumphouse at Wapato Lake, simply referred to as the “large pump” and the “small pump.” For downstream water-quality management reasons, the large pump typically is not used during May–October, whereas the small pump can be used anytime. Data were available during 2011–14 indicating when each pump was turned on or off, but pump discharges were not directly measured and no documentation was available to characterize pumping rates as a function of lift (the water-level difference between the pump intake and the discharge point on the other side of the levee). Pumping rates were estimated for the water budget by creating relations between lake-stage elevation, streamflow measured in Wapato Creek downstream of the pumphouse, and the duration and timing of pumping episodes. The pumping rate for the small pump originally was estimated to be 0.17 m^3/s (6.0 ft^3/s) and unaffected by variations in the required lift; subsequent calibration of the water budget increased that rate to 0.20 m^3/s (6.9 ft^3/s). For the large pump, the minimum pumping rate was estimated to be 0.453 m^3/s (16.0 ft^3/s), and the maximum pumping rate was originally estimated to be 0.651 m^3/s (23.0 ft^3/s); subsequent calibration of the water budget increased the maximum rate to 0.883 m^3/s (31.2 ft^3/s). To approximate a dependence on the required lift, the pumping rate of the large pump was linearly interpolated between the minimum rate at and below a lake-stage elevation of 49.40 m (162.07 ft) and the maximum pumping rate at and above an elevation of 49.50 m (162.40 ft). In the water-budget calcula-tions (2011–14), pumping losses accounted for the fraction of the day that each pump was operating. In the WMST calcula-tions, pumping losses were applied as if each pump was either on or off for the entire day.

Changes in Storage

Water on/in the lakebed can be stored either in the lake or in the groundwater and soil system (figs. 4–5). The volume of water in the lake was computed from the stage/volume table. For the soil and groundwater system, it was necessary to account for the fact that water can only fill open pore spaces. In the groundwater zone (below the water table), pore spaces are entirely filled with water, whereas in the unsaturated zone (above the water table), pore spaces typically are partially filled with water. Based on values from the Natural Resources Conservation Service SNOTEL station at Miller Woods, Oregon, about 23 km (14 mi) south-southwest of the study area (the closest SNOTEL station with geologic characteristics similar to the study area), the effective porosity (fraction of open pore space) of the soil is about 39 percent and the unsaturated soil zone typically has a moisture content of 25 percent. These values were used to determine the volume of water stored in the soil and groundwater systems for the initial lake water budget, and the moisture content of the unsaturated zone was assumed to be constant. Inputs and losses to the lake water budget were used to compute a change in overall storage, and that daily change in storage was distributed among the lake, groundwater, and unsaturated zones using the assumption that the water table in the lakebed was at the same elevation as the lake level.

Measurements of water level in the internal lakebed canal near the pumphouse (USGS station 14202630) generally were assumed to be representative of the water-surface elevation of the lake, which in turn was assumed to be the elevation of the water table in the non-inundated parts of the lakebed. When pumps were active, however, drawdown in the canal near the pumphouse caused the measured water level at that station to underestimate the actual lake level. To remedy that problem in the water-budget calculations, a correction was applied to the measured water-level data whenever pumps were activated and a sharp decline in water level occurred due to drawdown. The corrected water levels then were used as an indication of the lake level.

Although a constant moisture content in the unsaturated zone was assumed for the initial water budget for the lake, it was determined that a more rigorous treatment of the unsaturated zone (fig. 5) was needed for scenario evaluations. For that purpose, the moisture content of the unsaturated zone was allowed to vary from 5 to 30 percent, with an initial value of 10 percent. The effective porosity also was decreased to 30 percent. Using a variable moisture content in the unsaturated zone allowed that zone to "soak up" water from the first storms of autumn; otherwise, the water-budget calculations would assume those water inputs to infiltrate directly to the water table and cause the lake to form too quickly from a dry initial lakebed. Runoff from the soil surface directly to the lake was computed from a classic runoff equation (National Resources Conservation Service, 2004) using curve number 88, and the remaining rainfall was assumed to be absorbed into the unsaturated zone. Once pores in the unsaturated zone were filled, excess water entering the unsaturated zone would push water through to the saturated zone or run off to the lake, thus increasing the elevation of the water table and the lake level.

Seepage Through Levees, Groundwater Seepage, and Leakage Through Pumphouse

Groundwater seepage and levee seepage components of the water budget (fig. 4) were estimated using porous-media flow equations with estimated values of water levels and leakance. Seepage is proportional to the difference in water level between two points (head difference) and the ability of the sediments between the points to transmit water (hydraulic conductivity), and inversely proportional to the thickness of the sediments. For the water budget, leakance was used, which is the ratio of the hydraulic conductivity of the soil to the thickness through which the head is transmitted, with units of sec^{-1}. The water gained or lost was computed as a head or water-level difference through an effective area times the leakance. The leakance values for each of these flow processes were calibrated based on the residuals of the 2011–14 water budget. Specific values were set by minimizing residuals while staying within a range of expected values for each leakance calculation. For groundwater seepage, the water level in sediments outside the lakebed was assumed to be at the same elevation as stage in Wapato Creek at Gaston Road and the water level in sediments in non-inundated areas of the lakebed was assumed to be identical to the lake level. If the Wapato Creek stage and water level in sediments outside the lake ever were lower than the lake level, then water would seep from the lake through the levees into surrounding canals, from the lake into the underlying sediments, and through the pumphouse to the exterior canals. Such flows would be losses instead of inputs.

Water Management Scenario Tool

The Water Management Scenario Tool (WMST) is a user-interactive spreadsheet that applies a water-budget approach to predict the effects of water-management strategies on lake level and habitat tied to water depths in Wapato Lake. The WMST draws on results from the 2011–14 Wapato Lake water budget, and allows users to:

- Impose a range of hydrologic and meteorological conditions (dry, wet, or normal years), drawing on data from water years 1992–2014 or a statistical percentile of those historical conditions;
- Specify an initial lake level and starting date (the default is to simulate an entire water year starting on October 1);
- Route some or all flows of selected tributary streams into the lakebed;
- Add an optional outlet weir with a time-variable crest elevation to control maximum lake levels;
- Schedule the use of pumps based on time of year and lake level; and
- Select a set of habitat criteria based on water depth, duration of water depth, and time of year.

The WMST calculates daily water budgets over a full water year (October 1 through September 30), including all daily inputs and losses, daily water levels in the lake, and daily measures of habitat quantity.

Use of the WMST can be general—to understand the feasibility of potential management strategies by simply assessing whether enough water is available to attain certain goals—or more detailed. The user can select from among six tributaries that may be routed into the lakebed, the percentage of the tributary flows that are routed into the lakebed, and the dates of two seasons (irrigation/non-irrigation, wet/dry, hunting/non-hunting, etc.) in which those percentages might be different. Tributary flows not routed to the lake are assumed to be diverted around the lake. Lake levels can be actively or passively managed in the WMST through the addition of a variable-height weir and (or) target time periods and water levels that activate the pumps. The WMST required some data and information beyond what was needed to construct a current water budget for Wapato Lake, including streamflow in all lake tributaries and meteorological data for water years 1992–2014, algorithms to compute outflows over a weir, and criteria to compute habitat quantities related to water depth and lakebed topography. The following sections describe these data and features used by the WMST.

Tributary Inflows

Six tributaries drained into Wapato Lake before the levees were constructed (fig. 3; one tributary is small and unnamed). To allow WMST users to route one or more of these streams into the lake, flows in all these streams were required for water years 1992–2014. Such data did not exist, but daily mean streamflow in each tributary could be estimated using drainage-area ratio techniques and regressions against measured streamflow at other sites using methods outlined by Hirsch (1979). Streamflow in Ayers Creek, one of the Wapato Lake tributaries, was measured continuously by USGS at NE North Valley Road (station 14202550) from September 15, 2011 to April 11, 2013. To extend the length of that record, measured streamflow data from nearby sites with similar characteristics were examined to determine the viability of regression models. Several sites and models were tested, and the best model relied on streamflow data from East Fork Dairy Creek near Meacham Corner (USGS station 14205400) and Fanno Creek at Durham (USGS station 14206950). Streamflow in Ayers Creek responded relatively quickly to rainfall; therefore, including a flashy urban stream such as Fanno Creek in the regression model was important for capturing that fast response. Forcing the model intercept through zero to prevent the prediction of negative flows, the model produced a relatively small mean absolute error of 0.05 m^3/s (1.7 ft^3/s) and an adjusted coefficient of determination (R^2) of 0.85. The resulting model is:

$$Q_A = 0.02585\, Q_{EFD} + 0.04315\, Q_F, \tag{2}$$

where

Q_A is the estimated daily mean discharge in Ayers Creek at USGS station 14202550,

Q_{EFD} is the daily mean discharge in East Fork Dairy Creek at USGS station 14205400, and

Q_F is the daily mean discharge in Fanno Creek at USGS station 14206950.

Discharge data from the East Fork Dairy and Fanno Creek sites had some gaps for water years 1992–2014. Datasets were extended using comparisons with nearby, and hydrologically similar, gaged streams. East Fork Dairy Creek data were extended using a regression with streamflow data from Sain Creek above Henry Hagg Lake (Oregon Water Resources Department station 14202920). Fanno Creek at Durham data were extended using a regression with measured streamflows from Fanno Creek at 56th Avenue (USGS station 14206900). Using these measured and constructed datasets, equation 2 was used to generate a daily streamflow dataset for the Ayers Creek at NE North Valley Road site for water years 1992–2014.

A drainage-area ratio method was used to estimate daily mean streamflow in each of the Wapato Lake tributaries from the Ayers Creek flow data:

$$Q_1 = \frac{A_1}{A_A} Q_A, \tag{3}$$

where

Q_1 is the estimated daily mean discharge at the stream site of interest,

A_1 is the drainage area upstream of the stream site of interest,

A_A is the drainage area upstream of USGS station 14202550 on Ayers Creek, and

Q_A is the daily mean discharge in Ayers Creek at USGS station 14202550.

Drainage areas upstream of each of the sites of interest (table 1) were estimated using StreamStats (U.S. Geological Survey, 2014). Percentiles of daily streamflow (median, 10th, 25th, 75th, 90th) were computed for use in the WMST by calculating the daily cumulative streamflow for each water year from 1992 to 2014, then computing the percentile for each day.

Weir Losses

If an outflow weir is selected as part of a water-management scenario, the user can define as many as 24 crest elevations and the dates when those elevations are effective during the water year. The weir crest elevation sets a maximum lake level. If the computed water level for Wapato

Table 1. Drainage areas upstream of Wapato Lake tributary sites near Gaston, northwestern Oregon.

Site	Drainage area (square kilometers)
Ayers Creek at NE North Valley Road	6.27
Ayers Creek near confluence with Wapato Creek	16.73
Wapato Creek at confluence with Ayers Creek	6.53
Hill Creek at confluence with canal at Wapato Lake levee	16.14
Goodin Creek at confluence with Wapato Creek	8.73
Unnamed creek between Goodin and Olsen Creeks	0.34
Olsen Creek at confluence with Wapato Creek	1.84

Lake exceeds the weir height on any day, all excess water is assumed to flow out of the lake and the lake level is set to the weir height. Although water levels downstream of the weir, outside the lake, are estimated by the WMST, flows over the weir are assumed to be in one direction—out of the lake. Backflows into the lake because of downstream high-water conditions are not allowed in the WMST (without specifying a downstream open outlet; see Rounds and others [2020] for more information on downstream open outlets), but the user is warned of the potential for such conditions.

Water Depths and Potential Habitat

The WMST can compute the presence, abundance, and duration of different areas of water-depth categories within Wapato Lake NWR, derived from the predicted water level combined with information derived from the SMT. To quantify the amount of specific types of potential habitat for target species for each day throughout a water year in a manner useful for restoration planning, one must first (1) define the target species and set some criteria to define the potential habitats of interest, and (2) track each parcel of the lakebed to determine when such criteria are met. Although many criteria might be used to define potential habitats for a target species, the WMST focuses on water depth as the most important criterion, as research has shown that water depth is a critical factor linking the abundance and foraging success of waterbirds (Bancroft and others, 2002; Bolduc and Afton, 2008; Lantz and others, 2011). Knowing the water level of the lake, it is straightforward to determine the lakebed area that falls into a particular depth/habitat category each day. The utility of this information may be limited, however, because an increase in lake water level from day to day or season to season might cause shallow-water conditions to move from one part of the lakebed to another. Such a move might be acceptable for some waterbirds, but not for rooted aquatic plants. To establish and maintain certain types of vegetation, it may be necessary to restrict the range of water depths on parcels of the lakebed during the summer growing season; therefore, the WMST tracks each parcel of land to compute the duration of inundation or the number of days that each parcel is inundated to certain depths.

To achieve such tracking, the SMT was used to identify contiguous parcels of the lakebed with nearly identical lakebed elevations. For Wapato Lake, 851 parcels were defined with a range of sizes (mean = 3,900 m^2, or close to 1 acre). Those parcels then were numbered and programmed into the WMST along with their associated areas and average lakebed elevations. In this way, the WMST can calculate not only the area of the lakebed in each depth category every day, but also the duration of inundation in that depth category for every parcel and for a season of interest. At Wapato Lake, the water depth is likely to vary seasonally, with more water in the lake during winter than summer. In summer, a small lake may be surrounded by herbaceous wetland areas that become inundated in winter. Target water depths to produce desired habitats for waterbirds and aquatic plants likely are less than 1 m (3.28 ft); greater depths may be acceptable during winter, but might not provide useful areas for target waterbird species and could prove problematic for certain vegetation species in summer.

Results—Water Budget and Water Management Scenarios

Water Budget

Analysis of topographic data for the lakebed indicated that as water is added to Wapato Lake, it spreads out to reach the constraining levees relatively quickly, gaining surface area rapidly at low lake levels, then accumulating volume in a near-linear fashion as the lake becomes deeper (fig. 6). Post-development lake levels tend to be at the low end of these curves, as the levees were built to keep the lake level low and to facilitate the process of emptying the lake in spring for farming in summer. For example, during October 2011 through March 2014, the lake had a maximum water-surface elevation of about 51.1 m (167.7 ft), which corresponds to a surface area of about 276 hectares (683 acres) and a volume of about 2.75×10^6 m^3 (2,230 acre-ft).

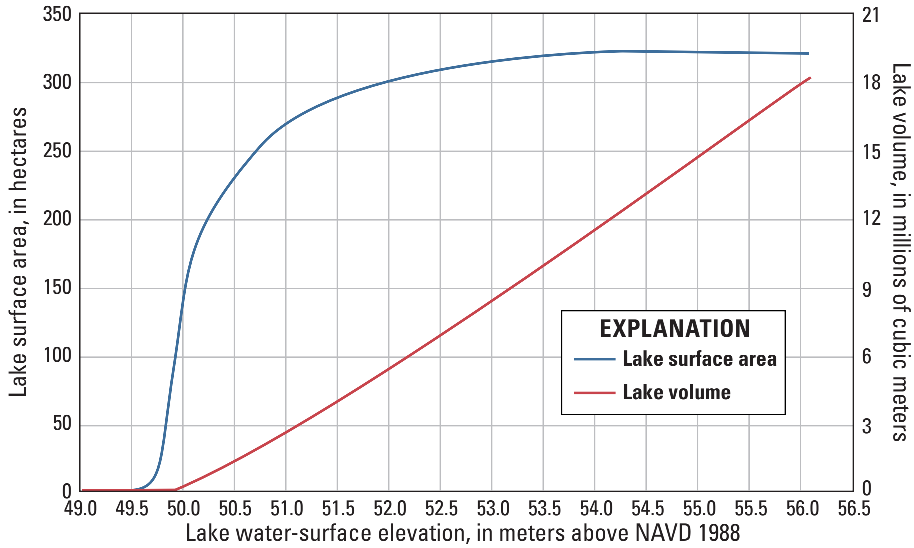


Figure 6. Area and volume as a function of water-surface elevation of Wapato Lake near Gaston, northwestern Oregon. One hectare = 0.01 square kilometers = 2.471 acres, and 1 million cubic meters = 811 acre-feet. NAVD 88, North American Vertical Datum of 1988.

A detailed daily water budget for Wapato Lake was constructed from measurements of rainfall, pumping, and evapotranspiration; computed rates of open-water evaporation; storage in the lake and subsurface; and calibrated estimates of groundwater and levee seepage, and leakage through the pumphouse. The daily water budget for October 2011 through March 2014 was calibrated by adjusting several unknown parameters (leakance rates, for example) and comparing the sum of input (positive) and output (negative) water volumes to the total change in storage as computed by the measured change in lake volume and the estimated change in water volume in the saturated and unsaturated zones of the lakebed. The resulting water-volume errors can be expressed as inputs minus losses minus total change in storage, and as a percentage of the sum of the input and output volumes—in other words, the volume not properly accounted for in the change in storage as a function of the water estimated to be moving in and out of the lake. Aggregated monthly results for months when a lake was present showed that the mean absolute error (typical error) was about 34 percent, with a mean error (bias) of -7 percent, confirming that most of the water was accounted for, but that substantial uncertainties still exist.

Results from the water budget showed that precipitation was the dominant input to the lakebed (82 percent of all inputs) and pumping was the dominant loss (80 percent of all losses; figs. 7–8). During that time, all tributary flows were diverted around the lake and the lake was pumped dry in spring so that the lakebed could be farmed in summer. Although those conditions are not likely to mirror a restored condition of a lake surrounded by seasonal wetlands, such pre-restoration conditions were sufficient to provide insights into the lake's hydrology and to estimate several of the water-budget components that were not directly measured.

Seepage and leakage inputs in the water budget were minor relative to precipitation, but they still accounted for about 18 percent of all inputs, underscoring the importance of calibrating the water budget and measuring such inputs in the future. The calibrated leakance values were 8×10^{-8} sec^{-1} for seepage through the levees, 2×10^{-4} sec^{-1} for groundwater seepage, and 2.5×10^{-5} sec^{-1} for leakage through the pumphouse; an adjustment to the calibration after water year 2016 resulted in increased leakance values (4×10^{-7}, 6×10^{-4}, and 7.5×10^{-5} sec^{-1}, respectively). Groundwater discharge (16.2 percent) was estimated to add more water to the lake than seepage through the levees (1.5 percent) and leakage through the pumphouse (0.4 percent), but more research and field measurements are needed to refine the rates of these inputs. More water was lost through evapotranspiration (14.9 percent) than open-water evaporation (5.5 percent), but the small quantity of open-water evaporation was caused mainly by the absence of a lake in summer. For the period of this analysis (October 2011 through March 2014), the lake was consistently inundated by December of each year, and typically was pumped dry by the end of March or April (fig. 9).

Despite the estimated nature of some inputs and losses, the water budget captured the major inputs and losses of Wapato Lake fairly well. Uncertainties in the predictions of the largest inputs (precipitation) and largest outputs (pumping) were small, although pumping rates were not definitively measured. The largest uncertainties among inputs and losses were associated with smaller inputs, which bodes well for garnering accurate insights from the results. For comparison, the total volume of water in diverted tributaries during October 2011 through March 2014 (79.8×10^6 m^3 or 64,723 acre-ft) was more than 8 times larger than all precipitation that fell to the lakebed (9.62×10^6 m^3 or 7,802 acre-ft), and precipitation was by far the largest input of water to the lake. Therefore, any routing of tributary flows into the lake in the future may constitute a primary and dominant input of water to Wapato Lake, further decreasing the significance of any errors in the seepage and leakage inputs.

The pre-restoration mixture of terrestrial and aquatic conditions in Wapato Lake varies seasonally. Appropriate conditions for aquatic animals and plants typically are either nonexistent or negligible from mid-April to the beginning of October because of farming activities and the absence of a lake. During October 2011 through March 2014, water depths never exceeded 1.7 m (5.6 ft). The period from October 2013 to February 2014 had a relatively constant maximum water depth (0.56-0.86 m [1.8-2.8 ft], fig. 9) that provided shallow-water conditions and substantial quantities of terrestrial land cover around the margins of the lake.

Water-Management Scenarios

Two hypothetical water-management scenarios were tested with the WMST to assess potential changes to water levels and habitat in Wapato Lake NWR and to show the utility of the WMST (table 2). In these scenarios, several tributaries were routed into the lakebed rather than around it, and a combination of weirs and pumps were used to control the lake level. The goal was to create a range of shallow-water conditions in a mixture of lacustrine and seasonally inundated wetland environments. Optimal water depths will depend on the habitat requirements of the fish and wildlife species of most interest, but research has shown that shallow-water habitats (<0.25 m [<0.82 ft]) tend to favor many species of shorebirds, wading birds, and dabbling ducks, whereas deeper water is selected by species such as diving ducks and coots (Fredrickson, 1991; Murkin and others, 1997; Elphick and Oring, 1998; Colwell and Taft, 2000; Taft and others, 2002).

Scenario 1—Reroute Three Tributaries and Install Variable-Elevation Weir

In both scenarios, all flows in Ayers, Wapato, and Hill Creeks were rerouted into Wapato Lake rather than diverted around the lake, resulting in greatly increased inflows to the lake in a normal year. These three creeks are the largest of the Wapato Lake tributaries and probably are the easiest to route into the lake because they are upstream of other tributaries—channels to route these tributaries into the lake could be cut directly through the levee without requiring infrastructure to accommodate the continued diversion of any upstream tributaries (fig. 3). The initial lake-stage elevation at the start of the simulated water year was set to 49.42 m (162.15 ft)—the level at which the lake is just barely dry. A range of hydrologic and meteorological conditions were imposed, drawn from conditions that occurred during water years 1992–2014. The meteorological conditions affect many components of the water budget, including open-water evaporation and evapotranspiration in addition to the more-obvious precipitation rate.

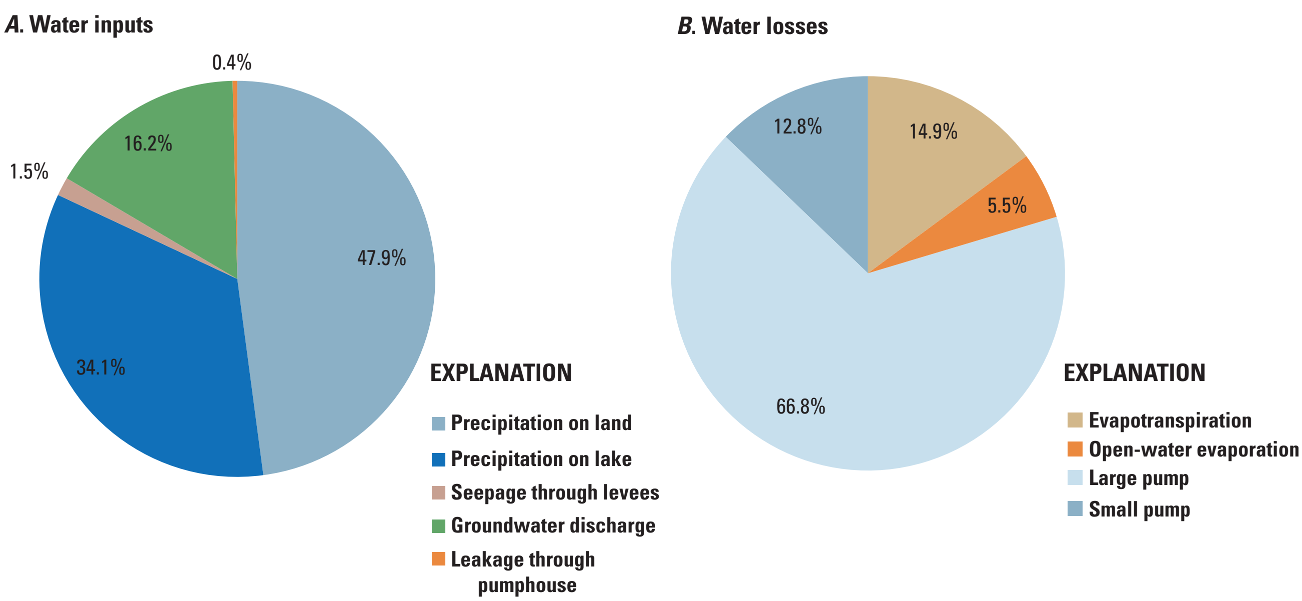


Figure 7. Percentages of total water (*A*) inputs to, and (*B*) losses from the Wapato lakebed near Gaston, northwestern Oregon, as computed from the daily lake water budget for October 2011 through March 2014.

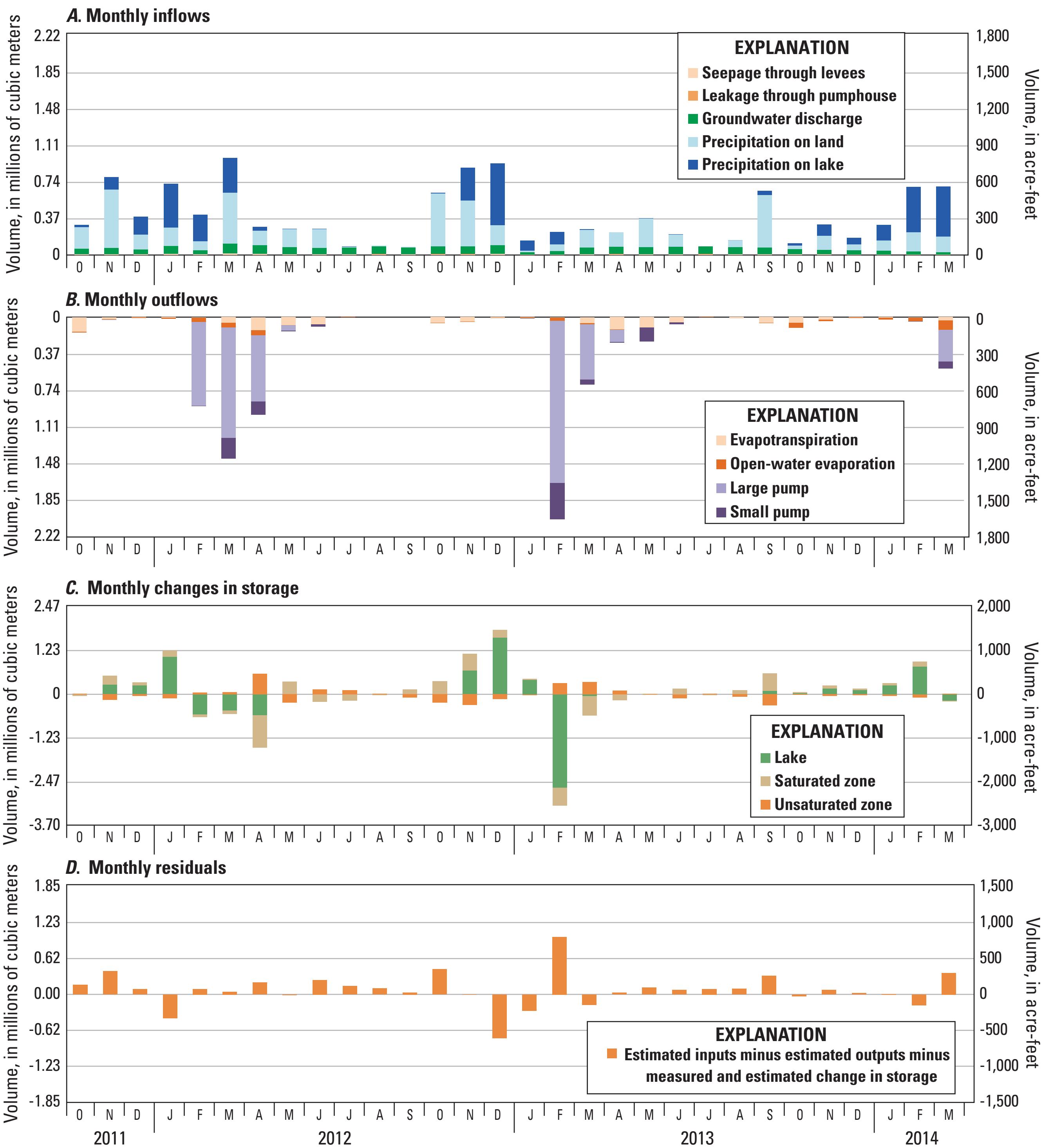


Figure 8. Monthly aggregated results of the daily water budget showing (*A*) estimated inflows, (*B*) estimated outflows, (*C*) measured changes in lake storage and estimated changes in water storage in the saturated and unsaturated zones, and (*D*) monthly residuals of the water-budget analysis, for Wapato Lake near Gaston, northwestern Oregon, for the calibration period of October 2011 through March 2014. One million cubic meters = 811 acre-feet.

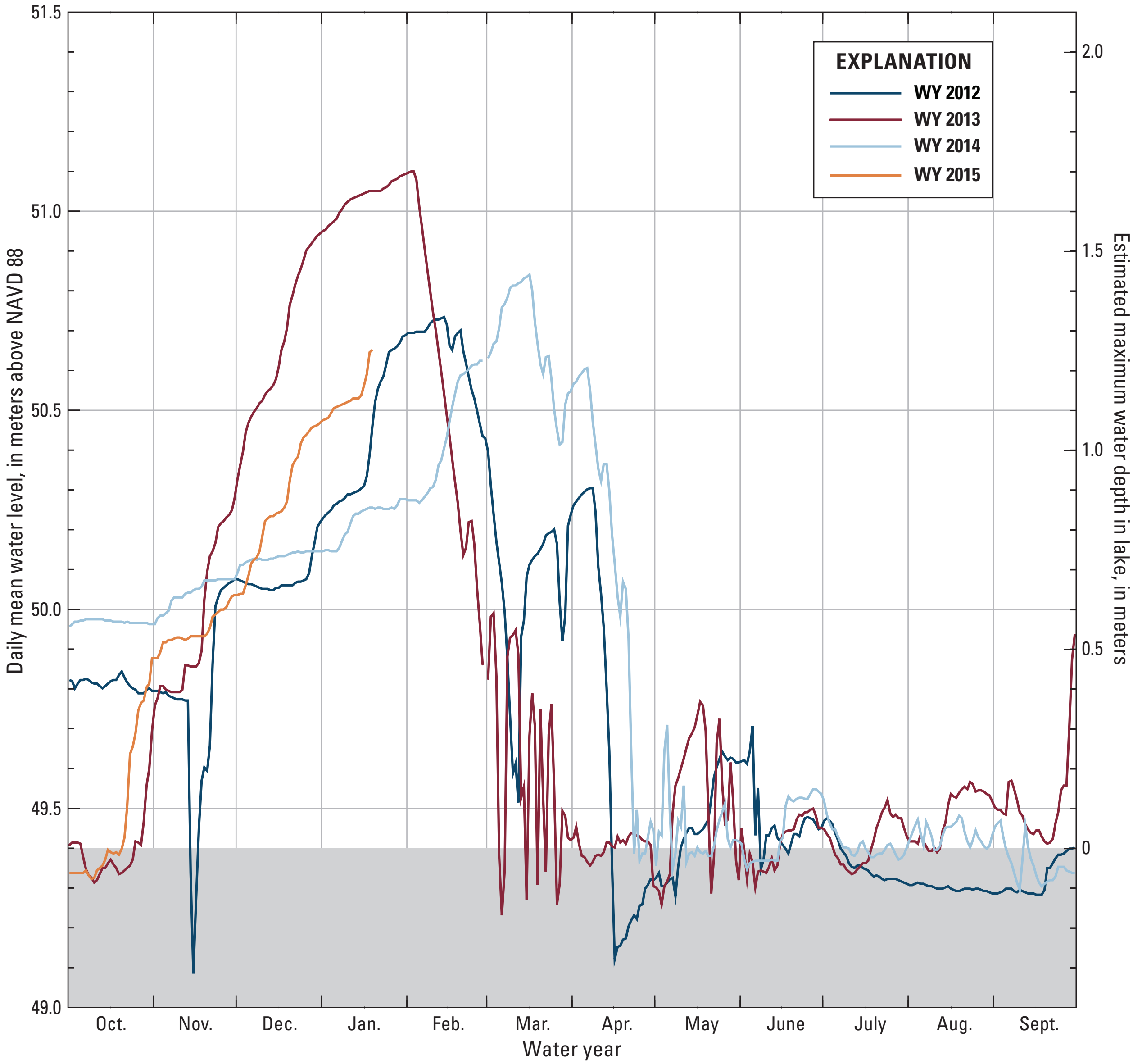


Figure 9. Daily mean water level at Wapato Lake as measured in the canal near the pumphouse (USGS station 14202630), near Gaston, northwestern Oregon. Gray area indicates water levels below the lake bottom. Lake is essentially empty at water levels less than about 49.5 meters above North American Vertical Datum of 1988. Estimated maximum lake depth is noted on the right-hand axis. NAVD 88, North American Vertical Datum of 1988; WY, water year.

Table 2. Hypothetical scenarios tested with the Water Management Scenario Tool for Wapato Lake near Gaston, northwestern Oregon.

[**Symbol:** –, option not used]

Input category	Details	Scenario 1	Scenario 2
Initial level	Set the initial lake water-level elevation on October 1 to 49.42 meters (162.15 feet).	X	X
Hydrology	Test a range of hydrologic and meteorological conditions, including the wettest and driest water years between 1992 and 2014.	X	X
Tributaries	Route 100 percent of the flow in Ayers, Wapato, and Hill Creeks to the lakebed during the entire year. Continue to divert other tributaries around the lake.	X	X
Pumps	Do not use pumps. Keep them only as a backup.	X	–
	Use pumps to help regulate lake level. Target lake levels were between 50.3 m (165 feet) and 51.8 meters (170 feet), with minimum levels between mid-July and mid-October, and maximum levels between mid-February and mid-May. The large pump typically cannot be used during May-October.	–	X
Weir	Use a variable-elevation weir to regulate lake levels between 50.3 meters (165 feet) and 51.8 meters (170 feet), with minimum levels between mid-July and mid-October, and maximum levels between mid-February and mid-May.	X	–
	Use a fixed-elevation weir to limit maximum lake level at 51.8 meters (170 feet).	–	X

A variable-elevation weir was used in scenario 1 to control the lake level, and pumps were not used. The weir sets the maximum lake level, such that excess inflows are exported over the weir and out of the lake. To show how a variable-elevation weir might be used to control the lake level, and to indicate a transition between deeper water in winter (maximum 2.4 m [7.9 ft]) and shallower water in summer (maximum 0.9 m [2.9 ft]), the weir elevation in this scenario was set between 50.3 m (165 ft) and 51.8 m (170 ft), with the lower level from mid-July to mid-October, the higher level from mid-February to mid-May, and small step changes were applied to transition between those levels. These levels and time periods are for illustration purposes and may not represent future water-management strategies, but they do provide a variation in shallow and deeper-water condi-tions over the course of the year. During part of the year, the weir crest elevation was lower than historical water levels in Wapato Creek downstream of the lake outlet at Gaston Road (fig. 3); it is unclear whether water would be able to flow out of the lake and over a weir crest set at 50.3 m (165 ft). Wapato Creek likely would not rise as high if some of the tributaries were routed into the lake, but obstructions and beaver dams in Wapato Creek downstream of the lake might limit the use of a weir at less than about 51.2 m (168.1 ft). The WMST provides warnings for potential downstream high-water conditions, but does not attempt to model backflow over the weir from the creek into the lake.

During a water year with 1992–2014 median values for the hydrologic and meteorological conditions, lake levels in scenario 1 followed the prescribed weir-crest elevations throughout most of the year, with tributary inflows allowing the lake to quickly rise to higher target levels and the weir allowing excess water to be exported downstream (fig. 10). This scenario started with a dry lake; if a higher initial lake level had been set for October 1st, the lake level would have followed the weir-crest elevations even more closely. The lake's water budget (just the lake, not the entire lakebed) under this scenario was dominated by tributary flows (86 percent) and precipitation (13 percent) as inputs, and weir outflows (88 percent) and open-water evaporation (9 percent) as losses (fig. 11). The seepage and leakage parts of the water budget constituted only 3 percent of the losses under these conditions. Results indicate that inflows from tributaries and groundwater are sufficient to maintain the target lake level through the dry summer season during a normal year. During a dry year such as water year 2001, tributary inputs were much smaller and, as a result, lake levels would not quite reach their higher targets during most of the winter season. The lake water budget under dry 2001 conditions would reflect the decreased tributary inflow (76 percent) among the inputs, and decreased weir outflow (61 percent) among the losses.

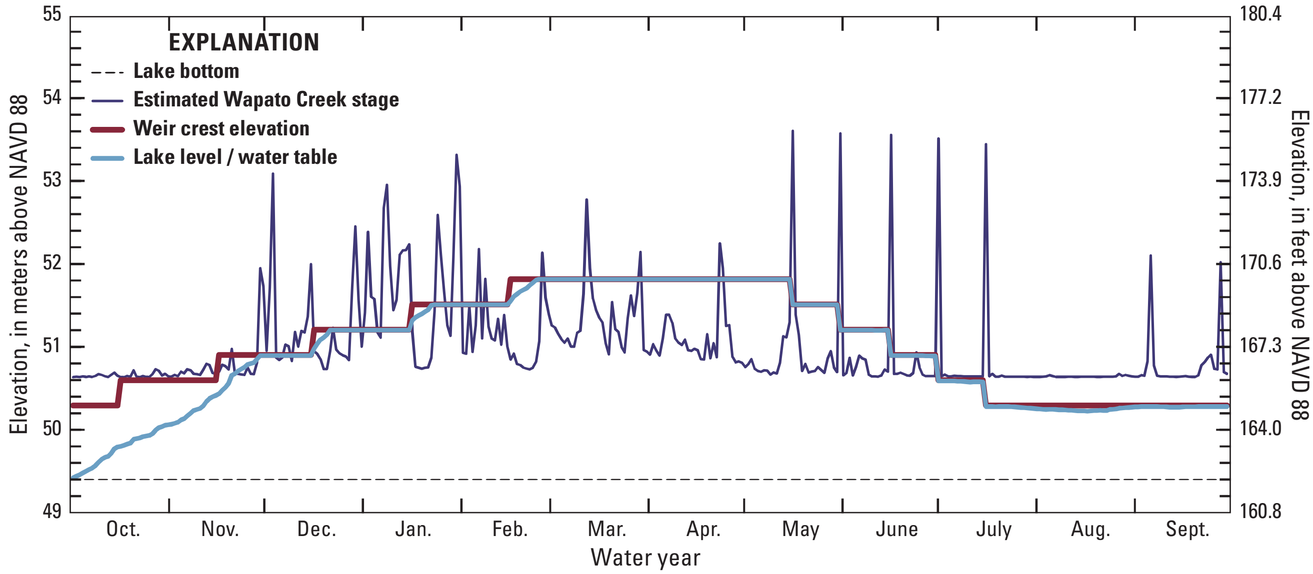


Figure 10. Water levels predicted from scenario 1 using median flow and meteorological conditions from water years 1992–2014 at Wapato Lake near Gaston, northwestern Oregon. NAVD 88, North American Vertical Datum of 1988.

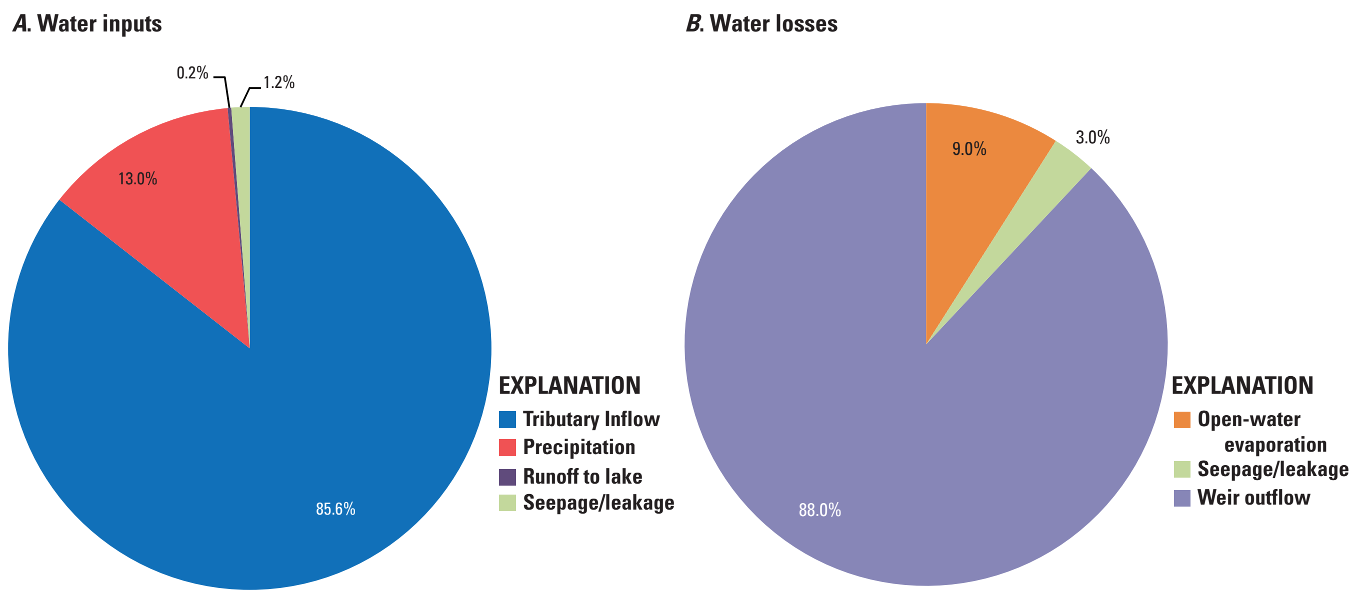


Figure 11. Percentages of total water (*A*) inputs and (*B*) losses as computed from the daily lake water budget for scenario 1 and using median flow and meteorological conditions from water years 1992–2014 at Wapato Lake near Gaston, northwestern Oregon. Total inputs were 22.2 million cubic meters (m³, 18,000 acre-feet). Total losses were 21.3 million m³ (17,300 acre-feet).

Managed water levels in this scenario produced water depths throughout most of the lakebed that were less than 2 m (6.6 ft) during most of the year, and less than 1 m (3.3 ft) during summer (fig. 12). Because the lake bottom is relatively flat, depths across most of the lake are somewhat uniform, only becoming shallower near its edges. The SMT was used to map lakebed water depths associated with the minimum and maximum target water levels in scenario 1. SMT results in figure 13*A* show that at a water level of 51.8 m (170 ft), the vast majority of the lakebed is inundated to depths of 1–2 m (3.3–6.6 ft) with a few areas deeper, whereas shallow water less than 1 m (3.3 ft) depth is restricted to areas along about half of the lake perimeter, constituting only 37 hectares (about 91 acres) and 13 percent of the lake area. In contrast, a water level of 50.3 m (165 ft; fig. 13*B*) results in a smaller inundated area and shallow water less than 1 m (3.3 ft) throughout the lake, covering roughly 208 hectares (about 513 acres). Target water depths for the Wapato Lake NWR will depend on the habitat requirements of prioritized species of fish and water-birds as well as the requirements of desired aquatic vegetation.

Scenario 2—Reroute Three Tributaries and Use Weir and Pumps

Scenario 2 was identical to scenario 1, except that the outflow weir was held constant at a maximum target lake level (51.8 m [170 ft]) and pumps were activated and used to attempt to meet a schedule of target water levels that was the same as the schedule of weir elevations in scenario 1 (table 2). A previous water-quality management plan for Wapato Lake (Wapato Improvement District, 2009) specified that the large pump could be used only during November–April, but the small pump could be used anytime; this scenario followed that recommendation.

Using 1992–2014 median values for the hydrologic and meteorological conditions, lake levels in this scenario increased in autumn and early winter to the maximum level specified by the weir by mid-January, but the lake was slightly deeper than target levels in January and early February because the pumps could not keep up with incoming tributary flows (fig. 14). Similarly, in late spring and early summer when target lake levels decreased, the capacity of the small pump was insufficient to export the large volume of water required to attain lower lake levels. Under these conditions, tributary flows (86 percent) and precipitation (13 percent) accounted for almost all inputs to the lake, whereas pumping (47 percent), flow over the weir (37 percent), and open-water evaporation (12 percent) accounted for almost all losses (fig. 15). Under the dry conditions of water year 2001, tributary inflows were not large enough to attain the target lake levels from autumn through early spring, the maximum lake level was never reached, and pumping with just the small pump again was insufficient to bring the lake level down to target levels in summer. Because of lower water levels, weir outflows in a dry year did not occur (0 percent) and open-water evaporation accounted for a larger fraction (43 percent) of total losses.

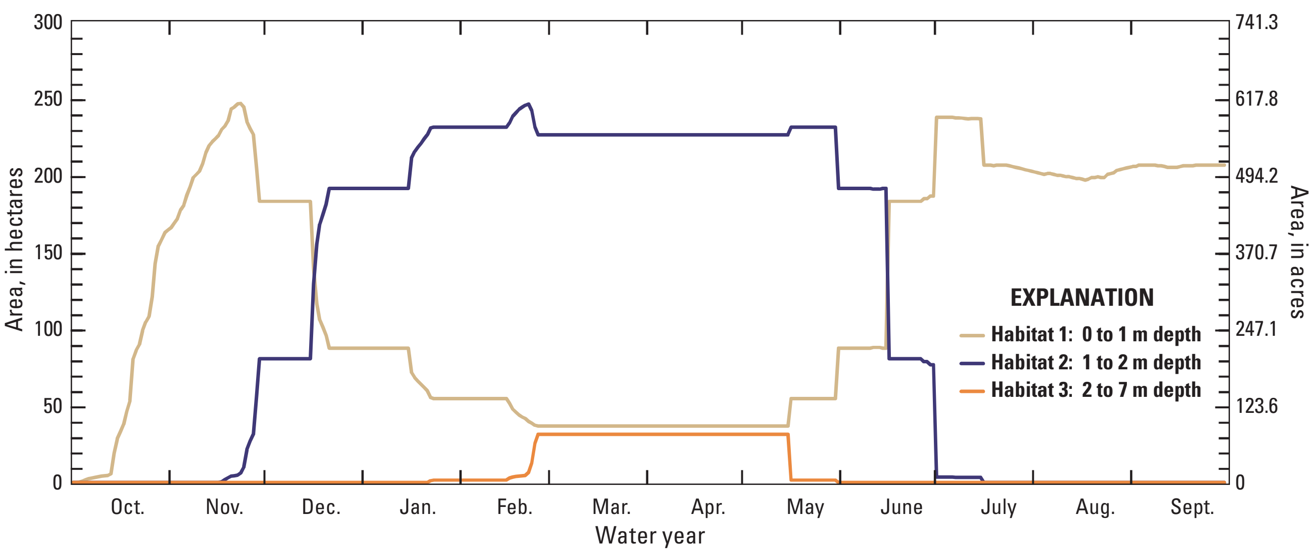


Figure 12. Water-depth and potential habitat areas associated with three water-depth ranges, as predicted from scenario 1 using median flow and meteorological conditions from water years 1992–2014 at Wapato Lake near Gaston, northwestern Oregon. m, meter.

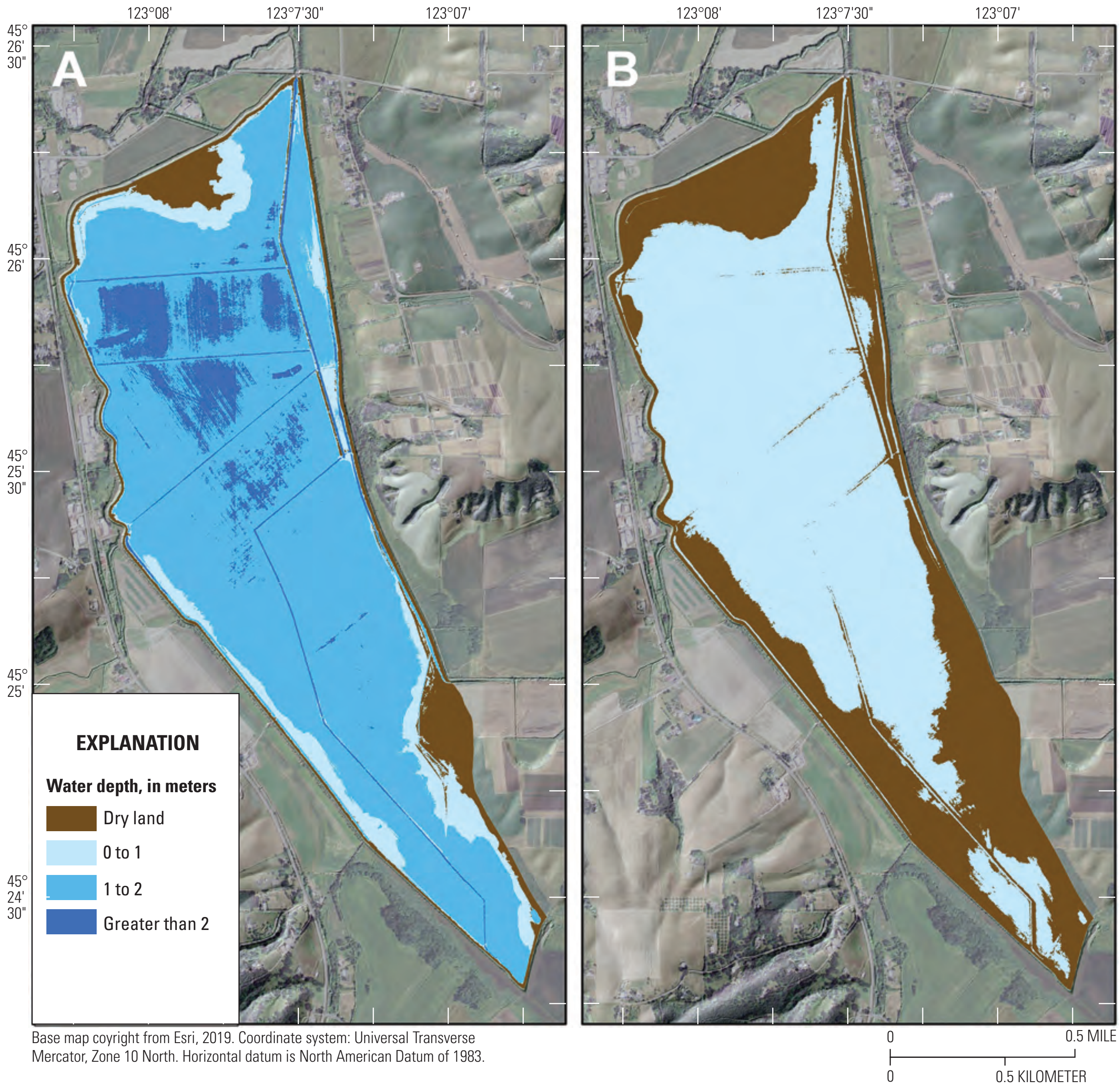


Figure 13. Specific locations that would meet certain water-depth criteria, using minimum and maximum depth targets for scenario 1, at Wapato Lake National Wildlife Refuge near Gaston, northwestern Oregon. Maps show depth categories for water levels of (*A*) 51.8 meters (m; 170 feet [ft]), and (*B*) 50.3 m (165 ft) above North American Vertical Datum of 1988.

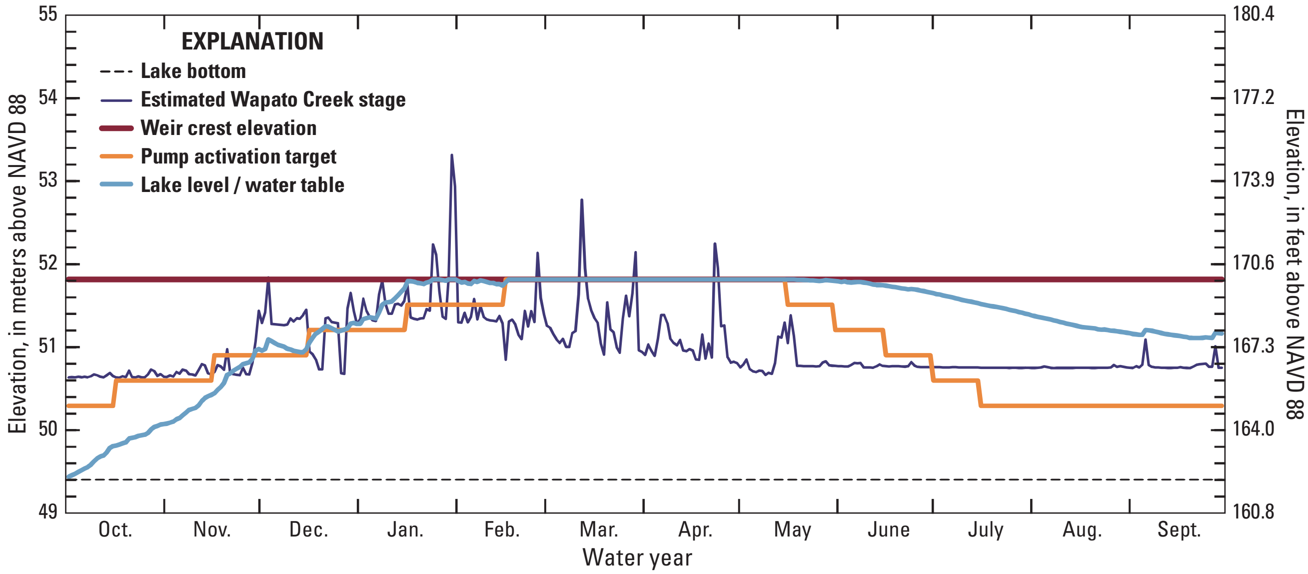


Figure 14. Water levels predicted from scenario 2 using median flow and meteorological conditions from water years 1992–2014 at Wapato Lake near Gaston, northwestern Oregon. This scenario did not use the large pump during May–October. NAVD 88, North American Vertical Datum of 1988.

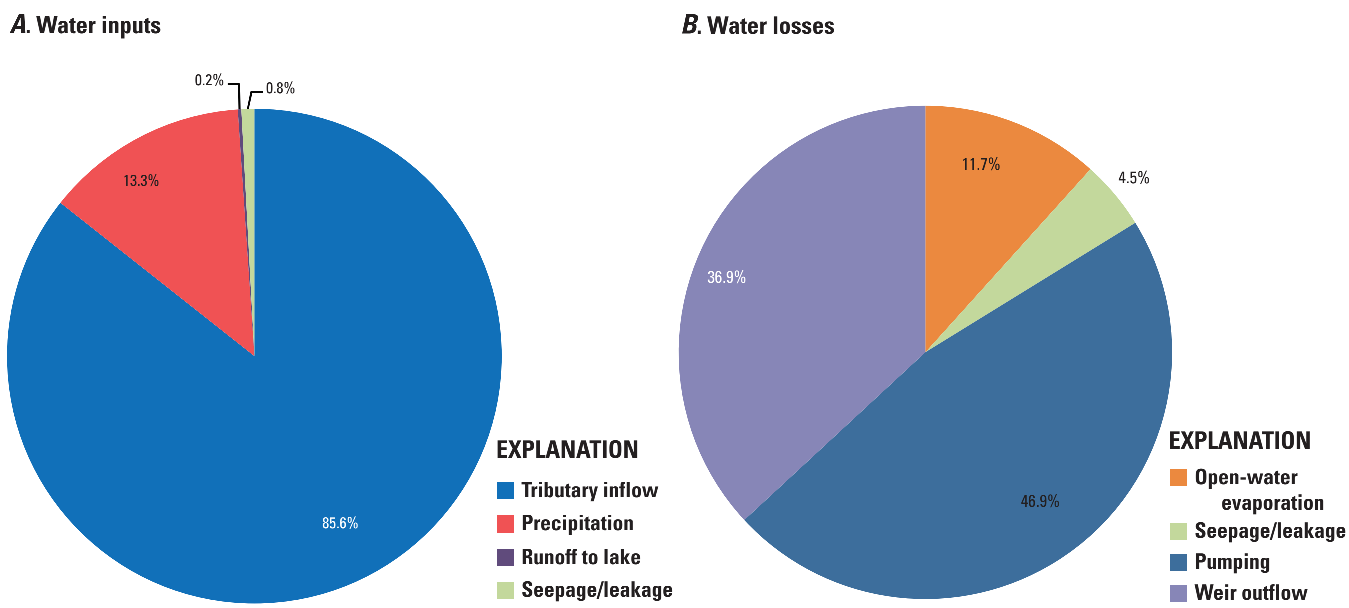


Figure 15. Percentages of total water inputs (*A*) and losses (*B*) as computed from the daily lake water budget for scenario 2 and using median flow and meteorological conditions from water years 1992–2014 at Wapato Lake near Gaston, northwestern Oregon. Total inputs were 22.2 million cubic meters (m^3; 18,000 acre-feet). Total losses were 19.1 million m^3 (15,500 acre-feet).

As a test to determine whether the existing pumps could be used to achieve target lake levels in summer, scenario 2 was modified to allow the large pump to be used year-round. Decreasing the lake level from 51.8 m (170 ft) to 50.3 m (165 ft) requires the export of about 4.1×10^6 m^3 (3,290 acre-ft) of water from the lake, plus additional water that would be released from groundwater storage as the water table declined. At a combined maximum pump capacity of 1.08 m^3/s (38.1 ft^3/s), evacuating that quantity of water by pumping alone would require at least 44 days, even if additional inputs did not exist. Using the small pump alone would require at least 237 days. Predictions from the WMST showed that using both pumps in summer would allow target water levels to be achieved, and with nearly the desired timing (fig. 16). Because this pumped drawdown of the lake level occurred in early summer when streamflow and rainfall was much lower than in winter, drawdown results were much the same regardless of whether wet or dry conditions were imposed.

Target water levels in scenario 2 were identical to those in scenario 1, but scenario 2 was not as successful in attaining the targets in summer; therefore, results for water depth and potential habitat were different. In scenario 2 without using the large pump in summer, water levels were substantially deeper than in scenario 1, putting most of the lakebed area in the deeper category (1–2 m [3.3–6.6 ft]) with less than 20 percent of the lake, mainly around the margins, in the shallower depth category (0–1 m [0–3.3 ft]; fig. 17). Using the large pump in summer in a modified scenario 2, resulting lake levels were more similar to those in scenario 1 and almost all the aquatic habitat in summer was in the shallower category (fig. 18).

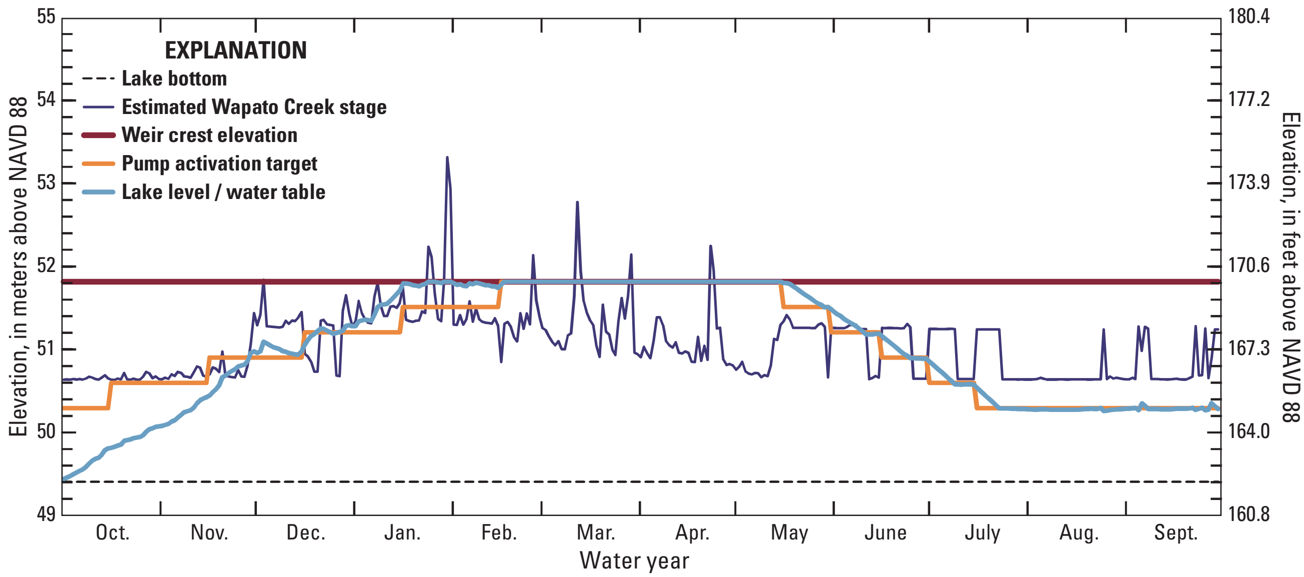


Figure 16. Water levels predicted from a modified scenario 2 using median flow and meteorological conditions from water years 1992–2014 and allowing the large pump to be used year-round at Wapato Lake near Gaston, northwestern Oregon. NAVD 88, North American Vertical Datum of 1988.

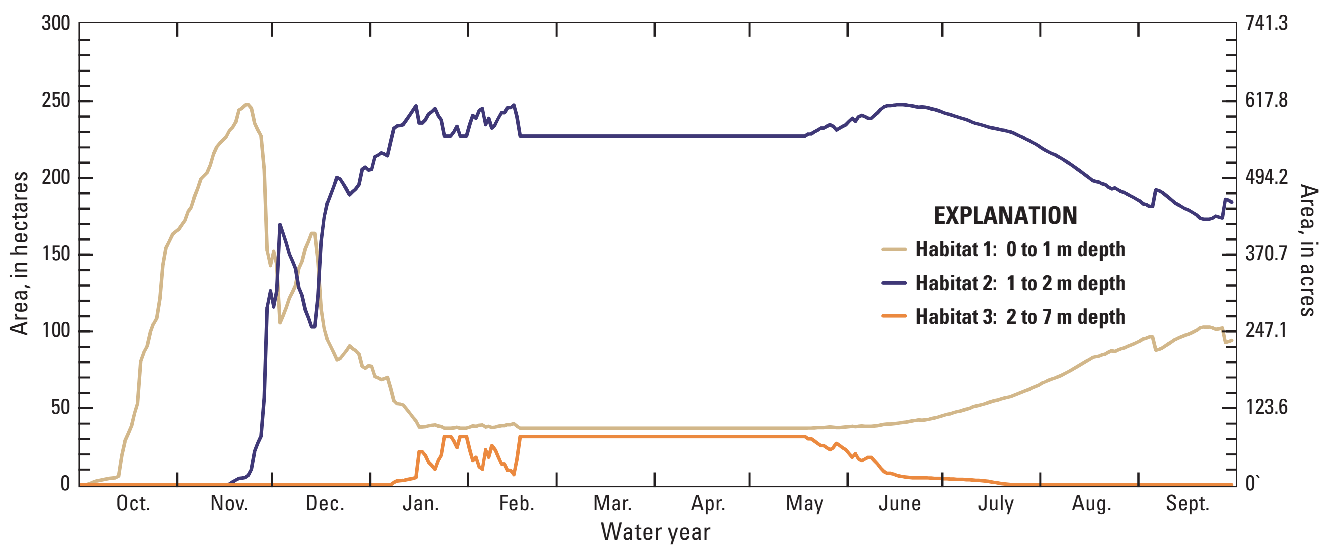


Figure 17. Water-depth and potential habitat areas associated with three water-depth ranges, as predicted from scenario 2 using median flow and meteorological conditions from water years 1992–2014 at Wapato Lake near Gaston, northwestern Oregon. This scenario did not use the large pump during May–October. m, meter.

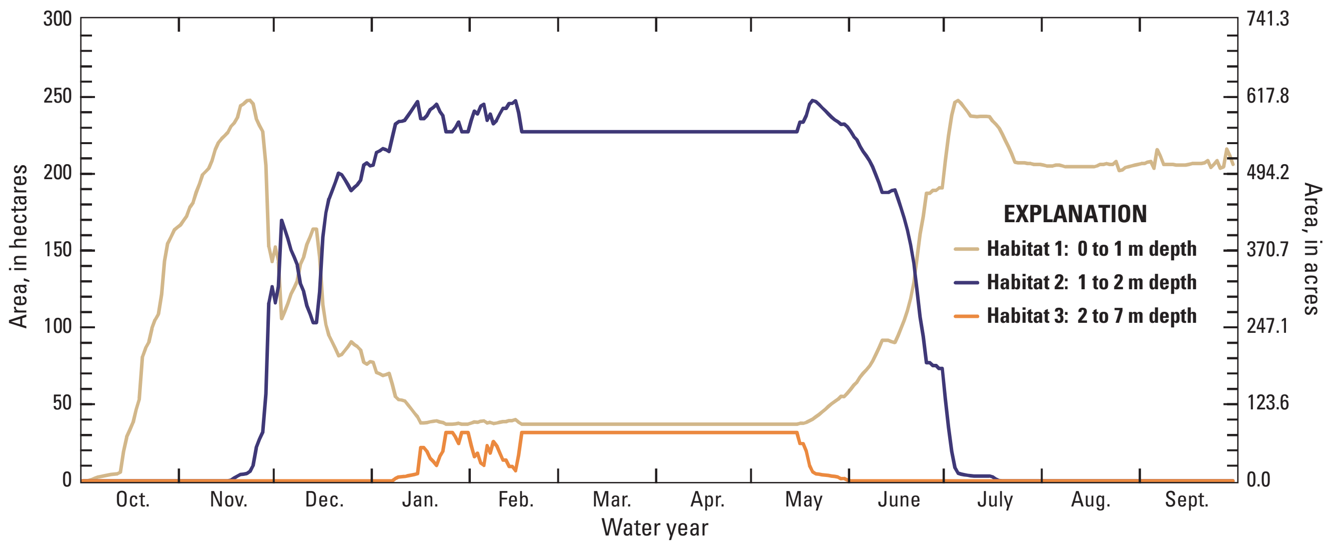


Figure 18. Water-depth and potential habitat areas associated with three water-depth ranges, as predicted from a modified scenario 2 using median flow and meteorological conditions from water years 1992–2014 and allowing the large pump to be used year-round at Wapato Lake near Gaston, northwestern Oregon. m, meter.

Implications for Restoration and Water Management

Effective use of water-budget analyses of wetland environments historically has aided in restoration planning and evaluation of potential water-management strategies. At the Levy Prairie wetland in Florida, Kirk and others (2004) successfully used a water-budget and mapping approach to compare potential restoration outcomes, with a goal of producing a wetland with water depths of 0.15–0.61 m (0.5–2.0 ft) for waterfowl habitat. Wilcox and others (2006) constructed a water budget for part of the Seney NWR in Michigan so that USFWS staff could more easily and reliably restore and manage water levels there. Without knowledge of the water fluxes moving through surface-water and groundwater systems at Seney NWR, managers would be less able to plan and implement a successful restoration. At Wapato Lake NWR, the issues are similar—refuge managers did not know what variations in water depth could be created in the lake through restoration strategies until a water budget was constructed to determine the quantity of water available to create aquatic conditions throughout the year.

Accordingly, water budgets and topographical analyses were used in the WMST and SMT to develop potential water-management strategies and to evaluate their effects on lake level and water depth at Wapato Lake NWR. The goal of the restoration and management strategies was to create a mixture of shallow-water conditions through the creation of lacustrine areas and seasonally inundated wetlands. Results showed that shallow-water targets could be achieved through the rerouting of tributaries into the lakebed and management of lake levels with weirs and pumps. Fewer tributary inputs would be needed if target water levels in the lake were lower than those applied in these scenarios, although some tributary inputs might be useful in a particularly dry year; the WMST could be used to determine how many and which tributary inputs would be sufficient to help meet certain water-level targets. The use of pumps could be minimized if outflows were controlled through the well-timed management of a variable-elevation outflow weir, assuming that downstream obstructions and beaver dams allowed gravity flow over an outflow weir of the desired target elevation.

The water-budget analyses showed that sufficient water should be available in the lake's tributaries in most years to keep the lake inundated to desired levels. Routing flows from Ayers, Wapato, and Hill Creeks into Wapato Lake seems to be almost enough in a dry year (and more than enough in a normal or wet year) to achieve the target lake levels and associated water depths used in the scenarios of this study. If tributary flows ever become too large, creating deeper water than desired or overwhelming the capacity of pumps to evacuate excess water, managers may need to divert excess flows around the lake. The WMST allows refuge managers to evaluate such possibilities and to plan accordingly. The WMST allows users to define two seasons (wet or dry, irrigation or non-irrigation, hunting or non-hunting, etc.) and to specify the percentage of flow in each tributary that is routed into the lakebed during each of those seasons.

Methods used to manage a restored Wapato Lake will depend in part on target water levels as well as water levels in Wapato Creek and the Tualatin River downstream of the refuge. If an outflow weir were used as a control on the maximum lake level (as in scenario 1), and if water levels on the downstream side of the weir ever became higher than the weir crest elevation, then water could flow into the lake from downstream and create deeper conditions in the lake than desired. Excess water would eventually flow out of the lake when downstream water levels receded, but high-water conditions could persist for long periods during winter. Given the fact that target lake levels used in scenarios 1 and 2 sometimes were lower than historical winter water levels in Wapato Creek and the Tualatin River downstream of Gaston Road, importing water into the lake from downstream is a possibility if a simple outflow weir were used. The WMST included calculations of estimated water levels in Wapato Creek downstream of the refuge, based on estimated flows and a historical stage/discharge relation, but those calculations are only rough estimates meant to warn the user of the potential for downstream high-water conditions. Routing some tributary flows into the lake would decrease water levels in the canals outside the levees, and those levels may be low enough during most of the year to enable the use of an outflow weir without threat of backflow into the lake. Under high-flow conditions in the Tualatin River, however, water may still back up Wapato Creek and create water levels that are higher than the weir crest. USFWS is evaluating the potential for such conditions to occur through the construction of a hydraulic model of the Tualatin River and Wapato Creek downstream of the refuge (see Rounds and others, 2020). Combined with results from the WMST, the hydraulic modeling will be helpful for planning the design of any outlet structures for the lake.

Managing lake levels with existing pumps in addition to an outflow weir may be a viable strategy, as in scenario 2, if the operating and maintenance costs survive a cost-benefit analysis. If the outflow weir included a one-way flap gate in conjunction with a higher structure, backflow into the lake because of high water downstream could be prevented while allowing the weir to control the maximum lake level during conditions with lower downstream water levels. Use of a one-way gate, however, likely would require increased pumping for times when downstream water levels exceed the level of that gate. When transitioning from a higher target lake level in winter to a lower target level in summer, results from the WMST showed that the large pump might be needed in the absence of a lower weir outlet, as the small pump was too small to export the large volume of water associated with the 1.5-m (5-ft) decrease in target water level used in these scenarios. Regardless, the use of pumping as a means of exporting water from the lake may be necessary if a variable-elevation weir cannot be used as a simple control on the lake level.

Restoration of Wapato Lake and implementation of water-management strategies likely will have downstream effects. Since the 1930s, the lakebed has been pumped dry in spring and farmed in summer, and canals around the lakebed have been used to deliver irrigation water in summer. As a result, little to no water from the Wapato Lake area has flowed downstream to the Tualatin River in summer. Depending on water-management strategies in the future, flows in Wapato Creek downstream of the refuge may be greater than zero during summer, particularly if water must be exported from the lake to transition from deeper water in winter to shallower water in summer. If a variable-elevation weir were used to control the lake level, outflows from the lake during a transition from higher to lower lake levels might result in pulses of higher flows in Wapato Creek. Assuming that each 0.3 m (1 ft) water-level transition occurred over a single day during a weir-height reduction, the WMST predicted daily mean outflows of 8.6–11.4 m^3/s (302–402 ft^3/s) in scenario 1 under median flow conditions for the days of transition. Drawdowns could be managed over longer time periods, producing lower exported flow rates, and could be managed such that they were completed before the summer season began. Nevertheless, flows exported via Wapato Creek to the Tualatin River in late spring or early summer could be substantial and might require management.

The water-quality effects of exporting water from Wapato Lake and downstream to the Tualatin River are important considerations for future water management at Wapato Lake NWR. Water pumped out of Wapato Lake during spring historically has led to minor issues with drinking-water treatment at the Joint Water Commission plant about 10 km (6.2 mi) downstream. In addition, an early summer algal bloom in Wapato Lake in 2008 combined with pumped export of that water led to downstream drinking-water treatment problems as well as a large algal bloom and associated water-quality issues in the lower Tualatin River (Bonn, 2008; Carpenter and Rounds, 2013; Rounds and others, 2015). High organic-matter concentrations, phosphorus loads, or plankton populations exported from Wapato Lake might cause water-quality and drinking-water treatment problems downstream. Since 2008, managers of Wapato Lake have been careful to consider the downstream water-quality effects of any exported water during the May–September dry season. During winter, discharges from the Wapato Lake drainage typically are diluted by relatively high flows in the Tualatin River, minimizing any water-quality effects.

The fact that water-quality issues have occurred in association with discharges from Wapato Lake in the past, however, does not mean that a properly managed and restored lake would produce problems in the future. The most altered water-quality conditions in Wapato Lake discharges often have occurred when the lake was being pumped out in the spring and nearly empty, such that the lake was quite shallow and interactions of the water with lakebed soils were maximized; these trends are embodied in water-quality data collected by USGS on Wapato Creek at Gaston Road (USGS station 14202650; see U.S. Geological Survey, 2015). Under such conditions, concentrations of organic matter and nutrients may be elevated. Under a restored condition, however, much more water may be in the lake and any rerouted tributary inflows might help to “flush” water through the lake, decreasing the time available for algal growth and the accumulation of organic matter and nutrients leached from the lakebed. Future water-quality conditions and downstream effects with a restored Wapato Lake remain unknown, however, and refuge managers and planners will need to continually assess and adapt as issues arise.

Although the WMST includes all important inputs and losses for the Wapato Lake water budget and makes predictions that seem to be sufficiently accurate for the development of water-management plans at the refuge, it makes some assumptions and simplifications that could be improved upon with additional data and refinement of algorithms. For example, estimates of groundwater discharge could be improved through measurements of groundwater levels in the lakebed combined with measurements of lakebed hydraulic conductivity. Compared to some of the other inputs, however, groundwater discharge typically is a minor component of the water budget.

The combined application of the Water Management Scenario Tool and the Shoreline Management Tool to Wapato Lake NWR provides a powerful means of helping to design potential water-management plans and evaluate their effects on lake level and habitat. With new or existing data, these tools could be applied to almost any refuge or managed wetland. On-the-ground adaptation and response to measured conditions always will be an important means of optimizing restoration strategies, but using the WMST and SMT as planning tools is proving to be valuable for evaluating a wide range of potential water-management and restoration actions at Wapato Lake NWR, and thereby determining in advance which may be the most feasible and effective strategies for meeting local objectives.

Supplementary Material

Copies of the Wapato Lake WMST and datasets to run the SMT for Wapato Lake are available from a USGS website at https://or.water.usgs.gov/proj/wapato_lake/. That website also provides links to archived flow and water-quality data at sites in and around Wapato Lake NWR. All datasets used to run the water-budget calculations in the WMST are included in the WMST spreadsheet and were obtained from archived sources cited in this report.

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