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The Hydrologic Benefits of Wetland and Prairie Restoration in Western Minnesota—Lessons Learned at the Glacial Ridge National Wildlife Refuge, 2002–15

Scientific Investigations Report 2019–5041

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

Cover. A pair of cranes in flight at the Glacial Ridge National Wildlife Refuge, northwestern Minnesota. Photograph by Timothy K. Cowdery, U.S. Geological Survey.

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By Timothy K. Cowdery, Catherine A. Christenson, and Jeffrey R. Ziegeweid

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
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Josh Eash, Regional Hydrologist, Midwest Region, U.S. Fish and Wildlife Service (USFWS), jump-started the postrestoration study by helping secure a USFWS Landscape Conservation Cooperative grant to begin postrestoration data collection. He also donated his and his staff's time (Jennifer Gruetzman and Dawn McDonald) to maintain study ditch gages and make ditch-flow measurements. Finally, Josh hired summer interns Katie Rittenhouse, Jacob Kaplan, Megan Zopfi, Jamie Nielsen, and Adam Kleinschmidt, who collected synoptic water levels and helped with groundwater sampling.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)		square kilometer (km^2)
	Volume	
million cubic feet (Mft^3)	28,320	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per hour (in/h)	0.0254	meter per hour (m/h)
	Hydraulic conductivity	
foot per day (ft/d)	0.0003528	centimeter per second (cm/s)
	Transmissivity	
square foot per day (ft^2/d)	0.09290	meter per second (m^2/d)

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

$$°C = (°F – 32) / 1.8.$$

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).

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

Supplemental Information

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

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

Turbidity concentrations are given in nephelometric turbidity units (NTU).

Year-long periods are water years, a 12-month period beginning December 1 of the previous year and ending November 30 of the water year.

Abbreviations

ARD	absolute relative percent difference
CDL	Cropland Data Layer
ET	evapotranspiration
GHCN	Global Historical Climatology Network
gSSURGO	gridded Soil Survey Geographic database
HEC–HMS	Hydrologic Engineering Center's Hydrologic Modeling System
lidar	light detection and ranging
MNDNR	Minnesota Department of Natural Resources
N	nitrogen
NLCD	National Land-Cover Dataset
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe efficiency
NWQL	National Water Quality Laboratory
RIFR	relative increase in flow rate
RL	laboratory reporting level
SCAN	Snow Climate Analysis Network
SWB	Soil-Water-Balance
TNC	The Nature Conservancy
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WMCES	Wisconsin-Minnesota Cooperative Extension Service
WRP	Wetland Reserve Program

The Hydrologic Benefits of Wetland and Prairie Restoration in Western Minnesota—Lessons Learned at the Glacial Ridge National Wildlife Refuge, 2002–15

By Timothy K. Cowdery, Catherine A. Christenson, and Jeffrey R. Ziegeweid

Abstract

Conversion of agricultural lands to wetlands and native prairie is widely viewed as beneficial because it can restore natural ecological and hydrologic functions. Some of these functions, such as reduced peak flows and improved water quality, are often attributed to restoration; however, such benefits have not been quantified at a small scale. To inform future restoration efforts, especially in northern prairie settings, the U.S. Geological Survey, in cooperation with the Minnesota Environment and Natural Resources Trust Fund, the U.S. Fish and Wildlife Service, and the Red Lake Watershed District, compared the hydrology of the Nation's largest wetland and prairie restoration, Glacial Ridge National Wildlife Refuge, before and after restoration.

Wetland and prairie restorations resulted in substantial changes in flows through the hydrologic cycle, in reduction of overland runoff and ditch flow during storms, and in improvements in water quality. Wetland and prairie restorations within the six basins characterized in this study resulted in a 14-percent decrease of cropland, a 6-percent increase of wetlands, and a 19-percent increase of native prairie between 2002 and 2015. During the same period, runoff rate decreased 33 percent (as a proportion of precipitation) and ditch flow rate decreased by 23 percent. Areal groundwater recharge rate increased from 30 to 35 percent (16 percent relative change in flow rate). Base flow as a proportion of total ditch flow increased from 25 to 35 percent (a 40-percent relative change). Peak ditch flow from storms decreased, ditch-flow recessions lengthened, and base flow from groundwater discharge increased, though only a small amount in some basins. These changes reduce the amount of ditch water leaving the study area, reducing flows that contribute to downstream flooding. Median surficial groundwater and ditch-water nitrate concentrations decreased by 79 and 53 percent, respectively. Median ditch-water suspended-sediment concentration decreased by 64 percent.

Neither the density of restorations nor the beneficial changes in hydrology were evenly distributed in the study area. The amount of hydrologic benefits within an individual ditch basin did not relate directly with the amount of restoration in that basin; however, the landscape characteristics that related most closely with hydrologic benefits were the area of a basin underlain by a surficial aquifer and the area of drained wetlands (indicating the potential for wetland restoration). In western Minnesota, the basins underlain by surficial aquifers that contain large areas of drained wetlands are the uplands of the Alexandria Moraine Complex and the beaches of glacial Lake Agassiz on the eastern side of the western one-third of Minnesota, north of Wilmar, Minnesota. These findings provide resource managers with information that can help focus restoration resources in areas where the greatest hydrologic benefits can be realized.

Introduction

Wetland and prairie restorations have a long list of benefits to humans and the natural world (Zedler, 2003; Gleason and others, 2008). These benefits accrue from the hydrologic and ecological services provided by newly restored ecosystems. Benefits include reduced downstream flooding, improved water quality, increased biodiversity, increased wildlife habitat, and increased carbon sequestration (Kucharik and others, 2006). Minnesota was a wetland- and prairie-rich State. Before European settlement, wetlands (28 percent) and prairies (34 percent) covered 62 percent of the State (Dahl, 1990; Marschner, 1930). By 1984, the wetland area in the prairie region of the State was reduced by 92 percent, and statewide, the prairie area was reduced by 98 percent (Minnesota Prairie Plan Working Group, 2011). Federal and State legislators and land managers have recognized the importance of wetlands and prairies. They have established an array of regulations to prevent further wetland loss and provide subsidies and programs to help restore former wetland and prairie areas. To administer these subsidies and programs efficiently, managers need to know how to maximize the benefits of these restorations.

Gleason and others (2008) studied wetland-restoration benefits in the Prairie Pothole Region of the north-central United States, including the study area. Their study estimated gross restoration benefits on a regional scale; however, because the scale of the study was large, hydrologic analyses either used models or were primarily volumetric. Some questions posed by legislators and land managers about the dynamics and scale of hydrologic change from wetland and prairie restorations were beyond the scope of that study:

- How much will water flows between groundwater and surface water change?
- How much will flood peaks be reduced in streams draining restored lands?
- How much will water quality improve and how quickly?
- Where on the landscape can similar dynamic changes be expected?

To answer these questions, a smaller-scale study was needed that intensively measured water flows and quality, in groundwater and surface water, before and after wetland and prairie restoration. Beginning in 2011, the U.S. Geological Survey (USGS) collaborated with the Red Lake Watershed District, the Legislative and Citizen's Commission on Minnesota Resources, and the U.S. Fish and Wildlife Service (USFWS) to do such a study at the Glacial Ridge National Wildlife Refuge in northwestern Minnesota (fig. 1).

The Glacial Ridge National Wildlife Refuge (hereinafter called "Glacial Ridge") is an ideal place for an integrated study about hydrodynamic changes from wetland and prairie restoration. Bought in 2000 by The Nature Conservancy (TNC), the land that would become the core of Glacial Ridge was 24,795 acres of mixed wetland, grassland, cropland, and woods about 11 miles (mi) east of Crookston, Minnesota (fig. 1). In 2002, TNC, in partnership with more than 35 organizations, began the ambitious project of restoring all the wetlands and prairies at Glacial Ridge in what would become the largest wetland-prairie restoration in the United States (Gerla and others, 2012). Recognizing the opportunity to establish a hydrologic baseline with which to quantify the hydrologic benefits of the restoration, TNC partnered with the USGS to conduct a prerestoration hydrologic baseline study in cooperation with them and the Red Lake Watershed District. That study, in a 124,000-acre study area (fig. 1) of public and private lands containing Glacial Ridge, was completed in 2005 (Cowdery and others, 2007) and documented the prerestoration state of the water flow and quality in the Glacial Ridge study area.

The postrestoration hydrologic study, conducted by the USGS in cooperation with the Minnesota Environment and Natural Resources Trust Fund and the Red Lake Watershed District, produced a complementary dataset during 2012–15 to document Glacial Ridge hydrology after wetland and prairie restoration. This study has four objectives:

1. Document the characteristics of water flow and quality (the hydrologic state) at Glacial Ridge after restoration.
2. Compare the postrestoration hydrologic state to the prerestoration baseline. Assess how much change can be attributed to restoration by accounting for other possible factors like weather variability.
3. Identify landscape characteristics that may relate to hydrologic changes, including changes in land use, restoration density, wetland density, soil type, and land slope.
4. Identify areas in western Minnesota with similar landscape characteristics that may benefit from future wetland and prairie restorations.

Like the prerestoration study, the postrestoration study concentrates on near-surface groundwater, surface water, and their interactions because they are closely connected and are in direct contact with the land undergoing restoration. Deeper aquifers exist in the study area but are hydraulically separated from shallower waters in most areas by thick layers of low-permeability glacial till. Discussion of these deep aquifers is limited to their effect on surficial hydrology.

Data collected during the prerestoration study were reanalyzed using more accurate methods used to analyze the postrestoration data to ensure that the results were comparable. Therefore, specific results reported herein may differ slightly from those in the prerestoration report. A substantial analysis change was that the prerestoration period was expanded from 2003–5 to include 2006 to complement the 4-year 2012–15 postrestoration period. All year-long periods in this report and the prerestoration report are water years, which is a 12-month period beginning December 1 of the previous year and ending November 30 of the water year.

The analysis of some data collected by the USGS in the study area is beyond the scope of this report. These include groundwater levels and certain water-quality data that were collected during the 5-year restoration period (2007–11) between the prerestoration and postrestoration periods to determine how rapidly Glacial Ridge hydrology responded to restorations (U.S. Geological Survey, 2019). Water samples were analyzed for herbicide and metabolites concentrations (largely triazine and acetamide compounds) during the prerestoration study (Cowdery and others, 2007). An equivalent dataset was not produced during the postrestoration study. The results of a study to assess the effects of wetland and prairie restorations on wetland mercury concentrations (Cowdery and Brigham, 2013), conducted between the prerestoration and postrestoration periods, also are not discussed in this report.

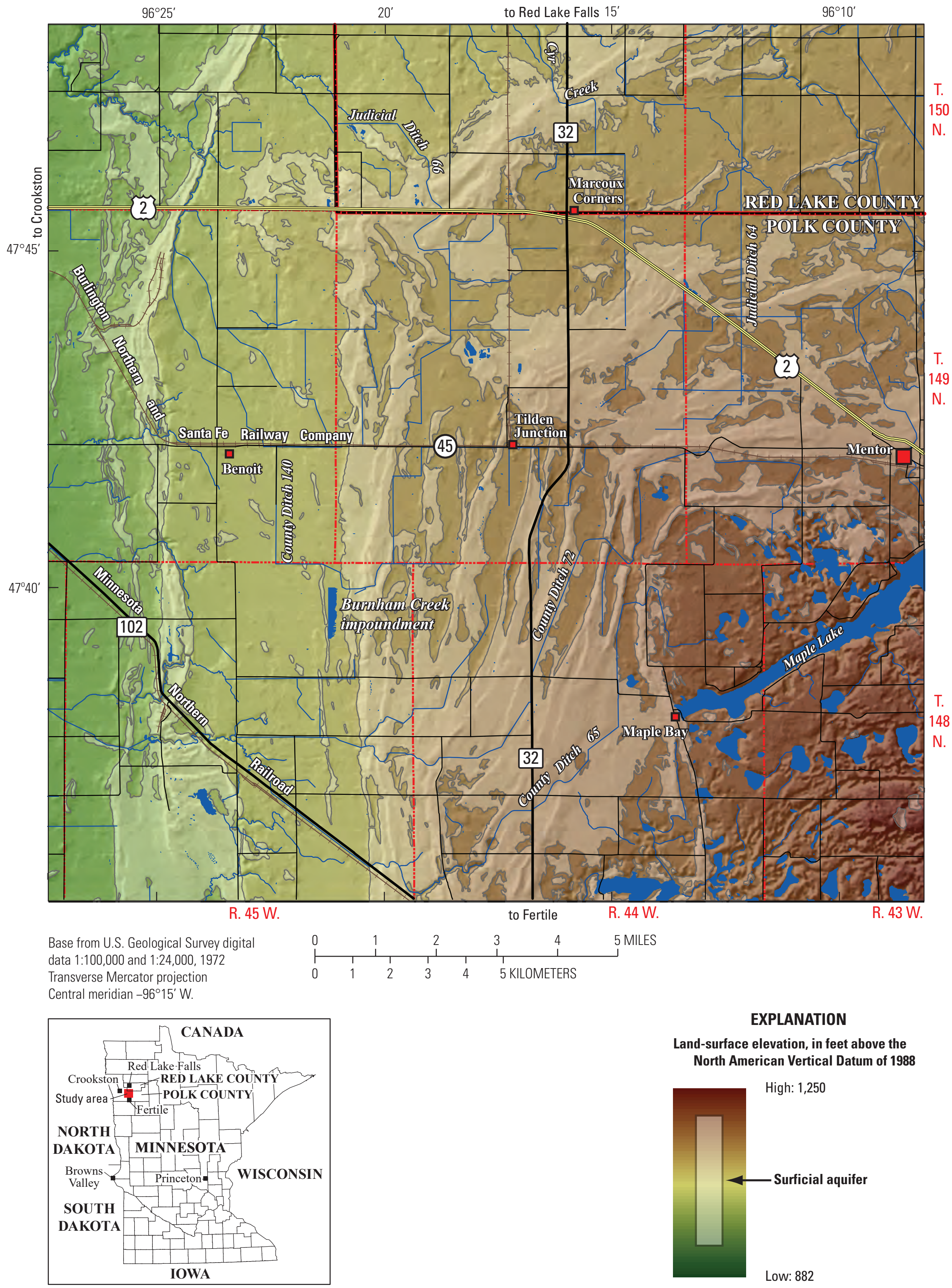


Figure 1. Topography and surficial aquifer extent, Glacial Ridge study area, northwestern Minnesota.

Purpose and Scope

This report presents the hydrologic changes in the Glacial Ridge study area between the prerestoration and postrestoration periods that can be attributed to land-use changes during 2002–15. It includes results from a landscape analysis that identifies areas of western Minnesota that would most hydrologically benefit from the wetland and prairie restorations that transformed Glacial Ridge. This report presents the findings of all USGS analyses at the Glacial Ridge study area not previously published. Some prerestoration data (Cowdery and others, 2007) are presented again to allow this report to be understood without reference to earlier reports. Methods from the prerestoration and postrestoration periods are detailed, emphasizing any changes between periods. A brief recapitulation of the general hydrology of the study area from the prerestoration report describes the main features of groundwater and surface-water flow and quality. Hydrologic changes between restoration periods are discussed and attributed to land-use changes where possible. Finally, the report includes a map that identifies areas of western Minnesota most likely to hydrologically benefit from wetland and prairie restoration.

Hydrologic Setting

The Glacial Ridge study area is on the eastern shore of what was glacial Lake Agassiz from about 13,800 to about 10,100 years ago. This lake formed as the Laurentide Ice Sheet retreated north of the continental divide at Browns Valley, Minnesota, about 30 mi southwest of the northeastern corner of South Dakota (Teller, 1987, fig. 2). The location of the study area in relation to this glacial lake has a profound effect on the hydrology at Glacial Ridge. Lake Agassiz's depositional processes control the shape and hydrologic characteristics of the aquifers and confining beds within the study area. The land surface, shaped by the preceding glaciers and then the lake, is the main control on the flow of water within and from the study area. This surface falls several hundred feet to the north and west, from uplands of the Erskine Moraine (not shown, the lake-rich area near Maple Lake, fig. 1) toward the center of the Lake Agassiz Basin (the western edge of the study area, fig. 2). The moraine is a complex composition of till and other sediments deposited by glaciers or their meltwaters (hereinafter called "glacial sediments"). Lake Agassiz curved around the morainal uplands, occupying the main basin to the west of the study area and the eastern basin (lake areas in fig. 2) to the northeast of the study area. After the lake drained from the deglaciation of Hudson Bay, the Red River of the North formed in the bottom of the main Lake Agassiz Basin, and the Red Lakes and the Red Lake River (not shown in fig. 2) formed in the bottom of the eastern basin. Groundwater and surface-water flow radiates from the morainal uplands in the southeast quadrant of the study area toward the Red River of the North and Red Lake River to the west and north of the study area, respectively.

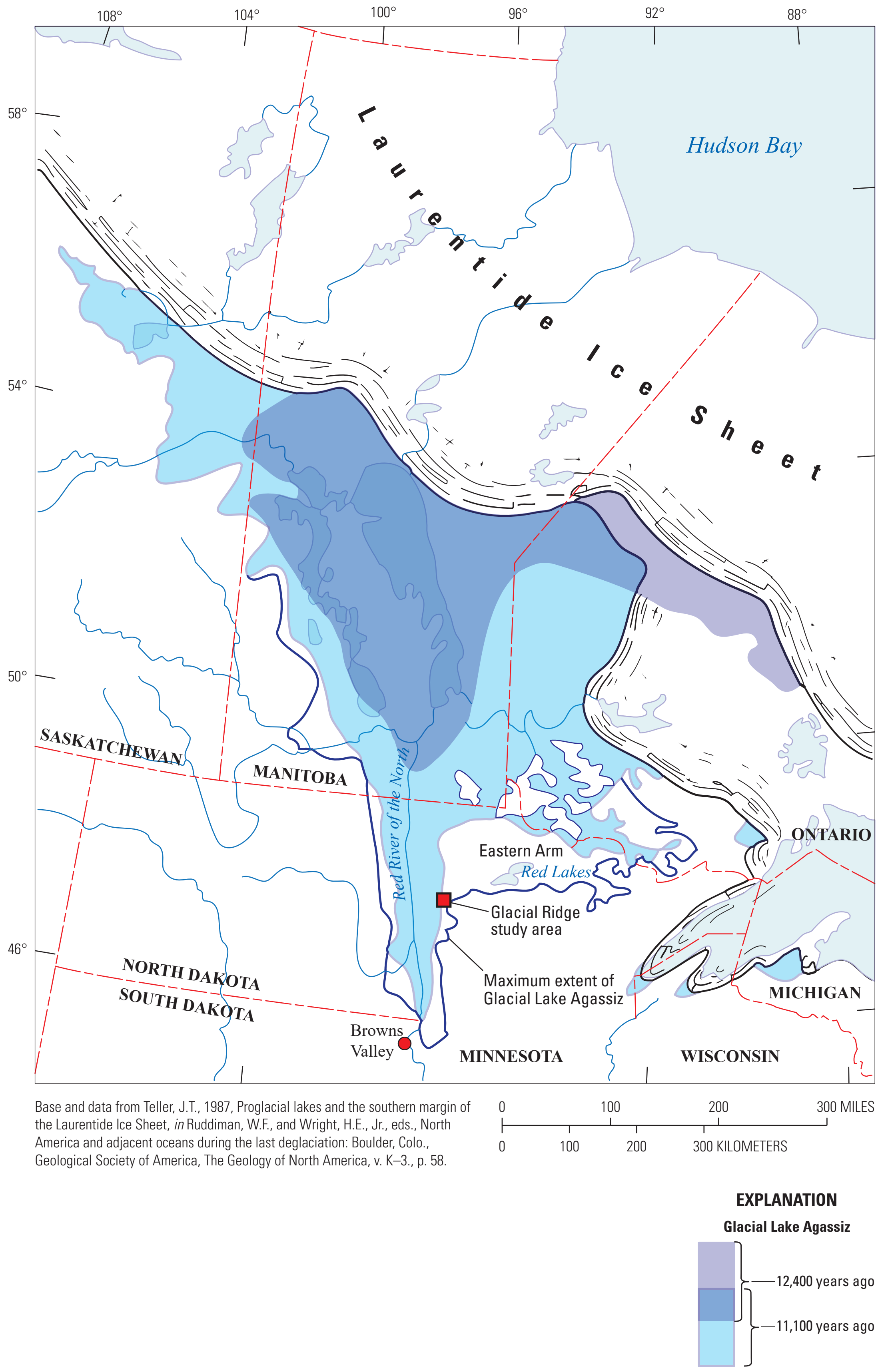
Buried and surficial aquifers exist within the study area. Confined (buried) aquifers are formed of sands and gravels buried within fine-grained glacial sediments. The areal extent and interconnectedness of these aquifers are poorly known. Surficial sands and gravels winnowed from and deposited on glacial tills by the waves of Lake Agassiz created beaches around the morainal uplands. These beaches form most of the surficial aquifers at Glacial Ridge, with the highest and oldest beaches to the southeast near Maple Lake and the lowest and youngest near the western and northern edges of the study area (fig. 1). Generally, surficial aquifers are as much as 35 feet (ft) thick and hundreds of feet wide. These aquifers can be continuous for tens to hundreds of miles. In several places, however, these surficial sands and gravels were deposited upon preexisting sands and gravels, creating localized surficial aquifers that are as thick as 78 ft and hydrologically connected to some buried aquifers. A more detailed description of the glacial history of the study area was provided in appendix 5 of the prerestoration report (Cowdery and others, 2007). The details of the glacial formation of the aquifers at Glacial Ridge provide insights that are useful in understanding the structure and hydrology of aquifers in the study area.

Originally, a complex of wetlands and wet prairies developed on till or lake sediments in swales between sets of beach ridges. Surface-water flow was originally diffuse, moving behind and parallel to a beach ridge. Flow would continue to an adjacent downgradient interbeach swale through a topographically low point in a beach ridge. These wetlands were partially drained by ditches in the early 20th century. Smaller ditches channelized the original drainage. Larger ditches flow perpendicular to the beach ridges and are deeply incised where they cross ridges. The resulting ditched drainage routes most of the flow at Glacial Ridge nearly at right angles to the original flow direction. Ditches in the study area are at the top of their watersheds and transmit flow that is highly variable and that often ceases in the winter or late summer.

Land Use and Restoration History

During the last 100 years, the Glacial Ridge study area was transformed from native wetland and prairie to various agricultural uses and is now restored to a close approximation to its original land cover. This land-use and restoration history of the Glacial Ridge study area helps put into perspective the current (2015) hydrologic conditions on this land. The following land-use history is based on a 2004 interview with Jason Eckstein, Restoration Ecologist for TNC at their Glacial Ridge project office. A more detailed land-use and restoration history of the Glacial Ridge National Wildlife Refuge also is available (Hayek, 2012).

Before European settlement, the study area was a treeless mixture of prairies occupying the beach ridges with many types of wetlands and wet meadows in the interbeach swales. Usually dry prairie-covered beach ridges made good trails used by native peoples, and later, European settlers, who



Base and data from Teller, J.T., 1987, Proglacial lakes and the southern margin of the Laurentide Ice Sheet, *in* Ruddiman, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colo., Geological Society of America, The Geology of North America, v. K–3., p. 58.

Figure 2. The extent of glacial Lake Agassiz, central North America.

established the Pembina Trail across the study area well before 1846 (Gilman and others, 1979). Homesteaders began settling in the area in the last quarter of the 19th century, growing crops (mainly small grains) on beach ridges and haying the meadows wherever they could. The area made generally poor cropland because the coarse-grained beach ridges quickly dried out, whereas the wet meadows could not be planted early enough in the spring.

To make some of the wet meadows tillable, the study area was extensively ditched during the early 1900s. Ditches helped remove water from the landscape during spring snowmelt so that fields could be planted earlier. Ditches also helped remove water during summer storms, reducing standing water in fields. Despite ditching, wetlands fed by groundwater discharge on the downgradient faces of the beach ridges and wetlands in deeper basins survived. Through the 1950s, small farms continued to operate in the area. Even with drainage improvements, however, the land was still agriculturally marginal, and farming was difficult. Beginning in the early 1960s, much of the central part of the study area was consolidated into a single holding of about 25,000 acres of mostly contiguous land for cattle grazing. Through the 1980s, the consolidated grazing operation remained largely intact and two large feedlots were added to the property.

By the late 1980s, the ecological value of the property was beginning to become apparent. Although the land was drained, many wetlands and native prairie parcels remained that were important for wildlife, particularly waterfowl. When the grazing property was put up for sale in the late 1980s, the Minnesota Department of Natural Resources (MNDNR), the U.S. Fish and Wildlife Service, and TNC considered acquiring the land for its ecological assets. However, a private investor interested in agriculture bought the land. The period 1986–92 was relatively dry. Many parts of the study area that had previously been impossible to farm were tilled for the first time during this period. Wheat, barley, corn, soybeans, and sunflowers (alfalfa and edible beans on ridges) were planted as closely as possible to land too wet to till. This farming destroyed large areas of native plant communities in temporarily dry wetlands and wet meadows. Farming at this scale was unheard of in the former homestead-cropping period. Thousands of field boulder piles, initially gathered by homesteaders, were buried in place to facilitate industrial agriculture, changing the hydrologic character of the area.

As precipitation returned to more normal levels in the later 1990s, large areas again became untillable, and the property was again offered for sale. TNC purchased the consolidated property in 2000 and began wetland and prairie restorations in 2001. The land formerly under cultivation was rented for continued planting to control noxious weeds until restoration activities could begin. TNC restored wetlands and prairies primarily through the U.S. Department of Agriculture, Natural Resources Conservation Service's (NRCS) Wetland Reserve Program (WRP), which stipulated how the land was restored. Restorations proceeded slowly because WRP funding and sources of local native prairie seeds were not abundant. As previously seeded prairie began to produce its own seed, the latter limitation eased. On October 12, 2004, the U.S. Congress established the Glacial Ridge National Wildlife Refuge administered by the USFWS with a planned area of 37,756 acres. As restorations were completed TNC transferred ownership to the USFWS. Restorations on TNC property were completed in 2011.

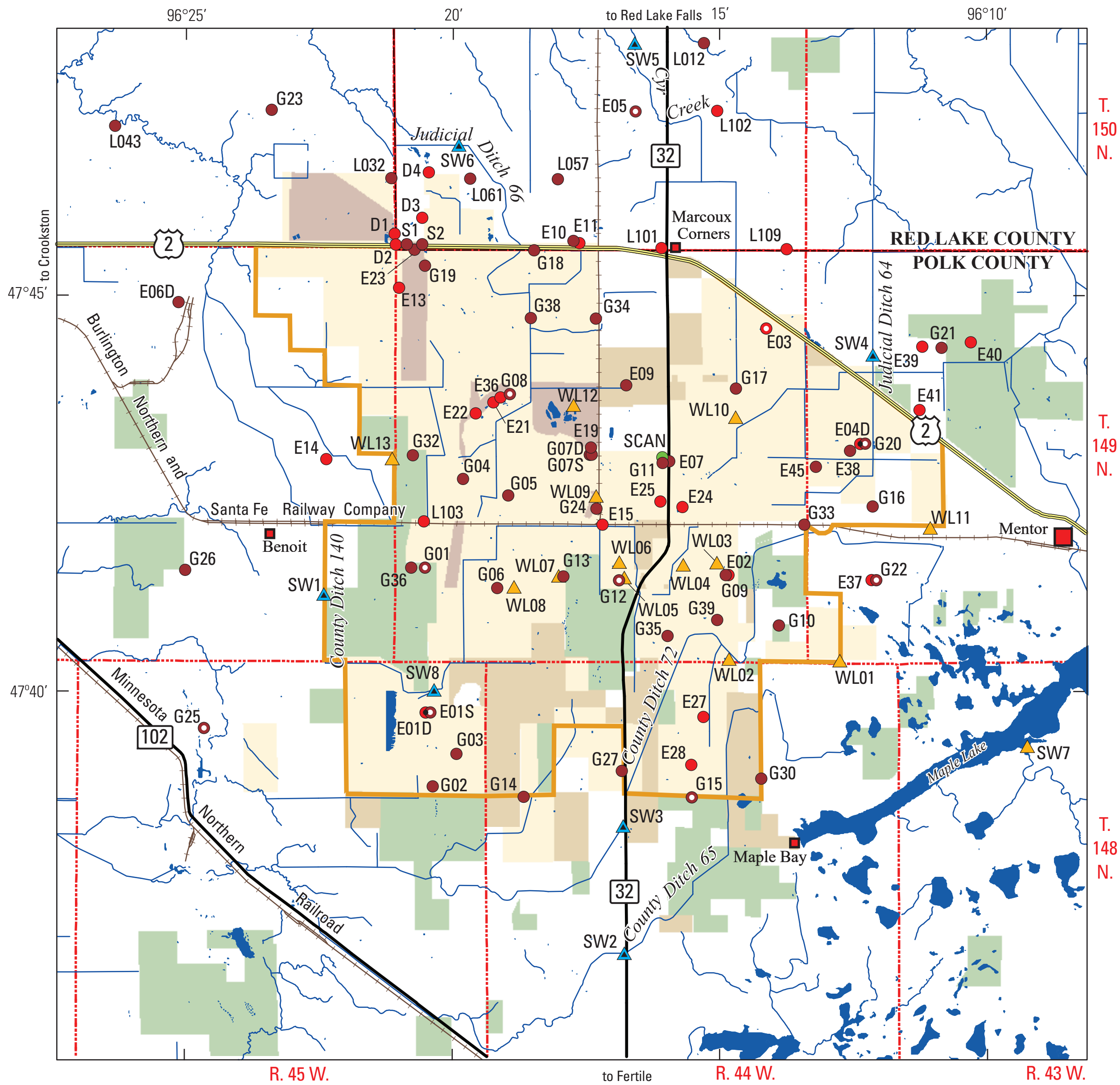
In fall 2015, more than 22,000 acres of formerly cropped or grazed land had been restored to native prairie (19,198 acres) or wetland (2,977 acres) (Greg Bengston, U.S. Department of Agriculture, Natural Resources Conservation Service, written commun., 2015), representing 89 percent of the original TNC-owned acreage in the study area. By that time, 95 mi of ditches were either filled or plugged. Within the study area, an additional 3,000 acres of other private land had been enrolled in permanent wetland easement and had been restored during 2000–5 (fig. 3).

Climate

The climate of the study area is subhumid continental. During most of the year, the upper-level winds flow from west to east in the region, and surface winds have a predominantly western component. The study area has cold winters and moderately warm summers. Climate statistics during 1981–2010 (the last available 30-year summary) from the High Plains Regional Climate Center (2016) for Crookston, Minn., about 16 mi west of the study area, are provided in the first four rows of table 1.

This climate station has a period of record extending back to 1890. These data are useful for putting the short-term climate data collected within the study area into historical perspective. Unfortunately, Crookston precipitation data are not complete during 6 of this study's 13 years when using a threshold of 5 missing days per year (2008–2011, 2014, and 2015 were incomplete). This makes direct comparisons between more recent and historical data difficult. Precipitation at Crookston varies substantially between seasonal and interannual wet and dry periods (fig. 4). Multiyear droughts such as those during 1928–40 and 1984–93 have caused water shortages in the region, and wet periods such as those during 1941–50, 1968–71, and 1994–2000 have caused recurring flooding. Annual averages of precipitation and temperature and precipitation extremes at Crookston for the period of record are shown in table 1.

Data for this study were collected during relatively dry years (2003 and 2011–14) and relatively wet years (2004, 2007, and 2010; fig. 4). Importantly, 3 of the 4 years of the prerestoration study period were normal to wet, whereas 3 of the 4 years of the postrestoration study period were dry. Direct comparison of the hydrology of these periods must consider this difference in weather. The average annual precipitation at Crookston during the prerestoration and postrestoration periods was 108 percent (67th percentile) and 86 percent (24th percentile) of the period of record (1890–2013) average,



	0	1	2	3	4	5 MILES
0 1 2 3 4 5 KILOMETERS						

Base from U.S. Geological Survey digital data 1:100,000 and 1:24,000, 1972
Transverse Mercator projection
Central meridian –96°15′ W.

Land use from Greg Bengston, U.S. Department of Agriculture, Natural-Resources Conservation Service, written commun., 2015

EXPLANATION

Land ownership and use

- National Wildlife Refuge or other restored lands
- Public conservation land
- Private conservation land
- Gravel lease
- Other, mostly private

Glacial Ridge National Wildlife Refuge boundary

Water-level site with short name (table 1.1)

- G15 — Continuous, surficial aquifer and precipitation
- E01D — Continuous, buried aquifer
- G14 — Synoptic, surficial aquifer
- E28 — Synoptic, buried aquifer
- SW2 — Continuous, ditch
- SW7 — Synoptic, lake and wetland
- SCAN — **Weather station**

Figure 3. Land ownership and use in 2011, water-level sites, and a weather station, Glacial Ridge study area, northwestern Minnesota.

Table 1. Climate statistics in the area of the Glacial Ridge study area, northwestern Minnesota, 1891–2015.

[Data from High Plains Regional Climate Center (2016) for Crookston, Minnesota. in., inch; °F, degree Farenheit; PET, potential evapotranspiration estimated by the Wisconsin-Minnesota Cooperative Extension Service; ET, actual evapotranspiration estimated by the Soil-Water-Balance model; pink cells, prerestoration period; blue cells, postrestoration period]

Measurement	Statistic	Period	Location	Value
Precipitation	Mean annual[1]	1981–2010	Crookston, Minnesota	22.12 in.
Precipitation	Mean May–Sept. sum	1981–2010	Crookston, Minnesota	15.44 in.
Temperature	January mean	1981–2010	Crookston, Minnesota	6.1 °F
Temperature	July mean	1981–2010	Crookston, Minnesota	69.1 °F
Precipitation	Mean[2] annual[1]	[2]1890–2013	Crookston, Minnesota	21.57 in.
Precipitation	Maximum annual[1] (1941)	[2]1890–2013	Crookston, Minnesota	30.83 in.
Precipitation	Minimum annual[1] (1936)	[2]1890–2013	Crookston, Minnesota	9.99 in.
Temperature	Mean annual[1]	1890–2015	Crookston, Minnesota	40.3 °F
Precipitation	Mean annual[1]	2003–6	Crookston, Minnesota	23.19 in.
Precipitation	Mean annual[1]	[3]2012–13	Crookston, Minnesota	18.49 in.
Precipitation	Maximum annual[1] (2004)	2003–6, [3]2012–13	Crookston, Minnesota	26.56 in.
Precipitation	Minimum annual[1] (2012)	2003–6, [3]2012–13	Crookston, Minnesota	17.48 in.
Temperature	Range of mean annual[1]	2003–6	Crookston, Minnesota	39.2–42.8 °F
Temperature	Range of mean annual[1]	[3]2012–13	Crookston, Minnesota	37.7–43.6 °F
PET	Mean annual[1]	2003–6	Glacial Ridge study area	23.14 in.
PET	Mean annual[1]	2012–15	Glacial Ridge study area	28.78 in.
PET	Maximum annual[1] (2012)	2003–6, 2012–15	Glacial Ridge study area	30.30 in.
PET	Minimum annual[1] (2004)	2003–6, 2012–15	Glacial Ridge study area	20.25 in.
ET	Mean annual[1]	2003–6	Core study area	18.40 in.
ET	Mean annual[1]	2012–15	Core study area	16.29 in.
ET	Maximum annual[1] (2004)	2003–6, 2012–15	Core study area	20.57 in.
ET	Minimum annual[1] (2012)	2003–6, 2012–15	Core study area	13.66 in.

[1]Annual means the period from December 1 of the previous year through November 30.

[2]This statistic excludes years with more than 5 days of missing precipitation: 1919, 1978, 1996, 2002, 2008–11, and 2014–15.

[3]Statistics could not be reliably calculated for missing years during this postrestoration period because of missing data.

respectively (values in table 1). Maximum annual precipitation in Crookston during the prerestoration and postrestoration periods (hereinafter, analysis periods) occurred during the prerestoration period (2004, 87th percentile), and the minimum annual precipitation occurred during the postrestoration period (2012, 20th percentile). Water stored during the winter in snowpack can have a substantial effect in the study area. A large snowpack can ameliorate a dry spring well into June. Temperatures at Crookston did not correlate with precipitation during the study period (table 1). Annual temperature ranges during both analysis periods was near the long-term (1890–2015) average (40.4 degrees Fahrenheit).

Precipitation is the largest flow component in the hydrologic cycle and is commonly measured (Cowdery and others, 2007). In the prerestoration report (Cowdery and others, 2007) and in this report, precipitation is assumed to be the total of all water flowing through the study area. Evapotranspiration (ET) is the next largest flow component but is not measured directly in the study area (Cowdery and others, 2007); however, two estimates of ET are available. The Wisconsin-Minnesota Cooperative Extension Service (WMCES) produces daily gridded (0.4-degree latitude by 0.4-degree longitude) estimates of potential ET, which are calculated from satellite-derived measurements of solar radiation and air temperatures at regional airports (Wisconsin-Minnesota Cooperative Extension Service, 2016). In the study area, the average annual potential ET estimate produced by the WMCES during the postrestoration period was 24 percent greater than during the prerestoration period (table 1). Average annual prerestoration potential ET was about the same as precipitation at Crookston; however, average annual potential ET during the postrestoration period was about 55 percent greater than precipitation at Crookston during 2012–13, the only postrestoration years with complete precipitation records. Extremes of annual potential ET in the study area are listed in table 1. Most of the potential ET in the study area occurs during the growing season (April–September; 2001–15 average, 94 percent of annual ET), particularly during the summer (June–August; 2001–15

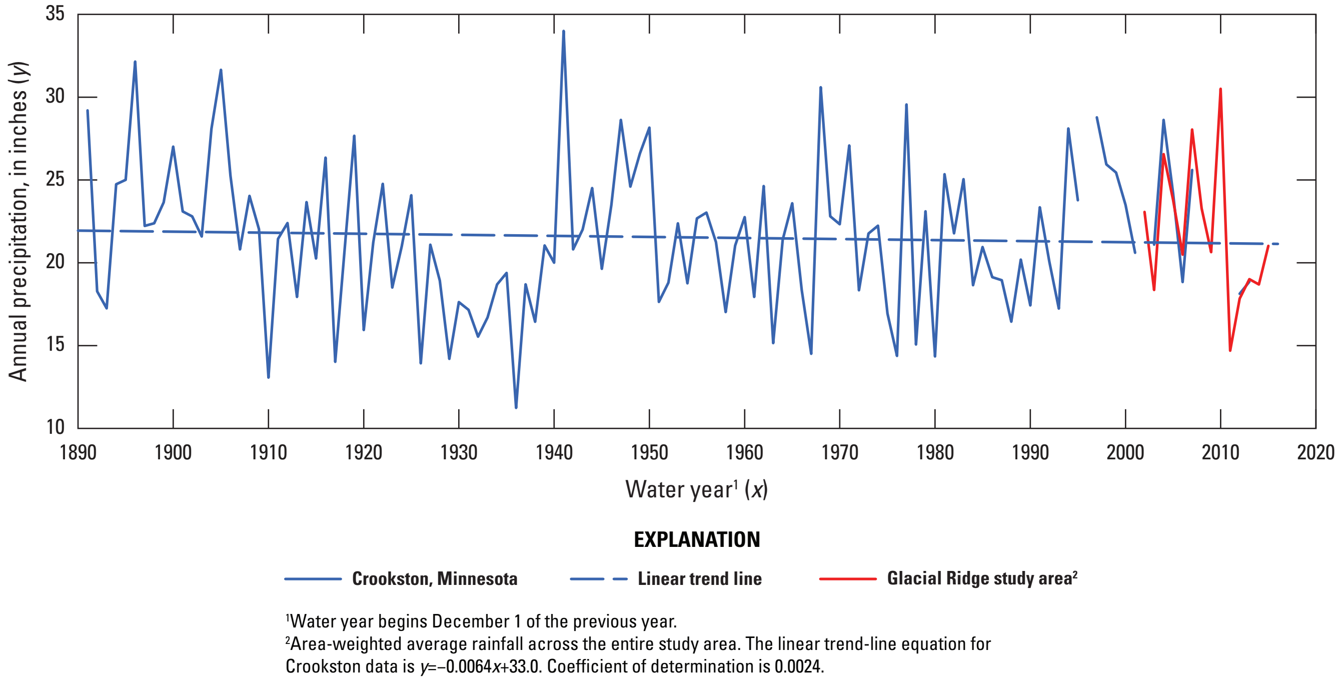


Figure 4. Annual precipitation in Crookston, 1891–2013, and in the Glacial Ridge study area, 2003–15, northwestern Minnesota.

average, 61 percent of annual ET). Generally, estimates of average annual and growing-season potential ET during this study exceeded the period of record average annual precipitation at nearby Crookston.

Smith and Westenbroek (2015) calculated the average annual actual (not potential) ET using a Soil-Water-Balance (SWB) model for the State of Minnesota during 2000–2013. The model was extended to 2015 with the same input data sources for this study. The SWB-calculated actual ET estimates for the core part of the study area are shown in table 1. During the prerestoration period, SWB-calculated actual ET was 80 percent of the WMCES potential ET and during the postrestoration study period was 58 percent of the WMCES potential ET. Maximum annual actual ET was in 2004 (112 percent of the 2003–15 average). Minimum annual actual ET during the prerestoration and postrestoration was in 2012 (75 percent of the 2003–15 average). Unlike the WMCES potential ET estimate, all SWB actual ET estimates are less than the average annual precipitation, as expected. Annual precipitation tended to covary with annual actual ET (wet years corresponded to years of high actual ET) but inversely varied with annual potential ET. Annual temperature did not covary with precipitation or ET.

Oberg and Melesse (2006) calculated actual ET at Glacial Ridge during June–September 2000–3 using satellite imagery combined with a locally calibrated energy-balance method. This estimate was calculated separately for a reference area, restored land, and unrestored land. The average of annual seasonal totals for Oberg and Melesse's actual ET, using an average of the estimates for restored and unrestored land, was 17 percent higher than the average annual SWB estimate during 2001–3. Oberg and Melesse's actual ET seasonal estimates were less than Crookston annual precipitation except in 2003, when it was 15 percent higher.

Methods

Measurements made during this study documented three aspects of the study area's hydrology: water flows, water quality, and runoff dynamics. These measurements include groundwater and surface-water levels, ditch-flow measurements, precipitation, and water-quality samples. Measurements made during the prerestoration period (Cowdery and others, 2007) were repeated using the same methods during the postrestoration to make data as comparable as possible between periods. Unlike the prerestoration study (Cowdery and others, 2007), extensive effort was made to quantify ET using a SWB model developed by Smith and Westenbroek (2015) for both analysis periods. Detailed historical land-use and weather data were compiled as inputs into a study-area specific version of this model. Runoff dynamics were documented with the same unit-hydrograph model used in the prerestoration study (Cowdery and others, 2007). Similar runoff events were chosen during both restoration periods to make restoration periods comparable. The only water-quality constituents analyzed in water samples from both restoration periods were field measurements, nutrients, and suspended sediment (in ditch-water samples). These samples were collected from groundwater and surface water several times per year.

Statistical summaries of all original measurements and derived flows were prepared seasonally and annually for each of six ditch basins. The summaries for all six basins were aggregated into one area representing the main part of the study area. This aggregated area is called the core area (basins SW2–SW8, fig. 5). The area of some basins differs slightly from those used in the prerestoration study because better topographic data became available in the interim. The annual statistical summaries were aggregated into the two analysis periods so that hydrologic and water-quality changes between the periods could be quantified, for each ditch basin and for the core area. Annual comparisons of some summaries indicate the rate at which they changed hydrologically.

Because all six ditches begin within the study area, substantial parts of their basins underwent wetland and prairie restorations. The amount of restoration varied among basins, as did the amount of hydrologic change between restoration periods. Correlating these changes with land-use and landscape characteristics within each basin may help identify characteristics that are particularly important for producing hydrologic benefits from restorations. Once identified, these land-use and landscape characteristics were mapped in the hydrologically and geologically similar western one-third of Minnesota to identify areas where the hydrologic benefits of wetland and prairie are most likely.

Land-Use and Landscape Data

Comparable maps of land use covering the entire study area were compiled annually during 2002–15 from the most accurate and detailed data available for each year. Each annual compilation took data from three original sources (table 2) and merged them into a study-area-wide map of land use. Each annual land-use compilation was resampled to a 60-meter (m) (197-ft) grid. Land use in these grids was populated with the land-use codes in table 3, column 1, and used in an SWB model to estimate ET fluxes (see details below; Methods, Water-Balance Analysis, Evapotranspiration) for this study. Codes from these grids were aggregated into eight broad land-use categories (table 3, column 3) and used in a landscape characteristics analysis (see details below; “Methods” and “Land-Use and Landscape Data” sections) for this study.

For each year, the compilation process started with National Land Cover Database (NLCD) land-use data as a base covering the study area (Homer and others, 2007, 2015; Fry and others, 2011). Any cells coded as “cropland” in the NLCD data were re-coded with the specific crop type code from the Cropland Data Layer (CDL) grids when available (U.S. Department of Agriculture, 2015). CDL data are available in Minnesota beginning in 2006. Areas coded as cropland in the NLCD data were nearly all coded as “corn” or “soybeans” in the CDL data. These corn and soybean areas seemed to alternate between the two crops annually. Therefore, during 2002–5, when CDL data are not available, NLCD areas coded as cropland were arbitrarily coded as either corn or soybeans based on the proportion of those crops in the 2006 CDL data. These crops were switched annually in these fields during these years to simulate the crop rotation indicated by the CDL data.

The annual land-use grids were modified with higher-quality land-use data in the form of areal polygons from the NRCS (Greg Bengston, U.S. Department of Agriculture, Natural Resources Conservation Service, written commun., 2015). The areas modified were the Scientific and Natural Area (managed by the MNDNR) and WRP lands (administered by the NRCS). Areal polygons were converted to the land-use grid using the ArcGIS polygon-to-raster tool (Esri, variously dated) using the nearest-neighbor resampling technique. Scientific and Natural Areas Program and WRP areas outside of TNC property did not change during 2002–15 and were coded as “conservation lands” on the base grids. These areas are mainly similarly managed State conservation lands and private WRP conservation lands.

Finally, the modified annual land-use grids were recoded as “restored wetland” or “restored prairie” in restoration areas in the year they were restored. Areal polygons of the restoration areas and restoration dates were provided by the NRCS (Greg Bengston, U.S. Department of Agriculture, Natural Resources Conservation Service, written commun., 2015), who managed the restorations through the WRP. In this way, each annual grid represents the land use in the fall of the year because restorations took place throughout the summer and early fall. Categories from the resulting annual land-use data also were aggregated into broader land-use categories according to the schema in table 3, producing 14 general annual land-use grids.

In addition to the land-use analysis at Glacial Ridge, this study also includes an analysis that identifies areas of western Minnesota that likely will produce the most hydrologic benefits from wetland and prairie restorations. The analysis was restricted to this area because it is geologically, climatologically, and hydrologically most similar to the study area. Western Minnesota was defined as all MNDNR Level-07 watersheds (Minnesota Department of Natural Resources, 2013) that partly or fully lie west of the eastern edge of native wet prairie or the line of 95 degrees longitude, whichever is farther west. The area of surficial aquifers and the area of drained wetlands within each MNDNR Level-07 watershed were required for this analysis.

To calculate the area of surficial aquifers, coarse-grained soils were identified using the Gridded Soil Survey Geographic database (gSSURGO, Soil Survey Staff, 2015a). The gSSURGO “parent group material name” and “particle size” fields were used together to identify soil classes that likely form surficial aquifers. This same method was used to identify surficial aquifers in the Glacial Ridge study area. A complete list of soil classes considered “sandy” in western Minnesota is listed in table 1.1 in appendix 1.

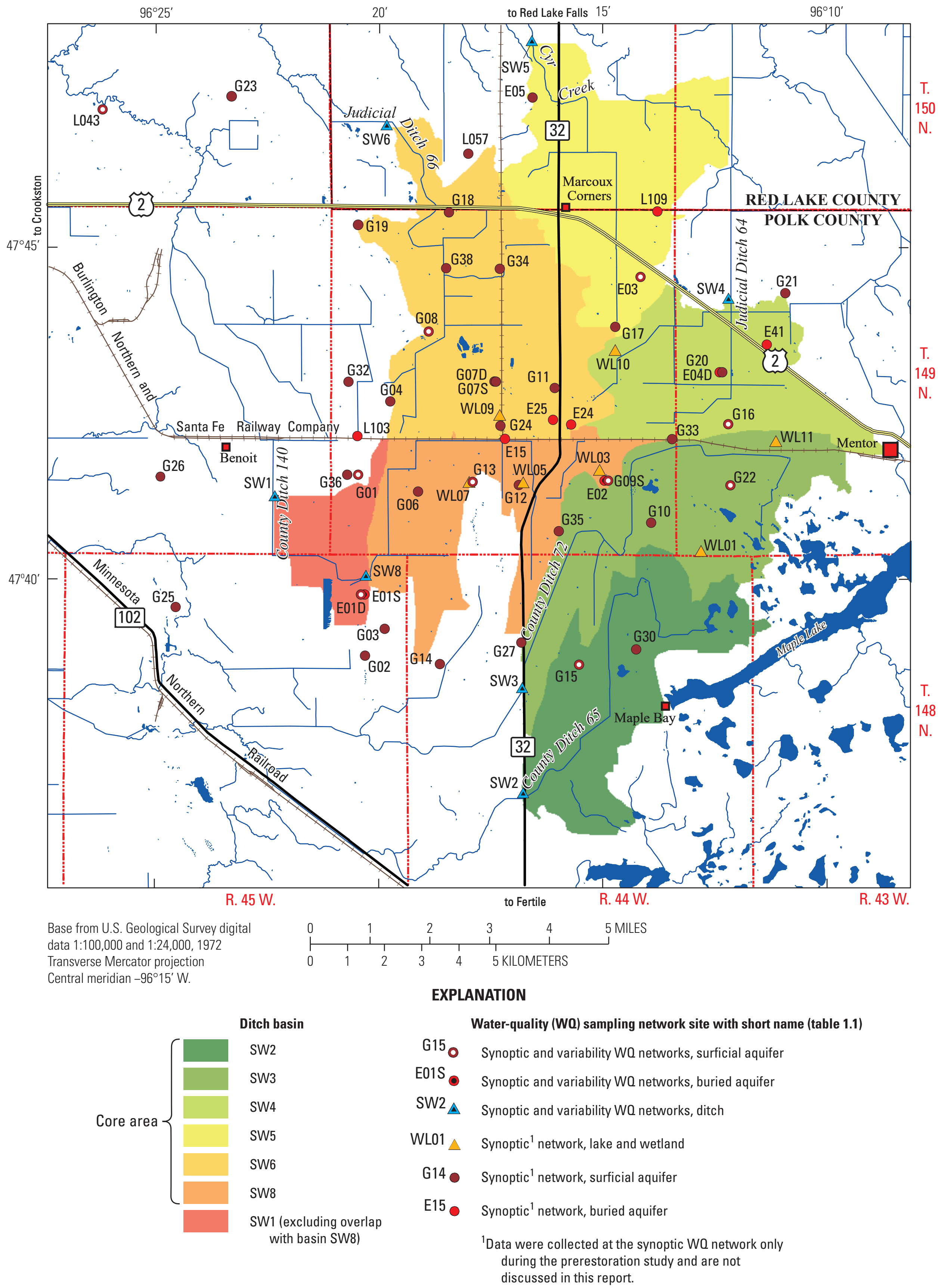


Figure 5. Ditch basins and water-quality sampling network sites, Glacial Ridge study area, northwestern Minnesota.

Table 2. Data sources for annual land-use maps, Glacial Ridge study area, northwestern Minnesota, 2002–15.

[m, meter; SNA, Scientific and Natural Area; WRP, Wetland Reserve Program; TNC, The Nature Conservancy]

Data	Source	Type	Period	Quality of land-use data	Category used
National Land Cover Database	Multi-Resolution Land Characteristics Consortium	30-m grid	2002–15	Low	All.
Cropland Data Layer	U.S. Department of Agriculture	30-m grid	2006–15	Medium	Cropland.
SNA	Natural Resources Conservation Service	Polygon	2009	High	Conservation lands.
WRP outside of TNC land	Natural Resources Conservation Service	Polygon	2002	High	Conservation lands.
WRP on TNC-restored land	Natural Resources Conservation Service	Polygon	2002–15	High	Restorations.

Data	Reference
National Land Cover Database	Homer and others (2007) for 2002–5; Fry and others (2011) for 2006–10; Homer and others (2015) for 2011–15.
Cropland Data Layer	U.S. Department of Agriculture (2015).
SNA	Greg Bengston (U.S. Department of Agriculture, Natural Resources Conservation Service, written commun., 2015).
WRP outside of TNC land	Greg Bengston (U.S. Department of Agriculture, Natural Resources Conservation Service, written commun., 2015).
WRP on TNC-restored land	Greg Bengston (U.S. Department of Agriculture, Natural Resources Conservation Service, written commun., 2015).

Areas of restorable wetlands in western Minnesota were identified as areas of drained and partially drained wetlands in the Restorable Wetland Inventory where these data are available (Ducks Unlimited, 2009). Where absent (north of Mahnomen County [not shown in fig. 1]), these restorable wetland areas were identified from the National Wetlands Inventory (Minnesota Department of Natural Resources, 2014). All wetland areas with a drained or partially drained classification were included, regardless of whether the wetland was ephemeral or permanent.

The resulting areas of restorable wetlands and areas of surficial aquifers were combined to categorize MNDNR Level-07 watersheds (Minnesota Department of Natural Resources, 2013) by the likelihood that wetland and prairie restorations will produce hydrologic benefits. Basins with the greatest density of restorable wetlands and surficial aquifers were assigned the highest likelihood of producing hydrologic benefits. MNDNR Level-07 watersheds have a size like the ditch basins in the Glacial Ridge study area. The area of both factors was calculated for each basin in western Minnesota using the "tabulate areas" ArcGIS tool (Esri, variously dated). These percentages were added to create the statistic used to rank the basins. Using this method assumes restored-wetland area and aquifer area carry equal weight to produce hydrologic benefit from wetland and prairie restorations.

Hydrologic-Data Collection

Hydrologic data were collected at sites that composed synoptic water-level and water-quality networks. The synoptic water-level network contained ditch gages, wetland gages, a lake gage, wells that existed before the prerestoration study (pre-existing wells), and wells that were drilled for the prerestoration study (table 4; fig. 3). In total, 49 of the synoptic water-level network wells were completed in surficial aquifers. Data collected from all synoptic sites during a short time are called a synoptic measurement and were intended to represent water at a moment in time in spatial detail. This period was about 2 to 3 days for the synoptic water-level network. Sites selected from the synoptic water-level network composed a continuous-data subnetwork (table 4; fig. 3). Data collected at this subnetwork were intended to document the variability of water levels through time. All surface-water gages and 12 wells were included in the continuous data subnetwork. The wells included in this subnetwork were selected to have even spatial coverage over the study area and to represent recharge, horizontal-flow, and discharge areas. Priority was given to wells open to the surficial aquifer at the water table (10 wells) because those wells are more sensitive to changes in land use. One well (E03) was open to a deeper section of the surficial aquifer (59–69 ft), and two wells (E01D and E04D) were completed in buried aquifers (fig. 3; table 2.1 in appendix 2).

Table 3. Summary of land-use types at the Glacial Ridge study area, northwestern Minnesota, 2002–15.

Land-use code	Land-use description	Broad land-use category
121	Developed/open space	Developed
122	Developed/low intensity	Developed
123	Developed/medium intensity	Developed
124	Developed/high intensity	Developed
131	Barren	Fallow, tame grass, noncrop
152	Shrubland	Fallow, tame grass, noncrop
37	Other hay/nonalfalfa	Fallow, tame grass, noncrop
61	Fallow/idle cropland	Fallow, tame grass, noncrop
59	Sod/grass seed	Fallow, tame grass, noncrop
36	Alfalfa	Fallow, tame grass, noncrop
141	Deciduous forest	Forest
142	Evergreen forest	Forest
143	Mixed forest	Forest
63	Forest	Forest
176	Grasslands: restored prairie, prairie, and grass pasture	Grasslands: restored prairie, prairie, and grass pasture
111	Open water	Open water
1	Corn	Row crop
4	Sorghum	Row crop
5	Soybeans	Row crop
6	Sunflower	Row crop
41	Sugarbeets	Row crop
42	Dry beans	Row crop
43	Potatoes	Row crop
26	Double crop: winter wheat/soybeans	Row crop
224	Vetch	Row crop
44	Other crops	Row crop
29	Millet	Row crop
31	Canola	Small grains
32	Flaxseed	Small grains
21	Barley	Small grains
23	Spring wheat	Small grains
24	Winter wheat	Small grains
27	Rye	Small grains
28	Oats	Small grains
58	Clover/wildflowers	Small grains
87	Wetlands	Wetland

Table 4. Data networks for the Glacial Ridge study, northwestern Minnesota.

[WL, water level; WQ, water quality; min, minute; —, none; WT, water temperature; ST, equipment shelter temperature (unventilated); RF, rainfall]

Site type	Maximum number of sites	Instruments	Continuous data collected	Synoptic WL network[1]	Continuous data subnetwork[1]	Synoptic WQ network[2]	Variability WQ subnetwork[1]	Frequency of continuous data
Ditch gages	7	Pressure transducer	WL	6–7	7/6	6	7/6	15 min
Wetland gages	13	Staff gage	—	12–13	0	7	0	—
Lake gages	1	Staff gage	—	1	0	0	0	—
New wells	36	Pressure transducer, rain gage[3]	WL, WT, ST, RF	33–35/26–36	7	34	7	60 min
Existing wells	46	Pressure transducer, rain gage[3]	WL, WT, ST, RF	33–43/37–38	5	14	5	60 min

[1]Number or range of the number of prerestoration period sites/number or range of the number of postrestoration period sites. A single number means that the number or range of the number of sites during both periods was the same.

[2]Data were collected at the synoptic WQ network only during the prerestoration study and are not discussed in this report.

[3]Only continuous data subnetwork sites were instrumented.

Data-Collection Sites

In total, 35 new wells were installed in surficial aquifers for the prerestoration study during August 2002 (17 wells) and July 2003 (18 wells). Well G39 was installed in September 2004 (fig. 3). Well G26 was removed in June 2012. These wells were constructed of 2-in.-diameter polyvinyl chloride and were open to the surficial aquifers at the water table when drilled. The new wells were distributed evenly across the study area. Construction details of these wells are published in figure 4 and appendix 3 of the prerestoration report (Cowdery and others, 2007).

In total, 21 surface-water gages were established at 7 ditches, 1 lake, and 13 wetlands (fig. 3; table 4). Six of the ditch gages were established in fall 2002. Interpretation of the hydrology of basin SW1 was complicated because the gage on County Ditch 140 (SW1, fig. 3) was downstream from the constructed Burnham Creek Impoundment (fig. 1), which substantially affected ditch flow below it. In fall 2004, a new gage (SW8, fig. 3) was established on County Ditch 140 just upstream from the impoundment. Both gages (SW1 and SW8) on County Ditch 140 ran concurrently until spring 2007 to ensure enough ditch flow data were available to estimate the record of gage SW8 back to fall 2002. Gage SW1 was discontinued in spring 2007. For the purposes of hydrologic analysis on the basin scale, daily flows were estimated at gage SW8 between fall 2002 and fall 2004 using data from gage SW1. Staff gages (WL01–WL12) were installed in 12 wetlands in summer 2003 and operated during 2003–4 and 2011–15. Wetland staff gage WL12 was discontinued in 2004. Wetland staff gage WL13 was installed in 2011 and operated through 2015. A staff gage (SW7) in Maple Lake was installed in April 2014 and operated through 2015.

Groundwater-Level and Precipitation Methods

Hourly groundwater levels, groundwater temperature, and precipitation were collected at wells in the continuous-data subnetwork during 2003–15. Groundwater levels and temperatures were measured with a calibrated submersible pressure transducer. Groundwater temperature was not used in this study and is not further discussed. Water levels in well E04D were often affected by pumping from City of Crookston municipal supply wells. Water levels in well G22S seem to be periodically affected by irrigation pumping from a lower, confined aquifer and by irrigation return flow. Precipitation was summed hourly using an unheated tipping-bucket rain gage at each surficial aquifer well site. The precipitation thus measured is accurate only during nonfreezing periods. Groundwater hydrographs were calibrated semiannually to independent manual water-level measurements accurate to 0.01 ft made with calibrated electric or steel tapes. The methods for calibrating and correcting groundwater hydrographs are documented in USGS quality-assurance plans (Cunningham and Schalk, 2011) and in USGS internal technical memoranda. Precipitation gages were inspected bimonthly and calibrated annually to 0.01 in. using methods documented in USGS numbered (U.S. Geological Survey, 2005) and internal technical memoranda.

Periodic groundwater levels were collected using calibrated electric or steel tapes during 50 synoptic water-level measurements (4 to 11 times per year during 2003–4 and 2012–15), during water sample collection, and to calibrate continuous water-level gages. Synoptic water levels were collected between the months of April and October during the years 2002–5 and 2011–15 by USGS and USFWS personnel. Groundwater levels were measured using standard USGS methods accurate to 0.01 ft (Cunningham and Schalk, 2011). Water levels were entered on electronic field forms. Water-level quality was assured by hydrograph comparison and water-table elevation maps. Once quality assured, the water levels were made available online in the National Water Information System database (available at https://nwis.waterdata.usgs.gov/mn/nwis/gw; U.S. Geological Survey, 2019) and can be accessed using the USGS site numbers provided in table 2.1. The measuring point of all wells was surveyed to 0.01 ft each spring to ensure readings were comparable among years. Adjustments to water levels were applied to correct any measuring point movement.

Surface-Water Level Methods

Quarter-hourly water levels accurate to 0.01 ft were collected at ditch gages, all of which were in the continuous-data subnetwork, during 2003–15. Water level was measured with a nonsubmersible pressure transducer connected to a nitrogen-purge system (Craig, 1983). Rating curves were developed that describe the relation between measured water levels and ditch flows according to USGS protocols (Rantz and others, 1982; Fallon and others, 2002) to provide continuous measurement of ditch flow from water levels. Flows in ditches and water levels at gages were independently measured at least every 6 weeks and the rating curves adjusted or extended as necessary. Flow was measured manually using a Doppler velocity meter or volumetrically at low flow. Summary information about the gaged basins is presented in table 5.

Periodic surface-water levels were collected at all surface-water gages during synoptic water-level measurements and water-quality sampling, and to calibrate continuous ditch gages by USGS and USFWS personnel. Water levels accurate to 0.01 ft were read from staff gages or measured with electric or steel tapes from measuring points above the water surface. Flow measurements were made at the same time in ditches using standard USGS protocols (Rantz and others, 1982; Fallon and others, 2002). The zero points of all wetland and ditch staff gages and measuring points were surveyed to 0.01 ft each spring to ensure readings were comparable among years. Adjustments to water levels were applied to correct any zero or measuring point movement. Once quality assured, the surface-water levels and flows were made available online in the National Water Information System database (available at https://nwis.waterdata.usgs.gov/mn/nwis/sw; U.S. Geological Survey, 2019) and can be accessed using the USGS site numbers provided in table 2.1.

Table 5. Characteristics of ditch basins, Glacial Ridge study area, northwestern Minnesota, 2002 and 2015.

[—, not applicable; mi, mile; mi^2, square mile; MC, main channel; ft/mi, foot per mile; %, percent of total area; Pre, prerestoration (2002), Post, postrestoration (2015)]

Basin name	U.S. Geological Survey streamgage number	Streamgage name
SW2	05079250	County Ditch 65 near Maple Bay, Minnesota (SW2).
SW3	05079200	County Ditch 72 (Burnham Creek) near Maple Bay, Minnesota (SW3).
SW4	05078470	Judicial Ditch 64 near Mentor, Minnesota (SW4).
SW5	05078520	Cyr Creek near Marcoux Corners, Minnesota (SW5).
SW6	05078770	Judicial Ditch 66 near Marcoux Corners, Minnesota (SW6).
SW8	05078720	County Ditch 140 above BR-6 impoundment near Tilden Junction, Minnesota (SW8).
Core area	—	—

Basin name	Drainage area (mi^2)	2002 MC length (mi)	Length of all channels[1] (mi)		MC slope (ft/mi)	Wetland and lake area (%)		Surficial aquifer area (%)
			Pre	Post		Pre	Post	
SW2	9.41	8.39	11.04	7.90	7.39	28	29	63
SW3	11.49	9.86	21.73	11.69	4.77	38	43	49
SW4	8.67	5.59	15.56	7.50	9.12	40	48	67
SW5	11.64	6.95	12.99	9.73	12.94	13	13	36
SW6	15.00	7.17	30.38	7.47	5.72	30	35	57
SW8	8.69	7.61	33.69	1.06	8.8	35	43	48
Core area	64.91	45.57	125.39	45.35	7.85	30	34	53

[1]Includes natural and ditched channels. Excludes abandoned channels during the postrestoration period.

Water-Balance Analysis

Flows in the components of the groundwater and surface-water cycles were calculated for the prerestoration (2003–6) and postrestoration (2012–15) periods using the water-balance method. To facilitate seasonal analyses, seasonal flow totals were first calculated and summed to produce annual flow totals. The winter season spans December of the previous year through February of the current year. In this way, annual totals begin on December 1 of the previous year and end on November 30 of the current year. The following are components of the water budget calculated in this analysis:

- R is areal recharge to surficial aquifers (calculated from hydrographs at 6 wells),
- G is groundwater discharge to ditches (calculated by hydrograph separation at 6 gages),
- ΔS is change in groundwater storage (measured at 58 wells and 16 surface-water sites),
- ET_g is groundwater evapotranspiration (calculated with the SWB model),
- L_g is unmeasured groundwater losses (residual from the water balance),
- P is precipitation (measured at 9 study sites and 6 other sites),
- D is flow out of the basin in ditches (measured at 6 ditch gages),
- ET_s is surface-water evapotranspiration (calculated with the SWB model), and
- L_s is unmeasured surface-water losses (residual from the water balance).

Unlike the water balances calculated in the prerestoration study (Cowdery and others, 2007), ET is explicitly estimated herein. Groundwater and surface-water budgets were calculated for six basins (SW2–SW6 and SW8, fig. 5) in the study area. Groundwater basins were assumed to be coincident with ditch basins. Budgets for these basins were aggregated to produce budgets for the core area (33 percent of the study area).

Surface-water-cycle components directly measured during this study include precipitation and ditch flow (locations in fig. 3). Groundwater-cycle components directly measured include continuous and synoptic groundwater levels (locations in fig. 3). Annual totals of precipitation and recharge calculated from continuous groundwater hydrographs are available during the years between the prerestoration and postrestoration period (2007–11). Ditch flow and the water-cycle components calculated from it (base flow as groundwater discharge, ditch flow, and runoff) are not available during 2007–11. Water-balance equations used in this analysis are detailed in appendix 3.

Precipitation

Precipitation used in water balances was recorded at 16 precipitation stations. Nine stations were operated for this study (Glacial Ridge stations) at the nine continuous groundwater-level recorder sites (fig. 3, excluding site G22). Precipitation data from 1 Natural Resources Conservation (2016) Service Snow Climate Analysis Network (SCAN) station near the center of the study area (fig. 3) and 5 stations maintained by the National Oceanographic and Atmospheric Administration (Menne and others, 2012) National Centers for Environmental Information's Global Historical Climatology Network (GHCN sites at Crookston, Red Lake Falls, Ada, Fosston, and Mahnomen; fig. 1) completed the precipitation data network. Data from the 5 GHCN precipitation stations were included to ensure that the entire study area was covered by the interpolations.

Precipitation in the study area was interpolated from the 16 precipitation stations by inverse-distance-squared to a 60-m (197-ft) grid that covers the study area (fig. 1) because two models (SWB and unit hydrograph) used in analyses of hydrologic change require precipitation in this format. For each day, a precipitation grid was interpolated during water years (the winter season and the water year begins December 1) 2003–15 (the analysis period), and hourly grids were interpolated during periods when ditch flow was modeled (appendix 4, table 4.1). All precipitation data in and around the study area were evaluated for accuracy and completeness and ranked on those bases.

The original daily total precipitation data from the nine Glacial Ridge stations and the SCAN station were adjusted to augment recorded rainfall during the freezing part of the year and to fill missing data. The rain gages at the Glacial Ridge stations were unheated, so precipitation data during late November through late March are unreliable in amount and timing.

To estimate the amount of precipitation lost during these freezing periods, average precipitation totals for each season during 2002–15 were compared to the average seasonal total of Daymet precipitation (Thornton and others, 2014) at the Daymet grid cells containing each Glacial Ridge rain gage. Daymet precipitation data are a 1-kilometer (km; 0.62-mi) gridded interpolation of daily precipitation for North America. The input data for Daymet are from the National Oceanographic and Atmospheric Administration National Centers for Environmental Information's Global Historical Climatology Network (GHCN) daily dataset from version 3.22 of the data distribution (Menne and others, 2012).

During the winter (December–February), precipitation recorded at the nine Glacial Ridge stations was 78 percent lower than the Daymet data (0.42 and 1.94 in., respectively). Each winter daily-precipitation total measured at Glacial Ridge stations was multiplied by 4.62 to produce a precipitation estimate equivalent to the Daymet data and to account for the winter precipitation lost from the unheated study rain gages. These augmented daily-precipitation totals were then summed into winter totals for each year. Because of the aggregated nature of this analysis, estimates of winter precipitation are only valid if aggregated into seasonal totals and cannot be used as actual measurements of total daily precipitation during the winter season.

Only 9 percent of average annual precipitation fell during the winter during 2002–14 (Menne and others, 2012), resulting in winter losses in precipitation at the unheated study rain gages of only 7.7 percent of average annual precipitation (about 1.5 in.). The losses at individual rain gages in individual winters were highly variable. Augmented winter precipitation differed from measured precipitation by a maximum of 3.43 in. (20.1 percent of annual precipitation) at gage G20S during 2014 to a minimum of −0.43 in. (−2.6 percent of annual precipitation) at gage G25 during 2007. The negative loss indicates that more precipitation fell at the gage G25 than was interpolated in the Daymet data during winter 2007. All other differences were positive. Because the winter precipitation from study gages is estimated, water-cycle flows in the winter were not computed because they are much less reliable than other seasons and likely are not valid.

Precipitation data missing from the Glacial Ridge or SCAN stations were replaced with the data from the nearest of the four nearest Glacial Ridge or SCAN stations that had data for the missing period. If all four of the nearest stations had missing data, the precipitation value from the Daymet precipitation grid that contains the station was substituted. Missing data at the GHCN stations were filled with data from the Daymet grid that contains the site. This process produced complete daily precipitation datasets for each precipitation station during the analysis period.

Daily total precipitation from the 15 precipitation stations was interpolated by inverse-distance squared to produce a grid of precipitation over the study area for each day of the analysis period. Likewise, hourly total precipitation from the 15 precipitation stations was used to produce hourly grids during selected periods of storm analysis. The daily precipitation grids were aggregated to produce seasonal total precipitation grids, and seasonal grids were aggregated to produce annual total precipitation grids. Finally, the aggregated total seasonal and annual precipitation grids were intersected with the areas of each ditch basin to produce annual and seasonal total precipitation for each basin. Only grid cells that completely fell within a ditch basin were aggregated to produce seasonal and annual totals for a basin. The area of each basin computed using these grids was used throughout the water-balance analysis. Precipitation data are available as a USGS data release (Roth and others, 2019).

Recharge

Recharge to surficial aquifers was calculated using the water-table fluctuation method (Healy and Cook, 2002; Lorenz and Delin, 2007) from daily groundwater levels at 10 surficial-aquifer wells throughout the Glacial Ridge study area. The DVStats package (Lorenz, 2016) was used in the R statistical environment (version 3.2.3; Venables and Others, 2010) for the calculation, modeling antecedent groundwater-level recession as a logarithmic-linear regression. A single porosity of 0.25 was used in water-table fluctuation calculations for all surficial aquifers in the study area (Fetter, 1998). The DVStats package requires complete daily groundwater level data. Missing data from E01S were estimated using hydrographs from nearby wells.

Rather than using average daily water levels directly to calculate recharge with the DVStats package, 3-day minimum daily water levels were used to remove minor water-level oscillations. In the study area, water-level oscillations of 1–2 days in frequency and less than 0.1 ft in amplitude can occur throughout the year but primarily occur in winter months at times of very low levels. Winter oscillations likely are unrelated to recharge because the ground is frozen and areal recharge is impossible. Most oscillations likely are produced by temporarily confined conditions from frozen ground.

Daily recharge at each well was aggregated into seasons. Recharge at wells G01 and G15 was not included in the water-balance analysis because it was affected by focused recharge and water-table ET from adjacent wetlands. Recharge from well G22 also was not included because it was affected by agricultural irrigation. Thiessen polygons for six of the seven remaining wells were contained inside the ditch basins used in the water-balance analysis. Seasonal recharge for each well was multiplied by the polygon area that intersected the surficial aquifer area in each ditch basin to produce a seasonal groundwater recharge volume. Seasonal recharge volumes were aggregated into annual recharge volumes for each basin. Surficial aquifer areas were defined in the prerestoration hydrologic study (Cowdery and others, 2007). Surficial aquifer areas were defined as areas having coarse-grained soils in the "parent group material" class of the gSSURGO soil survey data (Soil Survey Staff, 2015b). A complete list of these parent group material classes is shown in appendix 1.

Ditch Flow

Annual ditch flow was calculated from daily ditch flow computed at six ditch gages from continuous ditch flow. Flow records were generally complete for all sites for prerestoration and postrestoration water years. Gaging at SW8 began in 2005, so ditch flow during 2003–4 was estimated from the hydrograph of the downstream gage SW1. Flow was estimated at gage SW8 by calculating an average multiplication factor for low, mid, and high flow periods in the overlapping record of gages SW1 and SW8. The appropriate factor was applied to flow at gage SW1 to produce flow at gage SW8 where it was missing. Ditch flow measurement ended at some sites before the end of the 2015. Daily ditch flow from October–November 2015 at gages SW2, SW5, SW6, and SW8 was estimated from hydrographs of SW4 and SW3. Ditch flow during this period accounts for less than 5 percent of total ditch flow for water year 2015 at all six gages.

Groundwater Discharge to Streams (Base Flow)

Base flow at the six gaged ditches in the study area was estimated from daily average ditch flow using the base-flow index (standard) method (Wahl and Wahl, 1995) incorporated in the USGS Groundwater Toolbox (Barlow and others, 2015). By default, the base-flow index standard method uses an *N*-value of 5 days, but Glacial Ridge ditch hydrographs produced the most reasonable base flow with an *N*-value of 3 days (*N* is the length, in days, of the window used to calculate flow minima). These minima are then used to determine base-flow turning points.

Groundwater Storage

Changes in storage in surficial aquifers were calculated annually as the volumetric difference of consecutive October water-table surfaces (fig. 6, for example). The difference was calculated by subtracting the grid of an earlier water-table elevation surface from a later one using the ArcGIS "Raster Math" toolset (Esri, variously dated). The resulting difference grid was summed over the area of each ditch basin using the ArcGIS "Zonal Statistics" tool. This aquifer volume was multiplied by the aquifer specific storage, which was assumed to be 0.25 to produce the volume of groundwater gained or lost between synoptic measurements. October water-table surfaces for water years 2002–6 and 2011–15 were created from water levels measured in surficial aquifers using a water-table interpolation tool developed during this study. Some water levels in the synoptic data for 2002, 2005, 2006, 2012, and 2013 are missing and were estimated from continuous hydrographs, synoptic water levels, and annual water-level changes in nearby wells with similar hydrographs and hydrologic settings. The greater than 10-year record of water levels at most wells provided adequate resolution to compare hydrographs and accurately estimate missing periodic water levels. In this way, each annual water-table surface is interpolated from the same points.

The water-table interpolation tool was developed using ArcGIS model-builder (Esri, variously dated) to automatically and reproducibly interpolate water-table grids and maps from water-level measurements. If the locations of all water levels are the same in two synoptic measurements, reliable groundwater-storage change maps can be calculated from the difference between water-table elevation maps and the aquifer porosity. These maps also can be used to check the quality of measured water levels by subtracting subsequent water-table maps. Questionable water levels are identified as high or low differences and can then be further scrutinized. Ditch and lake levels are incorporated into the tool by assigning a corresponding section of ditch or a lake or wetland boundary (a hydrographic feature) to each measured water level. The hydrographic feature then is reduced to a set of points used in the water-table interpolation. The elevation of the hydrographic feature points was adjusted by an amount such that the elevation of the measuring location matches the measured water level.

In this analysis, land-surface elevations along these features were extracted to feature points at 500–800-m (1,640–2,625-ft) intervals from light detection and ranging (lidar) altimetry data (Minnesota Department of Natural Resources and Minnesota Geospatial Information Office, 2011). All feature point elevations were adjusted by the same amount so that the feature point nearest the location of the measured water level matched that water level. The surface elevation for Maple Lake feature points was fixed at the lidar elevation during 2003–13 because no water levels were measured until 2014. Thereafter, the elevation of the Maple Lake feature points was adjusted to match the measured water level. Wetland water levels are incorporated as simple points, like groundwater levels. To interpolate a water table that covers the core area, synoptic water levels were augmented with fixed groundwater levels outside the core area (about 1.5–5 mi from the core area boundary, called far-field groundwater sites). These groundwater levels were taken from water-table wells in the Minnesota Well Index water well database (Minnesota Department of Health and Minnesota Geological Survey, 2014).

Points representing the water-level elevation of adjusted and fixed hydrologic features, wetlands, measured groundwater sites, and far-field groundwater sites were combined to produce the final dataset for interpolation. This method produces a relatively high ratio of surface water to groundwater elevation points. This is appropriate when interpolating a water table because flow in shallow aquifers is largely driven by the elevation of surface waters. These data were interpolated using the natural neighbor method to create 30-m (98-ft) gridded synoptic water-table maps that cover the core area.

Evapotranspiration

Additional detail was added to the SWB model of Minnesota (Smith and Westenbroek, 2015, Westenbroek and others, 2010), and the model was extended through 2015 in the study area to estimate the ET component of the water cycle, which was not directly measured in this study (Roth and others, 2019). By modeling ET, the residual term in the water balances is small and composed mainly of measurement errors and unmeasured flows. The SWB model uses grids of daily precipitation and air temperature, land cover/land use, hydrologic soil type, and antecedent soil conditions to calculate daily recharge, runoff, rejected recharge, and ET. Rejected recharge is the amount of daily water that cannot infiltrate into the ground but also did not run off the land surface. It can be thought of as water that ponds on the land surface but cannot infiltrate within the daily timestep of the SWB model. Rejected recharge is lost from the SWB model but likely would recharge an aquifer in the real world. Smith

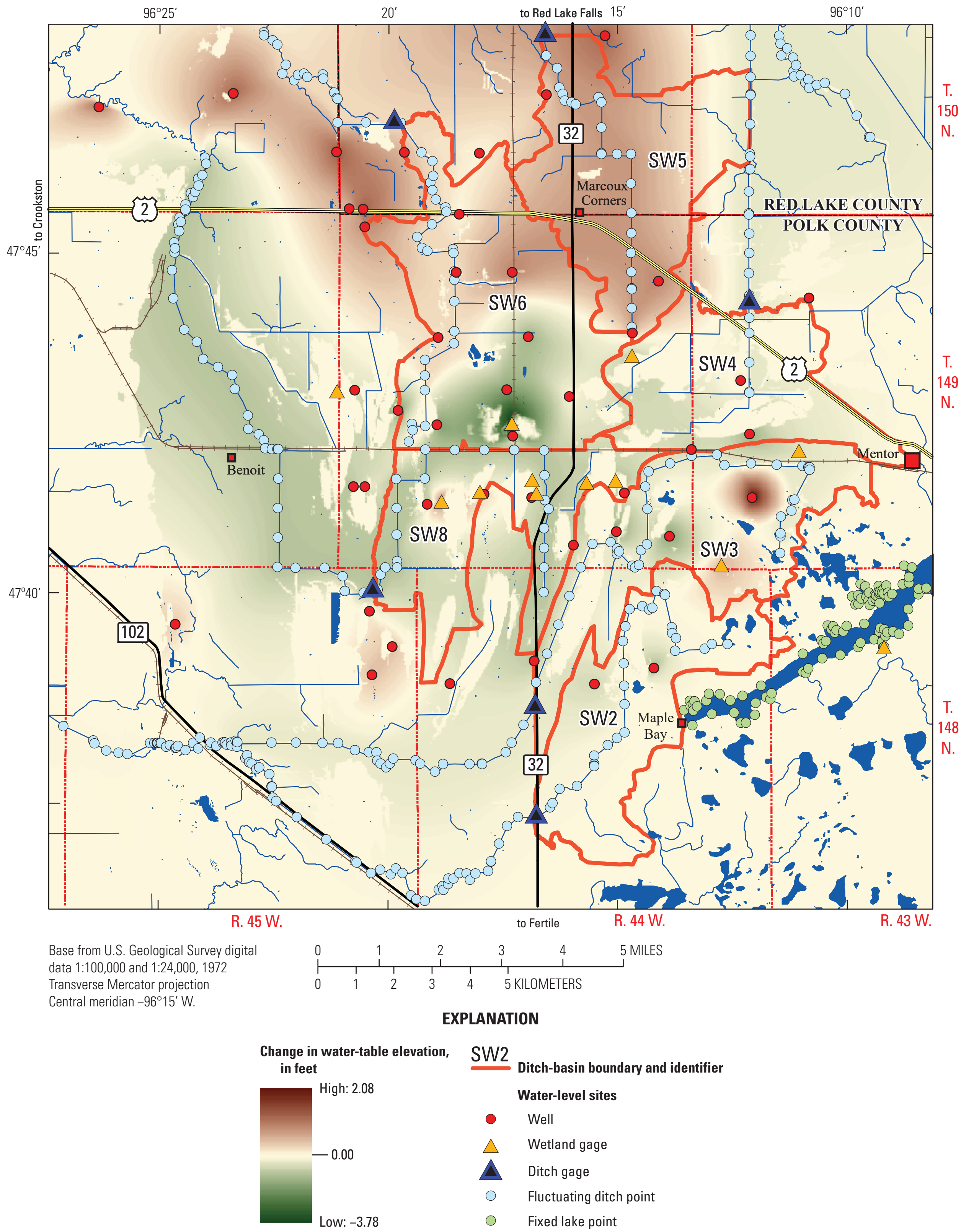


Figure 6. Change in water-table surface between October 2014 and October 2015, Glacial Ridge study area, northwestern Minnesota.

and Westenbroek's SWB model produced water-cycle flows for water years 2002–15 for the Glacial Ridge study area. The Glacial Ridge SWB model differs from the Statewide model in its finer resolution (60-m [197-ft] rather than 1-km [0.62-mi] grids) and more detailed precipitation, land use, and soil-property grids.

The same daily precipitation grids used to calculate total precipitation for the water balances were used in the SWB model. The same 1-km (0.62-mi) Daymet daily air temperature grids (Thornton and others, 2014) that were used in Smith and Westenbroek's statewide SWB model were used in the Glacial Ridge SWB model. The 60-m (197-ft) annual land-cover grids compiled for this study were used in the model (see the "Land-Use and Landscape Data" section for details).

The SWB model requires two lookup tables to populate model cells with soil properties and land-cover characteristics. The first table provides curve number, maximum recharge rate (in inches per day), and root-zone depth (in feet) for each combination of 35 land-cover classes and 4 soil classes. This table was adapted from the statewide SWB model (Smith and Westenbroek, 2015) by assigning each of the Glacial Ridge land cover and soil class combinations to a statewide SWB model land cover and soil class combination. The second table contains extended Thornthwaite-Mather soil-water retention curve information (Thornthwaite and Mather, 1957). No changes were made to the statewide SWB model Thornthwaite-Mather soil-water retention table. The more detailed available water capacity grid was derived from the gSSURGO database (Soil Survey Staff, 2015a) in the same way it was for the statewide SWB model.

The Glacial Ridge SWB model was not calibrated separately. This model merely adds detail through a finer grid and more accurate precipitation, land-use, and soil-property data. The calibrated parameters for the statewide and Glacial Ridge SWB models are identical. As in the statewide model, runoff routing was not implemented in the Glacial Ridge SWB model because it was not needed to calculate ET and was difficult to incorporate in an area like Glacial Ridge that contains a myriad of closed subbasins. Any SWB flow that directly depends on routing (recharge, runoff, and rejected recharge) is not accurate.

Only the ET component of the SWB model results was used in the water balances. Other components of SWB model results did not compare well with measured values, most likely because runoff routing could not be accurately represented in the model. The SWB model provides a calculation of total ET. This amount needed to be split between the ET components of the groundwater and surface-water water balances. In this report, groundwater ET is defined as that part of groundwater flow that evaporates from the water table (true groundwater ET) and groundwater that discharges to surface waters but does not leave a basin by ditch flow. By this definition, groundwater ET is actually a mixture of groundwater and surface-water processes. Although the water table in the study area is very shallow, under this definition, nearly all groundwater ET is groundwater discharging to lakes and wetlands that do not flow to ditches (closed subbasins). This water ends up leaving the study area through ET from these closed subbasins.

Surface-water ET is defined as water that leaves the basin by ET from the soil and from surface-water bodies that flow to ditches. By this definition, surface-water ET includes ET from soil, runoff, ditch channels, and from some lakes and wetlands. To apportion SWB model total ET to groundwater and surface-water ET, the residuals of preliminary water balances first were calculated without the SWB ET component. These residuals of these balances were large because ET was included in the residuals. Next, measurement error and unmeasured flows were assumed to be zero so that the residuals of the preliminary balances were assumed to be composed entirely of ET. This assumption is reasonable because ET composes such a large part of the groundwater and surface-water balances. The SWB model total ET was apportioned to groundwater and surface-water ET based on the relative size of the residual term in these preliminary water balances. Final water balances were calculated by including apportioned SWB-calculated ET. The residual terms in the final balances were small because they contain primarily measurement errors and unmeasured flows.

Unit-Hydrograph Analysis

A unit hydrograph is defined as the timewise distribution of 1 in. of surface runoff from a given drainage area for a rainfall duration (Roberson and others, 1988). In the prerestoration study (Cowdery and others, 2007), unit hydrographs were used to characterize relations among precipitation, basin characteristics, and ditch flow in gaged ditch basins within the study area. In this study, postrestoration unit-hydrograph models were used to determine how restoration activities affected relations among precipitation, basin characteristics, and ditch flow. Unit-hydrograph analyses provide a standardized method for comparing prerestoration and postrestoration hydrographs, but comparisons of hydrograph results are complicated by variability in seasons, antecedent moisture conditions, and the direction, intensity, and duration of storms (Roberson and others, 1988).

Unit-hydrograph analyses were completed for selected storms from prerestoration and postrestoration periods to assess whether ditch-flow response to precipitation changed because of restorations. Storms analyzed for the prerestoration period occurred from 2003 to 2005, and storms analyzed for the postrestoration period occurred from 2013 to 2015. Storms from both restoration periods with more than 1.0 in. of rainfall were selected for analysis (rainfall data available from Roth and others, 2019). During the prerestoration period, 35 storm-runoff hydrographs were analyzed, including 18 storm-runoff hydrographs (3 storms each for 6 ditch flow gages) analyzed in the original study (Cowdery and others, 2007) and 17 additional hydrographs from storms that were not previously analyzed. During the postrestoration period, 30 storm-runoff hydrographs were analyzed.

Excess rainfall was transformed into direct runoff for selected storms in each of the six ditch basins using the Clark unit-hydrograph method (Clark, 1945) in the U.S. Army Corps of Engineers Hydrologic Engineering Center's Hydrologic Modeling System (HEC–HMS, version 4.0; Feldman, 2000; U.S. Army Corps of Engineers, 2013). Runoff-model methods were like those used by Cowdery and others (2007). However, in this study, gridded precipitation data mentioned earlier in the "Precipitation" section were used in place of the Thiessen polygon method (Linsley and others, 1982; Cowdery and others, 2007, Roth and others, 2019) to partition measured precipitation among the six ditch basins. Prerestoration storms that were used to simulate runoff previously (Cowdery and others, 2007) were not re-analyzed using the gridded precipitation data. Additionally, results from 18 prerestoration storms not analyzed in the previous study were combined with storms previously analyzed for comparisons to postrestoration runoff models.

Data needed for HEC–HMS included ditch-basin area, gridded precipitation, measured ditch flows from ditch-basin outlet gages, and initial estimates of model variables. Gridded precipitation data were calculated from totals recorded at 60-minute intervals, and ditch flows were obtained at 15-minute intervals using stage-discharge relations developed from physical measurements of streamflow and stage (Rantz and others, 1982). Model variables include initial loss (in inches), constant loss rate (in inches per hour), time of concentration (in hours), Clark storage coefficient (in hours), initial ditch flow (in cubic feet per second), recession constant (unitless), and recession threshold (in cubic feet per second). Initial estimates of model variables for each storm and ditch basin were obtained by examining recorded hydrographs. Ditch basins were assumed to have no impervious area in all models.

Definitions of input variables used in unit-hydrograph models run in HEC–HMS are included in Cowdery and others (2007) but are repeated here for ease of interpretation by the reader. Initial loss is the amount of precipitation initially intercepted by the landscape that infiltrates the soil before runoff. Constant loss rate is the rate at which precipitation infiltrates the soils. Time of concentration is the maximum time required for water to travel as surface runoff from anywhere in the basin to the outlet, assuming no storage. Clark storage coefficient describes the effects of all storage within a basin. Initial ditch flow is the flow before an increase in flow caused by rainfall runoff. Initial ditch flow is assumed to consist entirely of base flow. Recession constant is the rate of base-flow decrease, and recession threshold is the flow at which groundwater base flow replaces overland flow as the source of water leaving the basin through the ditches.

Clark unit-hydrograph models of ditch hydrograph response to storms were optimized iteratively using the HEC–HMS modeling software to adjust initial model variables (U.S. Army Corps of Engineers, 2013). The software produced comparison plots and tables of simulated and measured runoff volume, peak ditch flow, time of peak, and time of center of mass to assess further how closely the hydrographs match. Optimized model variables from prerestoration and postrestoration storms then were compared to assess whether wetland and prairie restoration and landscape characteristics correlate with changes in storm hydrograph response in the study area. Peak-weighted root mean square error and Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970) values were used to quantify how well the computed hydrographs match the measured hydrographs. The NSE is a normalized statistic that is used to indicate how well simulated data match observed data. When the NSE is equal to 1, the simulated data match the observed data perfectly. When the NSE is equal to 0, the simulated data are as accurate as the average of the observed data. Finally, when the NSE is less than 0, the observed average is a better estimator than the model.

Optimized variables and selected results for each modeled storm were categorized by restoration period and ditch gage (table 4.1 in appendix 4). However, differences in storm characteristics (intensity, duration, and volume) and antecedent conditions complicate comparisons of prerestoration and postrestoration storms. To enhance comparability, data were normalized to either total precipitation or initial ditch flow. Variables that related most to landscape characteristics were normalized by dividing values by the total precipitation (in inches) of the storm and include time of concentration, Clark storage coefficient, initial loss, excess precipitation (in inches), constant loss rate, and initial ditch flow. Variables that related most to antecedent conditions were normalized by dividing the values by the initial ditch flow of the storm and include peak ditch flow (in cubic feet per second), recession threshold, and recession constant.

The model results from all ditches initially were pooled to calculate median values of model variables for prerestoration and postrestoration periods to reduce the high variability caused by differences in storm characteristics and antecedent conditions. All normalized model variables were plotted on a logarithmic scale to illustrate distributions of data for several variables in a single graph for prerestoration and postrestoration periods. Variable distributions from both restoration periods were compared using Tukey box plots created using the "smwrGraphs" package (Lorenz and Diekoff, 2017).

In addition, time-series plots of selected hydrographs are presented for visual comparisons of storms from both restoration periods. Tables of several model variables for paired prerestoration- and postrestoration-period storms facilitate further comparisons. The paired comparisons consist of modeled hydrographs from prerestoration and postrestoration storms in the same basin. To illustrate prerestoration and postrestoration differences, four storm pairs were selected that had (1) similar precipitation amounts at a similar time of the year, (2) similar precipitation amounts at different times of the year, (3) different precipitation amounts at a similar time of the year, and (4) different precipitation amounts at different times of the year. Selected modeled hydrograph comparisons do not account for differences in antecedent conditions.

During this study, the gage measuring flow in County Ditch 140 changed from gage SW1 to gage SW8 to eliminate the hydrologic complication of flow through the Burnham Creek Impoundment (figs. 1 and 3). Therefore, ditch flow is not available at gage SW8 for the three storms modeled in Cowdery and others (2007), and prerestoration storm-runoff behavior in basin SW8 is not as easily comparable as it is in other ditch basins. However, three storms during the prerestoration period were compared to three storms during the postrestoration period in basin SW8 (table 4.1 in appendix 4).

Water-Quality Data Collection

Water samples continued to be collected during the postrestoration period from the variability water-quality subnetwork (table 4; fig. 5) that was established during the prerestoration study (Cowdery and others, 2007). Care was taken to use the same sampling and quality-control methods and to use the same USGS laboratory and analytical methods for the same constituents during both restoration periods. Sites in the variability water-quality subnetwork were selected from the synoptic water-quality network, which was not sampled during the postrestoration period. Data collected in the variability water-quality subnetwork were intended to document the variability of water quality through time. All active surface-water gages and 12 wells were included in this subnetwork. The wells included were selected to have the full range of land uses and water quality in the study area. Priority was given to wells open to the surficial aquifer at the water table (9 wells) because such wells are more sensitive to changes in land use. One well (E03) was open to a deeper section of the surficial aquifer (59–69 ft). The remaining two wells were open to buried confined aquifers (E01D and E02D), with E01D being a flowing well. The variability water-quality subnetwork and the continuous-data subnetwork shared 7 of their 12 wells: E01S, E01D, E03, G01, G08, G15, and G22S.

Water-quality samples were collected two to six times per year during the nonfreezing period of the prerestoration and postrestoration periods from sites in the variability water-quality subnetwork (table 4). This subnetwork was sampled 17 times during April–October of 2003–6 and 15 times during April–October of 2012–15. All sites could not be sampled during each sampling event because some wells or ditches were dry. Samples were not weighted to produce prerestoration and postrestoration datasets that were more comparable in terms of sampling time, site, or sampling event number. In some cases, ponded ditch water was sampled even though there was no flow. These samples were excluded from all analyses because of the possibility of chemical and biological changes in water quality in stagnant pools.

Sampling procedures and variability water-quality network constituents analyzed were the same during prerestoration and postrestoration periods. Herbicide, water-isotope, and age-dating samples were not collected during the postrestoration period. Well water was collected using low-flow methods after purging with a peristaltic pump until physical properties (temperature, pH, specific conductivity, dissolved oxygen, and turbidity) of the water stabilized. Physical properties and the alkalinity concentration of the water were measured and sample bottles filled at all sites. Bicarbonate and carbonate concentrations were modeled from alkalinity concentration, temperature, and specific conductance (U.S. Geological Survey, 2012). Ditch water was collected using an equal-width increment, isokinetic vertical-transit sampling method to produce a flow-weighted sample. If ditch flow was too small for this method, a peristaltic pump was used to collect water from the center of flow. After sampling, all equipment that touched water was washed with nonphosphate detergent, rinsed with single-source tap water, and rinsed with deionized water. Details about sampling and decontamination procedures are in the USGS “National Field Manual for the Collection of Water-Quality Data” (U.S. Geological Survey, variously dated), as amended at the time of sampling and in the prerestoration Glacial Ridge report, appendix 3 (Cowdery and others, 2007). All samples were analyzed by the USGS National Water Quality Laboratory (NWQL) for various forms of nitrogen and phosphorus nutrients. Nutrients in groundwater samples were analyzed using NWQL schedule 2752 (dissolved nutrients) and in ditch water were analyzed using NWQL schedule 2702 (dissolved and particulate nutrients; Fishman, 1993). Ditch water also was analyzed for suspended sediment at the USGS Iowa Sediment Laboratory (Guy, 1969; American Society for Testing and Materials [ASTM], 2000). Prerestoration and postrestoration water-quality data are available in the National Water Information System database (available at https://nwis.waterdata.usgs.gov/mn/nwis/qwdata; U.S. Geological Survey, 2019) using the USGS site numbers provided in table 2.1 in appendix 2.

In many cases analytical methods at the NWQL improved between the analysis periods resulting in multiple reporting levels for many constituents. Log regression on order statistics (Helsel, 2012) was used to estimate concentrations below the detection limit so that descriptive statistics (average, median, standard deviation, and so on) could be calculated from data with multiple reporting levels. The statistical significance of differences between prerestoration and postrestoration water-quality data statistics was calculated using the nonparametric Wilcoxon rank sum test (as implemented in R statistical environment, version 3.2.3; Venables and others, 2010) and is reported with *p*-values. In this report, a test result is considered significant when a *p*-value is less than 0.05.

Some nutrient concentrations (for example, dissolved nitrate plus nitrate) are reported as the sum of several constituents. The concentration of other constituents (for example, nitrite) is reported individually, allowing the calculation of nonanalyzed constituents (for example, nitrate) from the summed constituents by subtraction. In these calculations, the concentration of any individual constituent reported as less than the reporting level was set to zero. If the result of this calculation was less than zero, that concentration was set to zero. Two groundwater samples were excluded from all analyses because this calculation resulted in a very unrealistic concentration (a negative organic nitrogen concentration that was more than 5 percent of the original measured nitrogen sum).

The postrestoration dataset consisted of 176 groundwater and 102 ditch-water samples, whereas the prerestoration dataset consisted of 178 groundwater and 154 ditch-water samples. Of the groundwater samples, only 153 prerestoration samples and 146 postrestoration samples from wells completed in surficial aquifers (excluding samples from wells E01D and E02D) were compared to evaluate the effects of restorations.

Sample Variability

A total of 678 water samples was collected and analyzed during both restoration periods. Of these, 68 were quality-control samples representing 11 percent of the environmental samples collected. The results of all 610 environmental samples were compared as a group and in subsets of samples from the same site to assess whether gross errors were made in bottle labeling or sample analysis. No gross errors were made.

Sequential duplicate samples quantify the variability of the source water being sampled and the variability introduced by the sampling and analysis processes. Groundwater and ditch-water duplicate samples were collected sequentially during the postrestoration period. Ditch-water duplicate samples collected during the prerestoration period only were split from a single sampling volume and, therefore, are only capable of showing variability from the analyzing process. During the prerestoration period, 14 groundwater and 7 ditch-water duplicate samples were collected. During the postrestoration period, 7 groundwater and 8 ditch-water duplicate samples were collected. The absolute relative percent difference (ARD) calculated for all constituents in all duplicate samples is defined as:

$$\frac{|DC - EC|}{(DC + EC)/2} \times 100$$

where

DC is the duplicate sample concentration, and

EC is the environmental sample concentration.

The maximum ARD for all field measurements except carbonate concentration, turbidity, and dissolved oxygen concentration (in one sample) was less than 8 percent, indicating good reproducibility. The ARD for carbonate concentrations was high because the concentrations were low (maximum of 10 milligrams per liter [mg/L] as calcium carbonate). The maximum ARD for turbidity, suspended sediment, and most nutrient constituents was above 15 percent, indicating high variability in at least one duplicate sample (table 6). Most of these high-variability samples had concentrations that were at or below the constituent reporting level, however. Small variability in samples with low concentrations can produce artificially high ARD values. Excluding these low-concentration samples, the only constituents that had ARD values greater than 33 percent in more than one duplicate sample were turbidity, suspended sediment, and unfiltered phosphorus. Variability in suspended sediment was high in prerestoration and postrestoration duplicate samples. Sediment in ditch flow is particularly variable, and the high ARDs of concentrations from the postrestoration period for turbidity, suspended sediment, and unfiltered phosphorus reflect this variability. Phosphorus has low solubility and tends to sorb to sediment (Hem, 1989). High variability of suspended sediment and unfiltered phosphorus concentrations probably relates to the variability of sediment in ditch water itself rather than from the sampling technique because constituents not related to sediment did not indicate high variability.

Sample Contamination

Field-blank samples document the effectiveness of sampling decontamination procedures and quantify minimum valid concentrations. Blank samples indicated that decontamination procedures were generally successful and that contamination does not invalidate comparisons of water quality between the restoration periods. Blank samples were collected in the field by passing water known not to contain constituents of interest (blank water) through sampling equipment in the same manner as environmental samples. As a worst-case scenario, blank samples were often collected immediately after sampling sites known to have high concentrations of analyzed constituents. During the prerestoration period, six groundwater and nine ditch-water blank samples were collected. During the postrestoration period, seven groundwater and eight ditch-water blank samples were collected.

The only field measurements for which blank samples are relevant are specific conductance, alkalinity (and, by extension, bicarbonate and carbonate concentrations), and turbidity. Blank water specific conductance and alkalinity were all less than 2 percent of the previous environmental sample measurement and never exceeded 6 microseimens per centimeter at 25 degrees Celsius (µS/cm at 25°C) for specific conductance and 8 mg/L as calcium carbonate for alkalinity. Concentrations in blank samples were more than eight times lower than the lowest environmental measurement, indicating that contamination did not affect these measurements. All but three turbidity concentrations in blank samples were less than 0.5 nephelometric turbidity unit. The greatest blank sample turbidity was 4 nephelometric turbidity units, indicating that turbidity was an unreliable measurement for most (120 of 141 samples, using a threshold of 3 times the highest blank sample value) environmental samples. Turbidity measurements will not be discussed further in this report.

Concentrations for all constituents for all blank samples were below the laboratory reporting level (RL), which is the concentration at which the false negative error rate is minimized to be no more than 1 percent of the reported results (Childress and others, 1999), except for filtered ammonia plus organic nitrogen, filtered ammonia, filtered nitrate plus nitrite, filtered total phosphorus, and suspended-sediment

Table 6. Duplicate sample absolute relative percent differences, Glacial Ridge study area, northwestern Minnesota, 2003–15.

[Differences calculated only for samples with concentrations greater than five times the analytical reporting limit. mg/L, milligram per liter; N, nitrogen; P, phosphorus; GW, groundwater; %, percent; SW, surface-water; —, no duplicate samples; NA, no samples greater than five times the analytical reporting limit; yellow cells, absolute relative percent difference is greater than 10%; grey cells, only one duplicate sample]

Parameter	Constituent									
	Suspended sediment	Ammonia, filtered	Ammonia plus organic nitrogen, filtered	Nitrate plus nitrite, filtered	Nitrite, filtered	Total nitrogen, filtered[1]	Ortho-phosphate, filtered	Phosphorus, filtered	Ammonia plus organic nitrogen, unfiltered	Phosphorus, unfiltered
Parameter number[2]	80154	00608	00623	00631	00613	62854	00671	00666	00625	00665
Unit	mg/L	mg/L as N	mg/L as N	mg/L as N	mg/L as N	mg/L as N	mg/L as P	mg/L as P	mg/L as N	mg/L as P
Reporting limit										
Prerestoration period	1	0.04–0.02	0.07	0.06	0.008	0.1	0.02–0.006	0.003	0.07	0.004
Postrestoration period	1	0.01	0.07	0.04	0.001	0.1	0.02–0.004	0.003	0.07	0.004
GW average										
Prerestoration period	—	3%	3%	3%	7%	2%	5%	7%	—	—
Postrestoration period	—	3%	—	1%	3%	2%	4%	4%	—	—
GW maximum										
Prerestoration period	—	3%	7%	13%	30%	12%	5%	11%	—	—
Postrestoration period	—	3%	—	4%	3%	3%	5%	7%	—	—
SW average										
Prerestoration period	9%	5%	2%	1%	NA	1%	NA	2%	1%	3%
Postrestoration period	31%	23%	3%	1%	4%	2%	NA	4%	2%	5%
SW maximum										
Prerestoration period	9%	5%	8%	1%	NA	1%	NA	3%	3%	11%
Postrestoration period	92%	38%	8%	1%	4%	8%	NA	7%	7%	21%

[1]Calculated from ammonia plus organic nitrogen and nitrate plus nitrite for the first four prerestoration GW duplicate samples.

[2]U.S. Geological Survey National Water Information System parameter number.

concentrations. Contamination in these constituents was small and did not affect the analyses that compared water quality before and after restorations. Analyses for each of these constituents are detailed in appendix 5.

General Hydrology of the Glacial Ridge Study Area

Water is present within the study area on the land surface, in surficial aquifers, and in buried aquifers. Surficial aquifers are exposed at the land surface. Buried aquifers are overlain by confining beds (till of lake clays) that are about 50 to several hundred feet thick. Most water flow within the study area is shallow, present as surface water and groundwater within thin surficial aquifers.

The structure and characteristics of the aquifers and confining beds within the study area are a product of the history of glacial advance, retreat, and lake formation that created them. The postglacial formation of the surface-water system and its subsequent substantial human modification control the flow of nearly all water within and near the study area. Water flow in surficial aquifers and in ditch basins forms a single hydrologic system. Within the study area, precipitation and the land-surface elevation drive the water flow, which moves through surface-water bodies and surficial aquifers and leaves the study area primarily as ET and ditch outflow.

Hydrogeology

The surficial aquifers in the study area were formed from the former beaches of glacial Lake Agassiz (fig. 2), an enormous glacial meltwater lake that occupied the central part of the Red River of the North Basin during 13,800–8,440 years ago (Fenton and others, 1983, p. 69–70). The beach-ridge aquifers are thin, narrow, and long sand and gravel deposits. The aquifers generally are distinct but merge with each other in places, particularly in the southern part of the study area. Flow in surficial aquifers may extend a few feet into underlying confining beds (coarser-grained wave-modified till, fig. 7) but is slower than in aquifers. Horizontal flow in all aquifers is radial from the Maple Lake area (fig. 1) in the southeastern part of the study area, following the downhill direction of the topography toward the Red Lake River to the north and northwest, and toward the Red River of the North in the center of the Lake Agassiz Basin to the west (Cowdery and others, 2007, fig. 10). These directions are generally perpendicular to the trend of the beach-ridge aquifers. Flow in the surficial aquifers is closely connected to the adjoining wetlands upgradient and downgradient, to the beach ridges, and to ditches where they cut through the surficial aquifers.

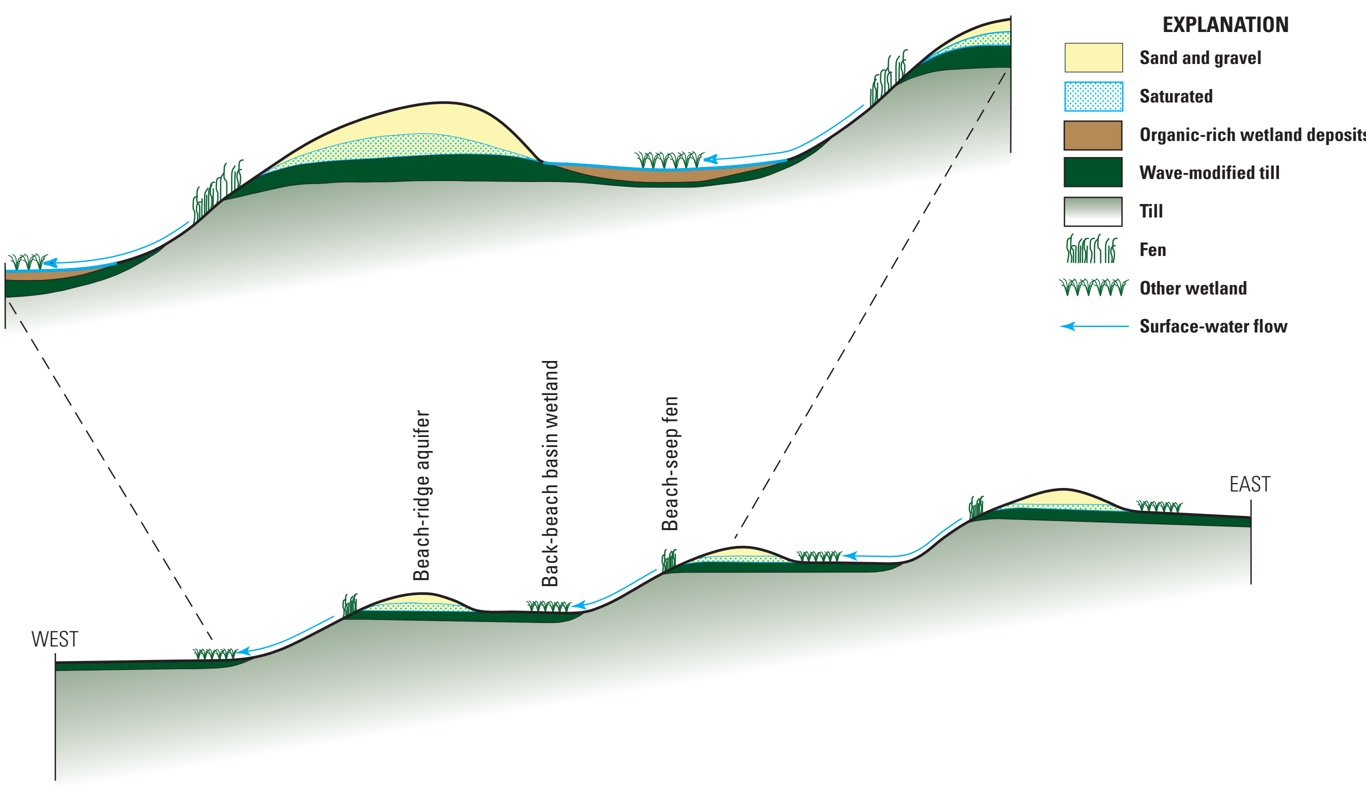


Figure 7. Conceptual hydrogeologic section through the Glacial Ridge study area, northwestern Minnesota.

The uppermost buried aquifers (50–100 ft below land surface; hereinafter, the term “buried aquifers” only refers to these uppermost buried aquifers) underlie much of the study area, but groundwater flow in them does not substantially interact with the shallow water system in most areas (fig. 7). Hydrologic descriptions of the buried aquifers and interactions between surficial and buried aquifers are detailed in the prerestoration study report (Cowdery and others, 2007), but because these interactions have little effect on flows within surficial aquifers, further analysis of buried aquifers is outside the scope of this report.

Aquifer Descriptions

Surficial and buried aquifers in the study area are composed of fairly well-sorted, coarse-grained sediments deposited by many glacial and glaciolacustrine processes and events. These aquifers are separated from each other by lower conductivity, fine-grained till, lake clay, and (or) organic-rich wetland deposits. The range of calibrated horizontal hydraulic conductivities of confining beds in Lindgren’s (1996) groundwater flow model in the study area was 10–50 feet per day (ft/d), which is about 10–20 times lower than the horizontal hydraulic conductivities of aquifers in the model.

Confining-bed deposits occupy a much greater volume than do aquifer deposits. Most surficial aquifers in the study area are beach-ridge sediments (figs. 1 and 7) winnowed from and deposited on till. Beach ridges are small and variable aquifers. Ridges are usually less than 20 ft thick but may be as much as 35 ft thick locally. Depth to water ranges from zero to 20 ft. Ridges are narrow (250–1,000 ft) but are tens to hundreds of miles long. However, ridges usually are hydraulically continuous for no more than several miles. In many places, beach ridges coalesce into areas of wider surficial sands, particularly in the southern part of the study area. The extent of these wider surficial-sand areas can indicate a more substantial aquifer than really exists. In most cases, only a veneer of sand less than 10 ft thick lies between each beach ridge and does not form an areally extensive aquifer. This veneer is probably sand redistributed by storm waves behind the active beach ridge of Lake Agassiz.

Beach-ridge sediments range from fine sand to gravel but are generally well sorted and sandy. The base of a beach ridge is usually composed of gravels lying directly on wave-modified till. Beach sands rarely contain beds of well-sorted silts and lake clays. The horizontal hydraulic conductivity of the surficial aquifers based on slug tests is 2.7–43.4 ft/d (transmissivity is 30–2,170 square feet per day [ft^2/d]) with a median of 8.1 ft/d (transmissivity is 124 ft^2/d) (Cowdery, and others, 2007). Horizontal hydraulic conductivity based on pumping tests is three to four times these amounts (Cowdery, and others, 2007). Horizontal hydraulic conductivity from a numerical model of groundwater flow in surficial aquifers in the study area was 200–300 ft/d with a saturated thickness of as much as 30 ft (Lindgren, 1996). The hydraulic-conductivity measurements in the study area follow the general pattern that their magnitude tends to increase with techniques that integrate larger parts of an aquifer.

In four parts of the study area, the surficial sand and gravel is much thicker (as much as 74 ft) than that of the beach-ridge aquifers just described. These areas form the only substantial surficial aquifers in the study area. The deposition of these thick aquifers seems to be unrelated to Lake Agassiz because the lake produced a land surface that is quite planar, but the aquifers are incised into the land surface. The thick aquifers are of limited extent, have steep lateral boundaries, and are adjacent to relatively large areas of thin sands. These thick aquifers trend along an east-southeast-west-northwest line from the ice-stagnation topography of the Erskine Moraine (not shown) near Maple Lake to the northwest corner of the study area (fig. 1; Cowdery and others, 2007, fig. 6). This direction is along the trend of the ice margin that deposited the Erskine and Itasca Moraines (not shown) and is likely related to the deposition of the moraine.

The last ice lobe to cover the study area exposed, or did not bury, these thick aquifers. When Lake Agassiz formed, the sands and gravels from the thick aquifers were locally distributed into adjoining thin sand plains, upon which beach ridges were subsequently developed. The thick aquifers are stratigraphically more complex than the overlying beach-ridge deposits. The conductive parts of the aquifer are mainly well-sorted, medium-to-coarse grained sands with some gravel beds. The sediments composing these aquifers are generally better sorted and thicker than beach-ridge sediments. The thick aquifers can contain lenses of till, silt, and lake clay, as much as 20 ft thick, which are generally of small areal extent. Beach ridges generally overlie the thick aquifers, but the contact between them cannot be distinguished.

Recharge

Areal recharge to surficial aquifers is from vertical infiltration of rainfall and snowmelt (areal recharge), from surface waters (particularly ephemeral wetlands), and from upward leakage of groundwater from buried aquifers through till confining beds (based on head gradients). Areal recharge is highly variable in space and time, depending on the amount and intensity of rainfall, the amount of storage potential remaining in wetland basins, snowpack, antecedent soil moisture, the depth of frost, and the particular history of each spring thaw. Average annual areal recharge calculated from groundwater hydrographs collected for this study ranged from 7.0 in. in 2012 to 17.8 in. in 2004. The infiltration rate, calculated as volume of recharge divided by volume of precipitation over the surficial aquifer areas, ranged from 38.9 percent in 2012 to 78.8 percent in 2013. Across the core area and during 2003–15, annual recharge averaged 13.3 in., which is an average infiltration rate of 63.2 percent.

Groundwater Flow, Levels, and Storage

Groundwater flow radiates from the topographic high near Maple Lake (fig. 1) to areas of lower elevation on northern and western edges of the study area (Cowdery and others, 2007, fig. 10). Shallow groundwater flow is complex, with water in surficial aquifers, ditches, and wetlands forming a single hydrologic system. Surficial aquifers contain and lie adjacent to wetlands of a variety of types within the study area. In many areas, wetlands underlain by low-permeability till lie in back-beach basins, upgradient from, downgradient from, and in physical contact with individual aquifers (fig. 7). In these situations, it is difficult to distinguish between groundwater and surface water, because they flow in one hydrologic system. That said, there is little water flow in till areas where there is neither aquifer nor wetland, even though groundwater heads may show the potential for such flow. What flow occurs probably is mostly vertical through fractures in the till, which anneal with depth (Ruland and others, 1991).

The water table was between 0 and about 28 ft below land surface in late June 2004, a time of typical water levels during the study (Cowdery and others, 2007, fig. 10). The median measured water depth in wells completed in surficial aquifers was 6.76 ft at that time. The water table mimics the topography in the study area (Cowdery and others, 2007, fig. 10). Although the land surface seems quite flat, there is a 185-ft drop in surficial groundwater elevation over about 11 mi from Maple Lake to the southwestern corner of the study area. This gradient is substantial and is the force that drives the flow of water in the study area.

The basic radial pattern of groundwater flow is interrupted where ditches cut through aquifers formed in beach ridges. Usually, groundwater flows perpendicular to beach ridges, which lie parallel to lines of equal land-surface elevation because of their formational history. Where a ditch cuts through a beach ridge, groundwater flow in the beach ridge turns 90 degrees, toward the ditch, where it usually discharges. How far from a ditch this turn in groundwater flow occurs is affected by the elevational height and saturated thickness of the aquifer. High aquifers with large saturated thicknesses have water levels far above a ditch, which is at the bottom of a beach ridge. Such aquifers will have an area of flow toward the ditch that is larger than a low aquifer that has a small saturated thickness. If a beach ridge is high enough, a groundwater mound can occur in the aquifer in areas away from ditches, and groundwater will flow locally with and against the general regional flow direction. This situation occurs especially where a ditch drains an upgradient wetland, producing a locally low water-table upgradient from a beach ridge.

Groundwater Evapotranspiration

Groundwater ET as defined in this report is that part of groundwater flow that evaporates from the water table (true groundwater ET) and groundwater that discharges to surface waters that are disconnected from a basin's stream network (closed subbasins). Most groundwater ET is groundwater that discharges to surface waters and evaporates or transpires from them. This part of groundwater ET is, in fact, surface-water ET but is not captured in the surface-water budgets calculated in this report because this groundwater discharge never flows to a ditch where it can be measured. In the core area, groundwater ET amounted to 85 and 87 percent of the groundwater recharge during the prerestoration and postrestoration periods, respectively (fig. 8). This amounts to 28 and 31 percent of total precipitation during these periods, respectively.

Surface-Water Hydrology

Before wetland and prairie restoration, surface water flowed across the clayey parts of the land surface, primarily from back-beach basins to ditches or closed subbasins. After restoration, many back-beach basins were restored to wetlands by filling in ditches that drained them. Restoring wetlands restored a more natural flow system. Originally, much of the surface water flowed in shallow swales that were dry most of the time. This flow network was substantially modified with the arrival of agriculture by channelizing these swales into ditches. The ditches reduced the time that water took to drain from the land surface, increasing maximum ditch flow and the volume of direct runoff. Ditches also drained ephemeral wetlands and reduced the size of permanent wetlands.

Back-beach basin wetlands (fig. 7) store runoff, which can reduce total ditch flow. Most of the water permanently retained in the wetlands is returned to the atmosphere as ET or recharges aquifers. Beach-seep fens (fig. 7) are less important to direct runoff because they have a smaller capacity to retain water. During very wet conditions, groundwater discharging into the beach-seep fens may flow overland into a back-beach basin wetland and then into a channel flowing parallel to a beach ridge and eventually into a ditch. However, such wet conditions are rare and form a small part of the ditch flow. Some fens can retain direct runoff, especially those among beach bars, berms, and ridge crests.

A general quantitative description of surface-water flow characteristics and differences in these characteristics among basins is presented in detail by Cowdery and others (2007). After restoration, the general features of these characteristics persist. Surface-water ET is the part of total ET that is not groundwater ET. Surface-water ET is composed of ET from soils, from runoff, and from water bodies connected to a basin's stream network (excluding closed subbasins). It also is composed of that part of the direct precipitation and runoff to water bodies in closed subbasins. The largest component of surface-water ET comes from water entering the atmosphere from these water bodies. About 55 percent of precipitation falling on the core of the study area leaves the basins through surface-water ET (fig. 8).

Changes in the hydrologic response of ditch flows to storms were characterized using the Clark unit-hydrograph method (HEC–HMS, version 4.0; Feldman, 2000; U.S. Army

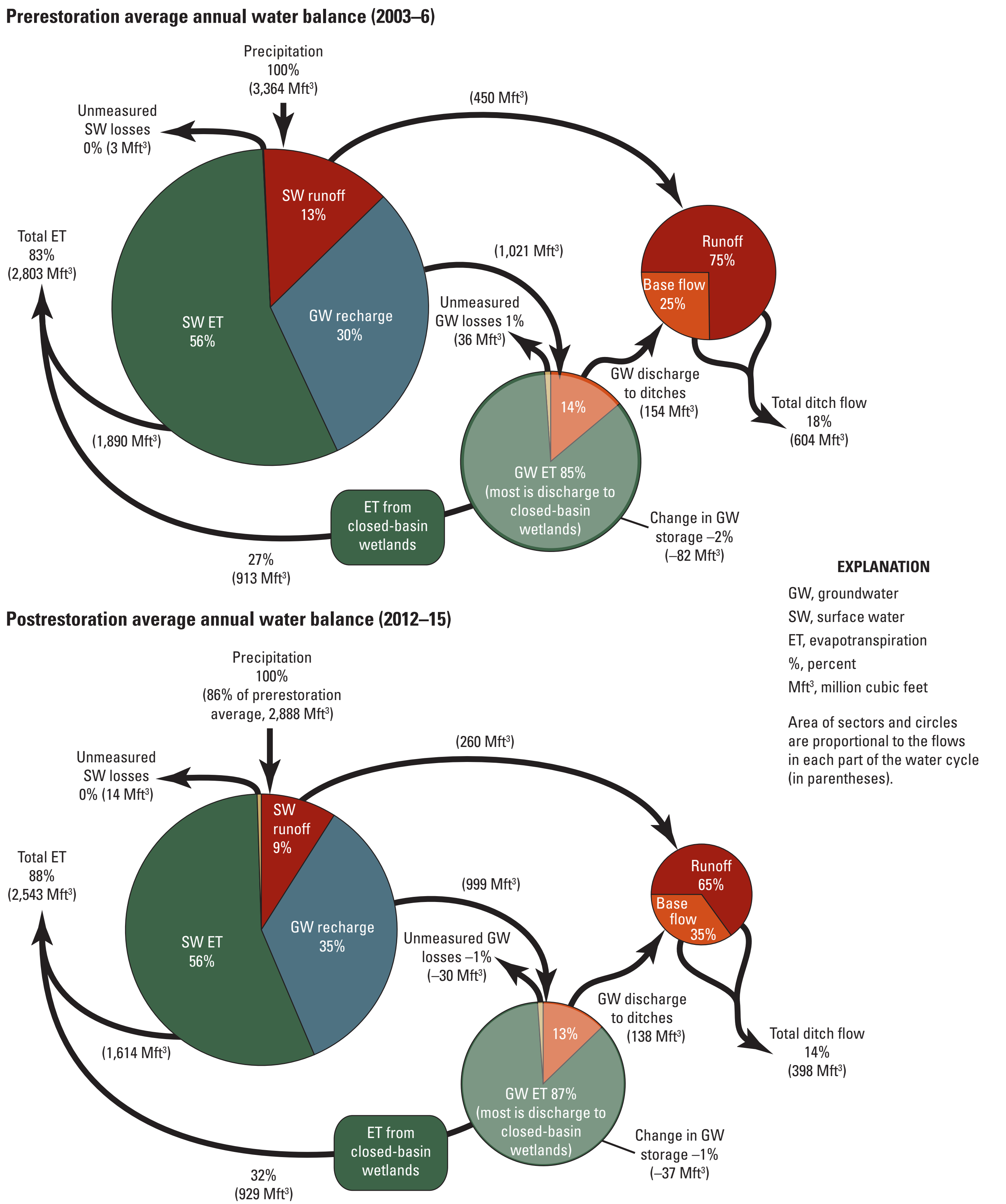


Figure 8. Prerestoration and postrestoration average annual water balances in the core area, Glacial Ridge study area, northwestern Minnesota, 2003–6 and 2012–15.

Table 7. Difference in median values used in calibrated Clark unit-hydrograph models of storm ditch flow, between 2002–6 (prerestoration period) and 2012–15 (postrestoration period), Glacial Ridge study area, northwestern Minnesota.

[in., inch; hr, hour; ft³/s, cubic foot per second; Pre, median value associated with prerestoration storms; Post, median value associated with postrestoration storms; Dir., direction of change; +, positive change, −, negative change; in/hr; inch per hour]

Ditch basin	Total precipitation (in.)			Time of concentration (hr)			Clark storage coefficient (hr)			Peak ditch flow (ft³/s)			Recession threshold (ft³/s)			Recession constant (unitless)		
	Pre	Post	Dir.	Pre	Post	Dir.	Pre	Post	Dir.	Pre	Post	Dir.	Pre	Post	Dir.	Pre	Post	Dir.
SW2	3.21	1.55	−	11.5	6.41	−	38.2	36.7	−	48.8	19.0	−	4.50	16.1	+	0.86	0.75	−
SW3	2.73	1.50	−	4.07	3.68	−	51.0	24.3	−	25.5	28.3	+	5.00	27.2	+	0.80	0.88	+
SW4	2.30	2.00	−	7.34	9.78	+	34.7	27.9	−	27.4	87.1	+	18.5	68.1	+	0.77	0.65	+
SW5	2.23	1.65	−	23.6	12.6	−	15.2	16.8	+	84.8	95.3	+	22.4	75.0	+	0.61	0.40	+
SW6	2.12	1.32	−	7.00	2.77	−	24.0	10.6	−	65.9	33.8	−	14.0	25.3	+	0.87	0.73	+
SW8	2.02	1.19	−	4.59	0.70	−	14.7	3.57	−	21.1	29.6	+	15.4	15.8	+	0.42	0.47	+

Ditch basin	Initial ditch flow (ft³/s)			Initial loss (in.)			Constant-loss rate (in/hr)			Peak ditch flow/ initial ditch flow (unitless)			Recession threshold/ peak ditch flow (unitless)		
	Pre	Post	Dir.	Pre	Post	Dir.	Pre	Post	Dir.	Pre	Post	Dir.	Pre	Post	Dir.
SW2	4.00	2.47	−	0.34	0.35	+	0.28	0.31	+	11.9	7.09	−	0.53	0.94	+
SW3	1.02	2.30	+	1.31	0.18	−	0.25	0.32	+	13.9	8.90	−	0.18	0.97	+
SW4	1.70	2.56	+	0.70	0.27	−	0.30	0.19	−	14.4	13.5	−	0.72	0.84	+
SW5	1.00	2.74	+	0.31	0.38	+	0.21	0.17	−	54.2	47.8	−	0.83	0.84	+
SW6	3.00	17.9	+	0.76	0.55	−	0.27	0.30	+	11.6	1.90	−	0.40	0.75	+
SW8	0.28	5.86	+	0.72	0.53	−	0.32	0.31	−	76.1	3.63	−	0.70	0.98	+

Corps of Engineers, 2013). Details of all storms modeled with the unit-hydrograph method are presented in table 4.1 in appendix 4. Changes between restoration periods of median total precipitation, initial ditch flow, peak ditch flow, recession threshold, time of concentration, Clark storage coefficient, initial loss, and constant loss rate for each individual ditch basin are summarized in table 7. Changes in medians for peak ditch flows normalized to initial ditch flows and recession thresholds normalized to peak ditch flows also are included in table 7.

Differences among unit hydrograph variables between restoration periods help demonstrate hydrologic changes after wetland and prairie restorations. Median total precipitation was consistently lower in the postrestoration period for all basins. Median initial ditch flows were higher in the postrestoration period for all basins except SW2 despite the decrease in total precipitation in the postrestoration period. Median peak ditch flows increased in basins SW3, SW4, SW5, and SW8 but decreased in basins SW2 and SW6 between restoration periods. Finally, median recession thresholds increased in all basins (table 7).

Water Quality

Cowdery and others (2007) reported that the quality of surficial groundwater (water from surficial aquifers) and ditch-water samples collected during the prerestoration study generally was suitable for most uses but was variable. All water samples were classified as hard in terms of mineral content. Water-quality data from the prerestoration and postrestoration studies are available in the National Water Information System database (available at https://nwis.waterdata.usgs.gov/mn/nwis/qwdata; U.S. Geological Survey, 2019) using the USGS site numbers given in appendix table 2.1. The general water-quality characteristics documented in the prerestoration study are reproduced here for convenience. Most groundwater samples collected during the prerestoration period were dominated by calcium, magnesium, and bicarbonate ions (Cowdery and others, 2007, fig. 14). Sum-of-solids concentrations computed from all ionic concentrations averaged 536 mg/L for surficial groundwater samples and 610 mg/L for buried aquifer groundwater samples. The corresponding standard deviations for sum-of-solids concentrations in surficial and buried groundwater samples were 160 and 95 mg/L, respectively.

Prerestoration nutrient concentrations in surficial groundwater samples were spatially variable, reflecting the spatial variability of land use in the study area at that time. Surficial groundwater samples had higher median concentrations of nitrogen compounds than of phosphorus compounds, except for nitrite (Cowdery and others, 2007, fig. 15). Nearly all surficial groundwater samples (36 of 38) contained nitrate at concentrations higher than the detection limit of 0.03 mg/L as nitrogen (mg/L–N). Nearly one-half of the samples (47 percent) contained nitrate at concentrations higher than 3 mg/L–N, which indicates the presence of some anthropogenic nitrate in the sample (Madison and Brunett, 1984). About one-quarter of the samples (26 percent) contained concentrations of nitrate above the drinking-water standard of 10 mg/L–N (U.S. Environmental Protection Agency, 2006). These nutrient concentrations reflect the agricultural land use in the study area during the prerestoration period.

Concentrations of corn and soybean herbicides and their degradates were measured in 39 surficial groundwater samples in 2004 (Cowdery and others, 2007). These samples contained detectable concentrations of 5 of the 16 parent compounds analyzed (atrazine, metolachlor, pendimethalin, prometon, and terbutryn) and 10 of the 19 degradates analyzed (Cowdery and others, 2007, fig. 16). In general, degradates were present more frequently and at higher concentrations than were the parent herbicides. The most commonly detected compound was 2-chloro-4-isopropylamino-6-amino-*s*-triazine (deisopropylatrazine), an atrazine degradate, which was detected in 28 percent of the surficial groundwater samples at concentrations as high as 0.46 microgram per liter (µg/L). The compound measured at the highest concentration was 2-[(2-ethyl-6- methylphenyl)amino]-2-oxoethanesulfonic acid, an acetamide degradate, which was measured in one sample (well G22) at 39 µg/L. The sample from well G22, taken from beneath an unrestored, irrigated agricultural field, contained the highest number of quantified compounds (9 of the 35). No herbicides or degradates were detected in the nine groundwater samples from buried aquifers that were analyzed.

Like surficial groundwater samples in the study area, ditch-water samples were dominated by calcium, magnesium, and bicarbonate ions. Nutrient concentrations in ditch-water samples tended to be about the same order of magnitude as those in groundwater samples with three exceptions. Ditch-water sample concentrations were lower in nitrate, higher in organic nitrogen, and higher in all forms of phosphorus. In general, ditch-water samples contained fewer detectable herbicides and metabolites, and their concentrations were lower than groundwater samples.

Benefits of Wetland and Prairie Restorations

This study was designed to quantify changes in the hydrology of land undergoing substantial restoration of wetlands and prairies. The changes documented were in the components of flow through the groundwater and surface-water cycles, in the dynamics of ditch-flow during storms, and in the quality of groundwater and surface water.

Land Use

Land use changed substantially between 2002 and 2015. Within the core area (fig. 5), wetland area increased by 6 percent; grass pasture, prairie, and restored prairie (hereinafter called grassland) increased by 19 percent; cropland (row crop and small grains) area decreased by 14 percent; and fallow, tame grass, and noncrop land area decreased by 7 percent between 2002 and 2015 after restorations (table 8; Greg Bengston, U.S. Department of Agriculture, Natural Resources Conservation Service, written commun., 2015). In the core area as a whole, 25 percent of the land area was restored. Restorations changed ditch basin SW6 the most (37-percent increase in restored lands [grassland and wetland]), and ditch basin SW2 the least (10-percent increase in restored lands, table 8). In ditch basin SW5, restored land increased 9 percent, but cropland increased 13 percent. The percentage of ditches abandoned (filled or no longer maintained) ranged from 25 (basin SW5) to 97 (basin SW8). In the core area, 64 percent of all ditches were abandoned. Ditch density in the core area decreased from 1.9 to less than 0.7 mi of ditch per square mile of basin.

The characteristics of restorations within each basin (table 8) are important to understanding the variability of hydrologic changes among the basins. Although prerestoration and postrestoration refer to multiyear periods throughout the rest of this report, in discussions of land-use change, 2002 conditions were used to represent prerestoration state and 2015 conditions represent postrestoration state (figs. 9 and 10).

Ditch basin SW2 was originally selected to be a land-use change control basin because few restorations were planned there. This proved true because only about 10 percent of the basin area was restored, almost all of it to prairie (fig. 11; table 8). The increase in grassland from 1 to 10 percent was largely at the expense of conservation lands, which likely function hydrologically like restored prairie. Basin SW2 also is characterized by small lakes (1 percent of the basin) in the easternmost part of the basin and forested (deciduous) areas throughout (10 percent of basin). After restoration, land use in SW2 was primarily characterized by fragmented areas of fallow, tame grass, and noncrop lands (27 percent of basin; table 8) and a contiguous part of conservation lands (19 percent of basin).

Basin SW3 is like basin SW2 in the eastern part (10 percent forest and 1 percent lakes), but the western one-half of basin SW3 underwent much more restoration than did basin SW2. In basin SW3, grassland increased from 9 to 25 percent of basin (table 8), primarily at the expense of cropland. Some fallow land was converted to cropland in the eastern part of the basin, but overall cropland decreased from 30 to 20 percent of the land cover in basin SW3.

Table 8. Land-use percentage and change in percentage by ditch basin between 2002 and 2015, Glacial Ridge study area, northwestern Minnesota.

Land-use category		Land use, in percent						
		SW2	SW3	SW4	SW5	SW6	SW8	Core area
Cropland (row crop and small grains)	2002	15	30	31	23	47	30	31
	2015	13	20	7	36	12	4	16
	Change	−2	−10	−23	13	−35	−26	−14
Restored prairie, prairie, and grass pasture	2002	1	9	14	1	16	34	12
	2015	10	25	36	9	45	60	31
	Change	9	16	22	8	28	27	19
Wetland	2002	14	14	17	2	4	7	9
	2015	15	19	25	2	14	16	15
	Change	1	5	8	1	9	9	6
Fallow, tame grass, noncrop	2002	28	25	21	64	19	5	28
	2015	27	15	15	42	18	3	21
	Change	−1	−9	−6	−22	−1	−2	−7
Conservation lands	2002	23	6	4	2	6	19	9
	2015	19	4	4	2	5	11	7
	Change	−5	−2	0	0	−1	−8	−2
Other (open water, forest, developed)	2002	18	16	12	9	7	6	11
	2015	17	16	12	8	6	6	11
	Change	−1	−0	−1	−0	−0	−1	−0

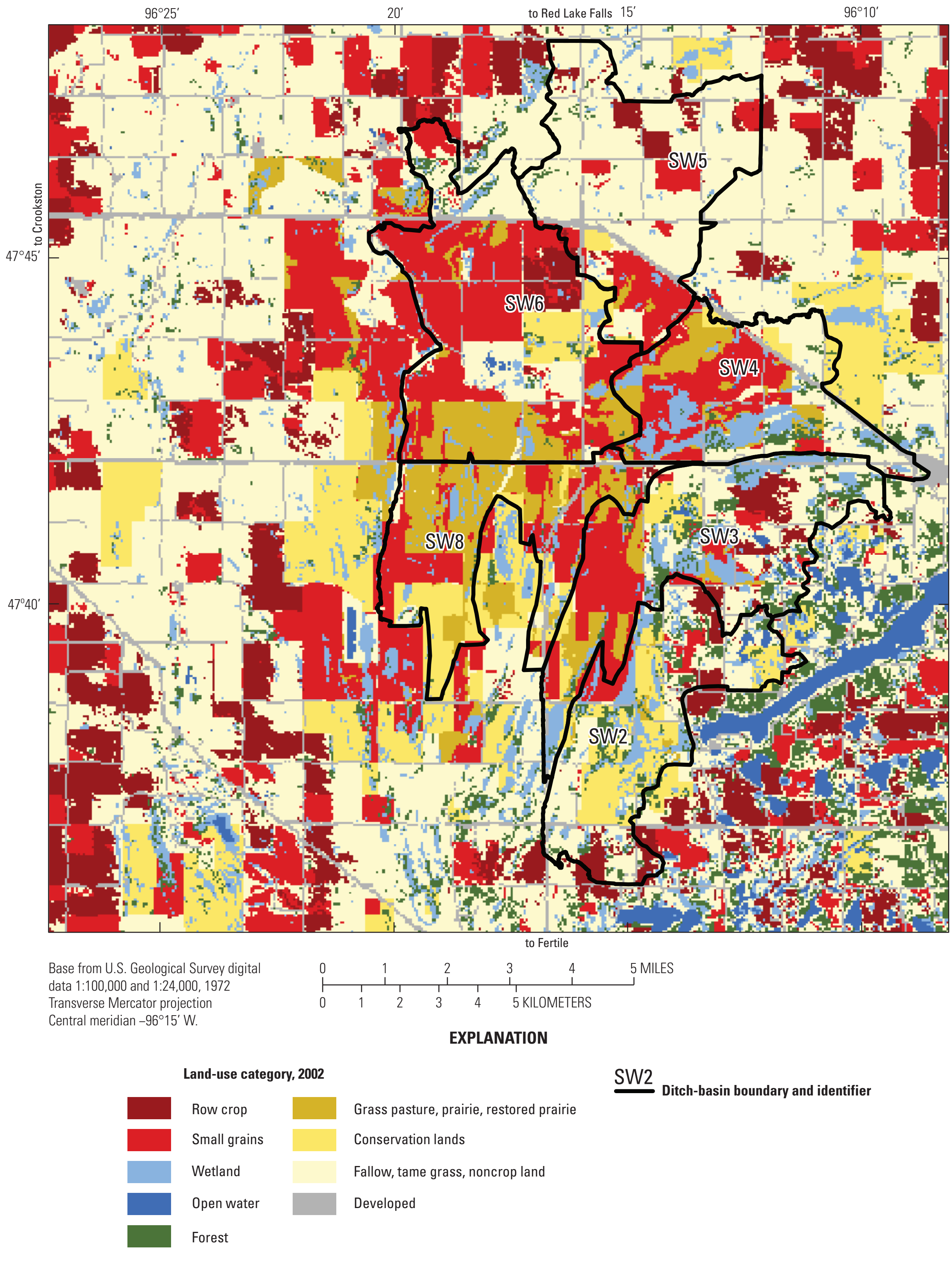


Figure 9. Land use, 2002, Glacial Ridge study area, northwestern Minnesota.

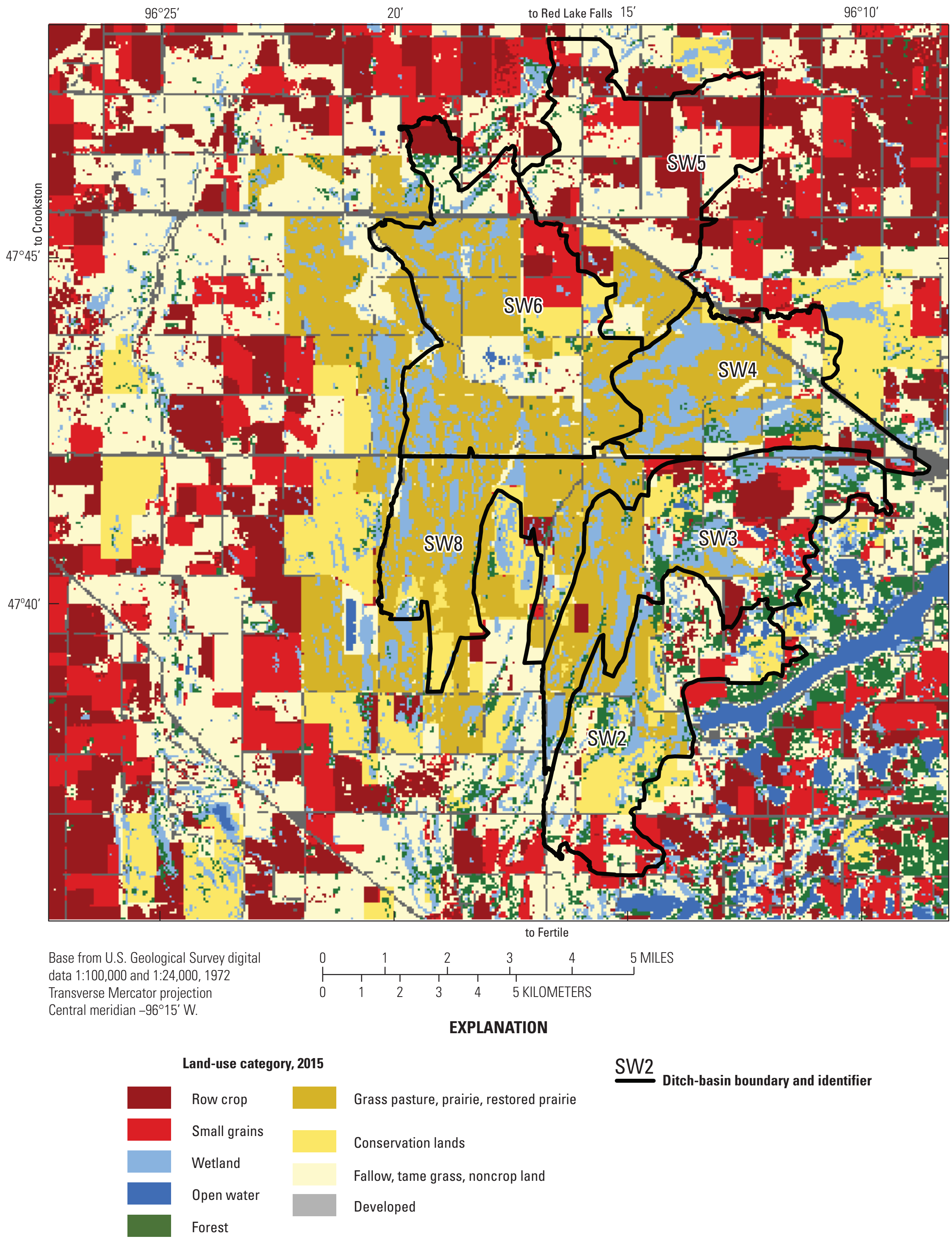


Figure 10. Land use, 2015, Glacial Ridge study area, northwestern Minnesota.

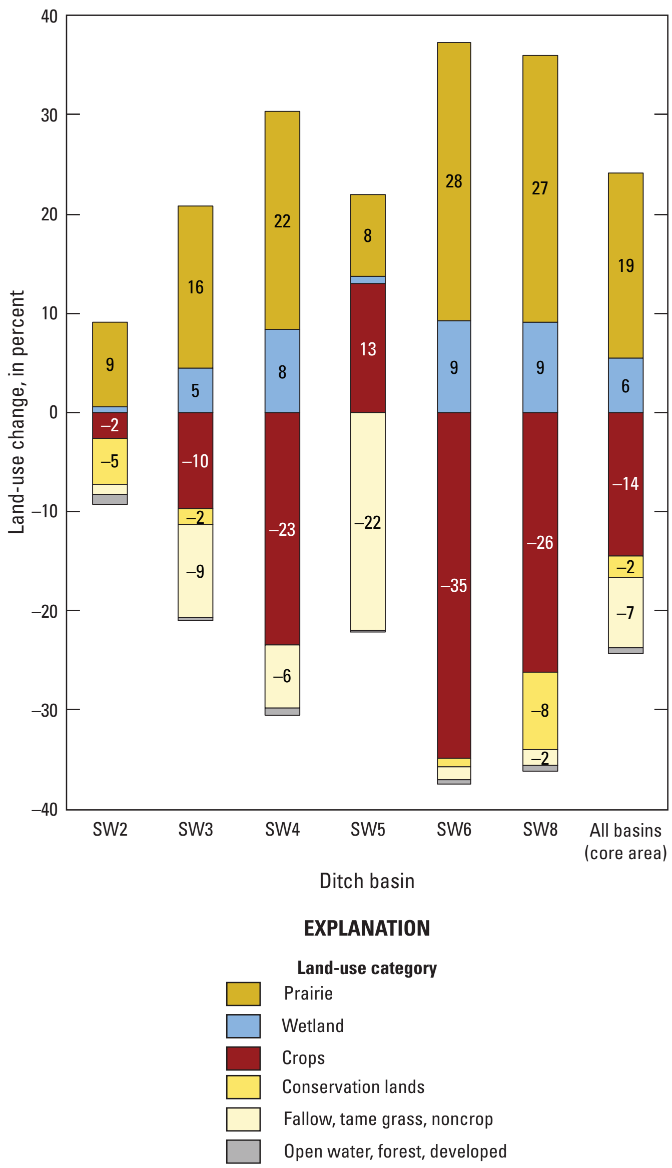


Figure 11. Land-use change by basin between prerestoration (2002) and postrestoration (2015) periods, Glacial Ridge study area, northwestern Minnesota.

Basin SW4 contains the highest proportion of wetland among the basins, accounting for 25 percent of basin area in 2015 (an 8-percent increase compared to 2002). Grassland area increased throughout the basin from 14 to 36 percent (a 22-percent increase; table 8). Fewer ditches were abandoned in basin SW4 than in other basins.

Land-use change in basin SW5 is different than other basins in the study area. Cropland area increased from 23 to 36 percent, with fallow, tame grass, and noncrop land uses converted to cropland. Wetland and prairie restoration in the southern part of the basin accounted for a basin-wide increase in restored grassland and wetland area from 3 to 11 percent (table 8). Few ditches were abandoned within the basin. SW5 is considered the least restored basin.

Restorations in SW6 accounted for a 37-percent change in basin area, primarily at the expense of cropland, which is the largest decrease in cropland among basins. Small restorations had already begun in SW6 before land-use analysis compilations in 2002. SW6 contains a large gravel mine in the center of the basin. The remainder of the basin remains cropland, is fallow, or is conservation lands. Basin SW6 has the second-largest percentage of grassland area postrestoration, after basin SW8 (table 8).

Basin SW8 is the most completely restored basin in the study area, with restored grassland and wetland area increasing 36 percent between 2002 and 2015 (table 8). However, unlike other basins, the 2002 to 2015 increase is less than the 41-percent increase during 2001–2, when most of the restoration occurred. This means that hydrologic data from basin SW8 was already substantially affected by restorations during the prerestoration period. This fact has the effect of diluting any land-use change effects in basin SW8 hydrologic data, making the restoration changes measured in this study smaller than those that actually occurred. By 2015, the remaining unrestored areas in basin SW8 were conservation lands (11 percent) and small percentages of crop, fallow, and forested land. Finally, 32.6 mi of ditches were abandoned in basin SW8, representing the greatest length and percent change in ditches among all basins.

Water-Cycle Changes

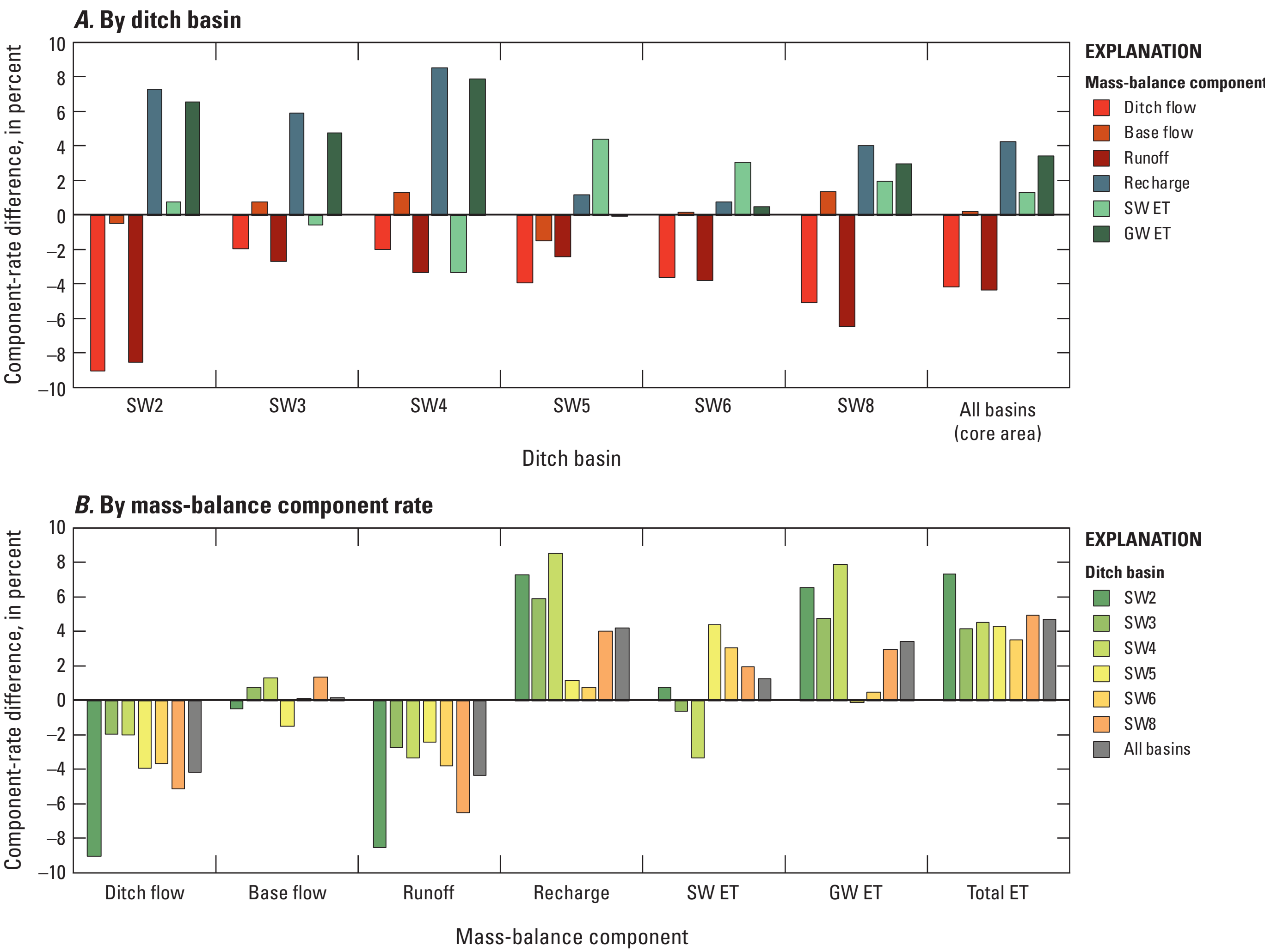
The measured changes in average water-cycle flows between the restoration periods (2003–6 and 2012–15) coincided with two large changes that likely affected all water-cycle flows: (1) an average 14-percent decrease in precipitation, and (2) the restoration of 19 percent of the study area to native prairie and 6 percent to wetlands. To address the effect of the decrease in precipitation during the postrestoration period, all water-cycle flows were normalized to the average precipitation of the restoration period. Hereinafter, these normalized flows will be called flow rates and will be reported as percentages of precipitation. This normalization has the effect of reducing the difference in precipitation during the restoration periods from the comparisons of flow. The differences compared in this analysis are differences in water-cycle-component flow rates between prerestoration and postrestoration periods, which also are reported as percentage of precipitation. These component differences may be expressed as changes relative to prerestoration flow rates to better express relatively large changes of small flow-rate components. These are called relative increase in flow rates (RIFRs) and are reported in percent increase of prerestoration flow rates. Any actual component of flow is reported in inches across the area of a basin so that flows among basins of different sizes are comparable.

Precipitation

Average precipitation over the core area (all six ditch basins) in which water-cycle flows were measured decreased 14 percent, from 22.0 to 19.0 in., between the restoration periods. Precipitation in the core area was highly variable in space and time. Even though the basins within the core area are adjacent and are within 14 mi of each other, substantially different amounts of precipitation fell in each basin. Basin SW6, in the northwest part of the study area, received the least precipitation during both periods (1.5 and 0.4 in., 7 and 2 percent less than the prerestoration and postrestoration period averages of the core area, respectively), and basin SW2, in the southeast part of the study area, received the most precipitation during both periods (2.5 and 1.0 in., 11 and 5 percent more than the core area average, respectively). The precipitation distribution measured in this study reflects spatial trends in the precipitation distribution statewide (Minnesota Department of Natural Resources, 2018). The maximum difference in annual precipitation among basins and water years was 34 percent between basin SW2 (27.6 in. in 2005) and basin SW6 (18.2 in. in 2006).

Groundwater and Surface-Water Flows

The largest increase in average water flows between the prerestoration and postrestoration periods in the core area was that 4.2 percent more precipitation infiltrated the land surface, increasing the areal groundwater-recharge rate by 14.0 percent (RIFR; fig. 12; tables 9 and 10). This increase in recharge rate caused increases in the base-flow rate of 0.2 percent (4.2 percent RIFR) and the groundwater ET rate of 3.5 percent



Abbreviations:
GW, groundwater; SW, surface water; ET, evapotranspiration. Component flow rates are average annual water-cycle component volumes normalized to precipitation during the prerestoration and postrestoration periods. These graphs show the differences in the rates between the periods.

Figure 12. Difference in water-cycle component flow rates between the prerestoration period (2003–6) and the postrestoration period (2012–15), Glacial Ridge study area, northwestern Minnesota. *A*, by ditch basin. *B*, by mass-balance component rate.

(12.4 percent RIFR; tables 9 and 10). See definitions of and distinction between groundwater and surface-water ET in the "Methods" section. These increases were at the expense of (overland) runoff rate, which decreased 4.4 percent (32.6 percent RIFR) and total ditch-flow rate, which decreased 4.2 percent (23.2 percent RIFR; fig. 12; tables 9 and 10). The decrease in ditch-flow rate amounted to a 206 million cubic feet (Mft^3) average annual decrease in water leaving the core part of the study area (fig. 8). Some of this decrease was from decreased precipitation during the postrestoration period. Had average annual precipitation been the same in the postrestoration period as it was in the prerestoration period, 141 Mft^3 less water would have left the core part of the study area annually. Unmeasured-loss rate (principally net measurement and modeling error) within the water balance accounts for less than 2 percent of total precipitation for the core area during both restoration periods. These changes align with expected changes in hydrologic flows from wetland restoration based on first principles (Adamus, 1993).

The increase in area of permanent vegetation and wetland in the core area probably accounts for the large increase in recharge rate and decrease in runoff rate between restoration periods. Permanent vegetation slows overland runoff allowing it to infiltrate into surficial aquifers. Likewise, precipitation running off into permanent wetlands that abut surficial aquifers is more likely to become recharge after snowmelt or high precipitation. These mechanisms may also account for the small change in groundwater-storage rate. The average groundwater-storage rate was negative (groundwater was released from storage) during both restoration periods (table 10). But the rate was less negative (less groundwater was released) during the postrestoration period (table 10).

Table 9. Change in average annual water-flow rates (flows as a percentage of precipitation) between 2003–6 (prerestoration period) and 2012–15 (postrestoration period), Glacial Ridge study area, northwestern Minnesota.

[SW, surface water; ET, evapotranspiration; GW, groundwater; blue cells, SW balance; yellow cells, summed quantities; green cells, SW and GW balances; brown cells, GW balance; dark brown cells, fundamental water-balance quantity]

Percent change in water-cycle component flow rate (percentage of precipitation, difference)							
Basin	**SW2**	**SW3**	**SW4**	**SW5**	**SW6**	**SW8**	**Core area**
SW ET	0.8	−0.6	−3.3	4.4	3.1	2.0	1.3
Ditch flow	−9.0	−1.9	−2.0	−3.9	−3.6	−5.1	−4.2
Runoff	−8.5	−2.7	−3.3	−2.4	−3.8	−6.5	−4.4
Base flow	−0.5	0.8	1.3	−1.5	0.1	1.4	0.2
Recharge	7.3	5.9	8.5	1.2	0.8	4.0	4.2
GW storage	0.7	1.3	1.1	4.0	0.2	−0.5	1.1
GW ET[1]	6.6	4.8	7.9	−0.1	0.5	3.0	3.5
Total ET	7.4	4.2	4.6	4.3	3.5	5.0	4.8
Total error	1.0	−3.5	−3.6	−4.4	−0.1	0.6	−1.7
Relative percent increase in water-cycle component flow rate (RIFR) (difference/prerestoration percentage of precipitation)							
Basin	**SW2**	**SW3**	**SW4**	**SW5**	**SW6**	**SW8**	**Core area**
SW ET	1.6	−1.0	−6.3	7.1	5.9	3.6	2.3
Ditch flow	−48.1	−13.8	−9.2	−26.1	−20.4	−22.5	−23.2
Runoff	−61.2	−29.2	−20.3	−19.9	−29.7	−35.6	−32.6
Base flow	−10.2	15.5	23.8	−51.6	2.9	31.4	4.2
Recharge	21.0	22.6	26.3	4.8	2.2	13.5	14.0
GW storage	−130.5	−63.8	−58.5	−113.0	−4.2	30.5	−46.6
GW ET[1]	22.4	21.7	26.5	−0.3	1.5	10.4	12.4
Total ET	9.4	5.1	5.5	5.0	4.2	5.9	5.7
Total error	31.6	−72.7	149.0	−155.3	−7.1	−12.5	−146.4

[1]GW evapotranspiration is composed of GW discharge to closed basins (where it then primarily evaporates) and evapotranspiration from the water table.

Table 10. Average water-flow rates (flows as a percentage of precipitation) between 2003–6 (prerestoration period) and 2012–15 (postrestoration period), Glacial Ridge study area, northwestern Minnesota.

[Pre, prerestoration average (2003–6); Post, postrestoration average (2012–5); RIFR, relative increase in flow rate, in percent; SW, surface water; ET, evapotranspiration; GW, groundwater; blue cells, SW balance; yellow cells, summed quantities; green cells, SW and GW balances; brown cells, GW balance; dark brown cells, fundamental water balance quantity]

Parameter		SW2	SW3	SW4	SW5	SW6	SW8	Core area
Precipitation	Pre	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Post	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Difference	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	RIFR	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SW ET	Pre	49.3	60.9	52.8	61.6	52.0	55.2	55.4
	Post	50.1	60.3	49.4	66.0	55.0	57.2	56.7
	Difference	0.8	−0.6	−3.3	4.4	3.1	2.0	1.3
	RIFR	1.6	−1.0	−6.3	7.1	5.9	3.6	2.3
SW Error	Pre	1.9	3.6	−1.6	2.0	0.8	−3.3	0.8
	Post	2.4	0.9	−3.5	−1.1	0.7	−2.8	−0.3
Ditch flow = runoff + base flow	Pre	18.8	14.1	21.8	15.0	17.8	22.6	17.9
	Post	9.7	12.2	19.8	11.1	14.2	17.5	13.8
	Difference	−9.0	−1.9	−2.0	−3.9	−3.6	−5.1	−4.2
	RIFR	−48.1	−13.8	−9.2	−26.1	−20.4	−22.5	−23.2
Runoff	Pre	13.9	9.3	16.3	12.1	12.7	18.2	13.4
	Post	5.4	6.6	13.0	9.7	8.9	11.7	9.0
	Difference	−8.5	−2.7	−3.3	−2.4	−3.8	−6.5	−4.4
	RIFR	−61.2	−29.2	−20.3	−19.9	−29.7	−35.6	−32.6
Base flow = GW discharge	Pre	4.8	4.9	5.5	2.9	5.1	4.4	4.6
	Post	4.3	5.6	6.8	1.4	5.3	5.8	4.8
	Difference	−0.5	0.8	1.3	−1.5	0.1	1.4	0.2
	RIFR	−10.2	15.5	23.8	−51.6	2.9	31.4	4.2
Recharge	Pre	34.8	26.3	32.5	24.3	34.6	29.9	30.4
	Post	42.1	32.2	41.0	25.5	35.3	33.9	34.6
	Difference	7.3	5.9	8.5	1.2	0.8	4.0	4.2
	RIFR	21.0	22.6	26.3	4.8	2.2	13.5	14.0
GW storage	Pre	−0.5	−2.0	−1.9	−3.5	−4.1	−1.6	−2.4
	Post	0.2	−0.7	−0.8	0.5	−3.9	−2.1	−1.3
	Difference	0.7	1.3	1.1	4.0	0.2	−0.5	1.1
	RIFR	−130.5	−63.8	−58.5	−113.0	−4.2	30.5	−46.6
GW ET	Pre	29.4	22.1	29.7	24.1	33.0	28.9	27.9
	Post	35.9	26.9	37.6	24.0	33.5	31.8	31.3
	Difference	6.6	4.8	7.9	−0.1	0.5	3.0	3.5
	RIFR	22.4	21.7	26.5	−0.3	1.5	10.4	12.4
GW Error	Pre	1.1	1.3	−0.9	0.8	0.5	−1.7	0.3
	Post	1.7	0.4	−2.6	−0.4	0.5	−1.6	−0.2
Total ET = GW + SW ET	Pre	78.7	83.0	82.5	85.7	85.0	84.1	83.3
	Post	86.1	87.2	87.0	90.0	88.6	89.0	88.1
	Difference	7.4	4.2	4.6	4.3	3.5	5.0	4.8
	RIFR	9.4	5.1	5.5	5.0	4.2	5.9	5.7

The increase in recharge documented in this study is at odds with the results of other research in the study area. Gerla (2011) instrumented two areas just west of well G36, finding that prairie plants allowed less water to move through the upper 2 ft of soil and recharge the surficial aquifer. The scale of Gerla's study was much smaller than that of this study, underscoring that the hydrologic-flow changes documented herein are areal averages on highly variable landscapes.

The increase in groundwater ET rate likely is a consequence of increased groundwater recharge and increased wetland area. All else being equal, as more water enters surficial aquifers, more water must discharge from them. As more of the land surface is occupied by the closed subbasins of reconstructed wetlands, less water can leave by ditch flow. Both mechanisms would produce more groundwater ET at the expense of ditch flow. Increased groundwater-recharge rate also caused ditch-base flow rate to increase slightly (0.2 percent, 4.2 percent RIFR) between restoration periods. However, the base flow-rate increase was not large enough to offset the substantial decrease in the runoff rate, resulting in an overall decrease in ditch-flow rate of 4.2 percent (32.6 percent RIFR). Groundwater ET increased nearly three times more than did surface-water ET between restoration periods, although surface-water ET remained about 50 percent higher than groundwater ET (table 10). The large changes in water-flow rates across the core area likely were substantially a result of the wetland and prairie restorations in the area.

However, when disaggregating flow rates into individual ditch basins during individual years, the variability among rates from individual water-balance components indicates that other factors are interacting to affect water-cycle changes in individual basins. The changes in water-cycle component flow rates among individual ditch basins (absolute and relative to prerestoration rates) between restoration periods are detailed in figure 12 and table 10. Individual flow rates are provided in table 10, and annual water-cycle component yields in inches, by basin, are provided in appendix 6, tables 6.1 and 6.2. Changes in flow rates will hereinafter be referred to by the component name; for example, an increase in the recharge flow rate or relative recharge flow rate between restoration periods will be called an increase or relative increase in recharge, respectively. In general, basins SW2 and SW4 had the largest changes in flows between restoration periods with changes similar to but larger than those in the core area as a whole (fig. 12*A*). Basins SW5 and SW6 had the smallest changes with increases in surface-water ET being balanced by decreases in runoff and ditch flow. Basins SW3 and SW8 had intermediate flow changes that were similar to the core area in direction and magnitude.

Among the six basins, SW2 had the smallest percentage of restored area (fig. 11) but the largest decrease in ditch flow and runoff (−9.0 and −8.5 percent respectively; fig. 12*A*; tables 9 and 10). Additionally, basin SW2 was one of only two basins (with SW5) where base flow decreased. Recharge and groundwater ET in basin SW2 increased substantially (7.3 and 6.6 percent, respectively), whereas surface-water ET barely increased. Water on the landscape was more likely to flow into closed subbasins and contribute to groundwater ET than contribute to base flow because basin SW2 contains several permanent lakes in its upper parts (see fig. 5). The postrestoration period was substantially drier than the prerestoration period, meaning that water levels in the basin's many closed subbasins and surficial aquifers were lower. For example, the average water level in well G15 (in basin SW2) was 0.29 ft lower during the postrestoration period than during the prerestoration period. Lower levels in closed subbasins and surficial aquifers cause less water to flow out of the basin through the ditch and more to leave as groundwater and surface-water ET from closed subbasins. Although basin SW2 was originally chosen as the land-use change control basin in this study, it is unfit for that purpose because, unlike the five other basins, it contains many closed subbasins and has a high groundwater gradient (Cowdery and other, 2007, fig. 10). Water cycle changes in this basin were more likely a result of the drier weather during the postrestoration period than a result of the small area of restorations it contained.

All water-cycle components changed in the same direction in basins SW3 and SW4, but the magnitude of the changes typically was much greater (58 percent, on average) in basin SW4 (component rate differences, fig. 12*A*, table 10). Both basins had similar types of land-use changes, but basin SW4 had a 43 percent larger increase in land area restored to wetland and prairie than did basin SW3 (fig. 11). The correspondence between restoration area and magnitude of water-cycle change is evidence that the land-use changes caused the changes seen in the water cycle. Like flows in basin SW2, ditch flow and runoff decreased, whereas recharge and groundwater ET increased in basins SW3 and SW4. The previously discussed mechanisms probably caused these changes in all three basins. However, unlike in basin SW2, base flow increased in basins SW3 and SW4, indicating that the open-subbasin ditch drainages in these basins may be more connected to surficial aquifers. Nevertheless, all three basins had high relative increases in groundwater ET (21.7–26.5 percent RIFR, tables 9 and 10) compared to other basins, indicating a shift of water flows to closed subbasins. The main causes were different among the basins, however. Drier weather was the main cause in basin SW2, whereas wetland restorations were the main cause in basins SW3 and SW4, which had far fewer closed-subbasin wetlands before restoration. The shift of flow to closed subbasins may have occurred on the surface as runoff or through aquifers as groundwater discharge. Regardless of the mechanism, more water left these basins from closed subbasins during the postrestoration than during the prerestoration period. The biggest difference in flow changes between basins SW3 and SW4 was in surface-water ET, which decreased 4.7 times more in basin SW4 than in basin SW3. Basin SW4 had a 60 percent larger increase in restored wetlands, which no longer flow to basin ditches and do not contribute to surface-water ET. This difference indicates that restorations may have disconnected a substantial part of the basin from its ditch and diverted flows to closed-subbasin wetlands.

Water-cycle flows changed the least between restoration periods in basins SW5 and SW6 despite having different amounts of land restored to wetland and prairie and ditches abandoned. Basin SW5 had the smallest amount of restored land (9 percent) and was the only basin that had an increase in cropland (13 percent). Nearly all the cropland increase came at the expense of fallow, tame-grass, and noncrop land. Basin SW5 also had the smallest percentage of ditches filled (25 percent of all channelized flow, 3.3 mi of ditches, table 5). Between restoration periods, basin SW5 had small decreases in ditch flow and runoff and similarly small increases in groundwater ET and recharge (fig. 12). The largest flow increase in basin SW5 was in surface-water ET. These flow changes make sense in basin SW5. A basin with small restoration area, a large increase in cropland, and few miles of abandoned ditches should have small changes in most water-cycle flows.

In contrast, basin SW6 had the largest amount of restored lands (37 percent), almost all of which came at the expense of cropland. Basin SW6 had 75.3 percent of all channelized flow filled or abandoned (no longer maintained as a ditch, 22.9 mi total, table 5). However, like basin SW5, basin SW6 had small decreases in ditch flow and runoff, similarly small increases in groundwater ET and recharge, and a relatively large increase in surface-water ET (fig. 12). The much greater area of restored wetlands and greater length of abandoned ditches in basin SW6 than in basin SW5 (9 and 1 percent for wetlands, respectively) should have caused a relatively greater increase in groundwater ET at the expense of runoff and surface-water ET than what was measured. The relatively greater aquifer area in basin SW6 (57.2 percent; SW5, 36.2 percent; table 11) also should have contributed to these flow changes.

One explanation for the relatively high increase in surface-water ET in basins SW5 and SW6 could be that most of the wetland and prairie restorations did not occur over surficial aquifers, thereby neither increasing recharge nor decreasing runoff to surface waters. The decrease in base flow in basin SW5 and no change in base flow in basin SW6 support this explanation. This explanation is contradicted, however, because basin SW5 had about 7 percent of wetland area over surficial aquifers before and after restoration (table 11). Basin SW6 had the largest increase in wetland area over surficial aquifers of any basin, increasing by 3 percent from 12.7 to 15.7 percent after restorations. The relatively large decrease in base flow in basin SW5 may have occurred because ditch abandonment may have further disconnected the remaining drainage system from surficial aquifers. However, the small amount of wetland restoration in the basin leaves most of the prerestoration ditch system intact.

Ditch abandonments complicate the explanation of water-cycle changes in basin SW6. Although most ditches were abandoned in the basin, a substantial length of Judicial Ditch 66 was not truly abandoned but rather redesigned and managed differently (Philip Gerla, Assistant Professor, University of North Dakota, written commun., 2019). Judicial Ditch 66 (the basin's main channel) was redesigned to operate as a normal ditch at low flow to continue to carry overflow from a gravel-pit lake and as a restored swale at higher flows. Redesigned ditches in basin SW6 may not have as effectively isolated wetlands from the remaining ditch drainage system as did abandoned and filled ditches. This difference would have reduced the effect of ditch restorations in the basin, lessening increases in groundwater ET and reductions in ditch flow by allowing water to flow down Judicial Ditch 66 during times of high water. It would also have the effect of increasing surface-water ET.

The similar changes in water-cycle flows in basins SW5 and SW6 produced from such different amounts of restoration cannot be explained by the data collected in this study. The decrease in rainfall during the postrestoration period may have decreased groundwater recharge disproportionately, at least in basins SW5 and SW6. Normalizing water-cycle flows to precipitation, as was done in this analysis, presumes that all flows will respond to precipitation proportionally, which may

Table 11. Surficial aquifer and wetland area by basin, Glacial Ridge study area, northwestern Minnesota, 2002 and 2015.

[mi^2, square mile; POB, percentage of basin; RPD, relative percent difference, %, percent]

Basin	Surficial aquifer area		Wetland area over aquifers						
			Prerestoration		Postrestoration		Increase		
	mi^2	POB	mi^2	POB	mi^2	POB	mi^2	POB	RPD
SW2	5.970	63.4%	1.958	20.8%	2.007	21.3%	0.048	0.5%	2.5%
SW3	5.654	49.2%	1.325	11.5%	1.409	12.3%	0.084	0.7%	6.3%
SW4	5.835	67.3%	2.032	23.4%	2.083	24.0%	0.050	0.6%	2.5%
SW5	4.218	36.2%	0.802	6.9%	0.812	7.0%	0.010	0.1%	1.3%
SW6	8.579	57.2%	1.907	12.7%	2.360	15.7%	0.454	3.0%	23.8%
SW8	4.194	48.3%	1.064	12.2%	1.237	14.2%	0.173	2.0%	16.3%
Core area	34.451	53.1%	9.089	14.0%	9.908	15.3%	0.819	1.3%	9.0%

not be the case. Other unidentified differences between the basins likely contributed to the similarities in water-cycle flow changes in these basins.

Flow changes in basin SW8 had the largest decreases for ditch flow and runoff and the largest increases for base flow of all basins except atypical basin SW2. Basin SW8 had among the highest amounts of restorations and ditch abandonments. After restorations, basin SW8 had the highest percentages of restored prairies (60 percent; table 8) and the most abandoned ditches (32.6 mi, 96.9 percent, table 5). Restored wetlands provided surface storage, thus reducing runoff and increasing surface-water and groundwater ET. Basins SW8 and SW6 had relatively large increases of wetlands over aquifer areas (2 and 3 percent of basin area, respectively), helping to explain the increase in base flow in basin SW8 but confounding the little change in basin SW6. The restorations in basins SW8 and SW6 were quite similar, but the water-cycle flows in basin SW8 changed as expected from the land-use changes it underwent, unlike in basin SW6. One factor that may have lessened the water-cycle changes measured in basin SW8 is that much of the land that was restored was taken out of the "conservation" land-use category (8 percent, table 8). This change is not as hydrologically substantial as the change from cropland to prairie, for example.

Water flows in each of the six basins measured in this study responded differently to the land-use changes that each basin underwent. Basin SW2 had the smallest amount of restorations and the largest water-cycle changes, especially in streamflow and runoff. This result may be related to the large area of more permanent wetlands in the basin. Basin SW2 clearly is an outlier among basins, both in the few land-use changes it underwent and in the hydrologic changes between restoration periods. Basin SW4 had especially large changes in the groundwater part of the water cycle. This may have resulted from a large percentage of the basin being overlain by surficial aquifers. The small water-cycle changes in basin SW6 are difficult to explain because the basin had large amounts of restorations. Finally, flow changes in basin SW8 most closely matched expectations, with relatively large decreases in streamflow and runoff, increases in flow through the groundwater system, and increases in groundwater and surface-water ET. Water-cycle flow changes in basin SW8 are most similar to changes in the entire core area.

Ditch-Flow Response to Precipitation

Changes in ditch-flow response to precipitation between restoration periods were quantified using Clark unit-hydrograph models (Clark, 1945) run in HEC–HMS (version 4.0; Feldman, 2000; U.S. Army Corps of Engineers, 2013). Several storms were modeled for each ditch (SW2–6 and SW8). Storm precipitation and unit-hydrograph model information for each storm and ditch gage are provided in table 4.1 in appendix 4. Unit-hydrograph model information for the three storms used in Cowdery and others (2007) were included in table 5.1. Cowdery and others (2007) assigned numbers to the unit-hydrograph storms (storms 1–3), and the additional storms used for analyses presented in this report are numbered in table 4.1 (appendix 4), starting with storm 4.

Quality-assurance data for models not previously presented in Cowdery and others (2007) were evaluated using information presented in table 4.1 (appendix 4). NSE values ranged from 0.81 to 1.00 for the prerestoration models and from 0.76 to 0.99 for postrestoration models. The observed ranges of NSE values indicate that modeled unit hydrographs closely matched unit hydrographs based on observed ditch flow and precipitation data. Peak-weighted root mean square error values ranged from 0.14 to 8.22 cubic feet per second (ft^3/s) for the prerestoration models and from 0.50 to 9.71 ft^3/s for the postrestoration models. Initial values, optimized values, and sensitivities for model variables also are presented in table 5.1. Initial values were optimized in HEC–HMS to produce modeled hydrographs that best fit the actual measured storm hydrographs. The distributions of optimized variables are presented in the box plots in figures 13 and 14. Sensitivity indicates how much model results are affected by a change in model variables. Models generally were most sensitive to initial-loss and constant-loss rate variables.

In the prerestoration report, Cowdery and others (2007) speculated that restoration activities would (1) increase time of concentration, (2) increase Clark storage coefficient, (3) reduce peak ditch flows, and (4) make recessions after ditch flow peaks more gradual. Data from this study demonstrate that, when normalized to initial ditch flow, median peak ditch flows did decrease from prerestoration to postrestoration periods for all basins (table 7). Also, hydrograph postpeak recessions were more gradual, with generally decreasing median recession constants (basins SW2, SW4, SW5, and SW6). Unexpectedly, however, median time of concentration decreased in all basins except SW4, and median Clark storage coefficients decreased in all basins except SW5.

Explaining the unexpected change in time of concentration and Clark storage coefficient is difficult. However, components of unit hydrograph models are sensitive to antecedent conditions and storm-specific characteristics (Roberson and others, 1988). Other findings in this report indicate that restoration activities increased the amount of precipitation that infiltrated into soils so that more water eventually reached the ditches as base flow. Furthermore, precipitation in the postrestoration period consisted of more frequent storms with smaller amounts of precipitation. Soils that were more saturated and ditches that were flowing more consistently (from increased base flow) may have reduced overall basin storage and shortened the time needed for new precipitation to reach the ditch outlet. Finally, the increase in the number of closed-subbasin wetlands created during restoration may have reduced the area that drains to ditches, thus reducing time of concentration.

Changes between restoration periods in time of concentration and Clark storage coefficient for SW4 and SW5, respectively, seem related to changes in land use in those

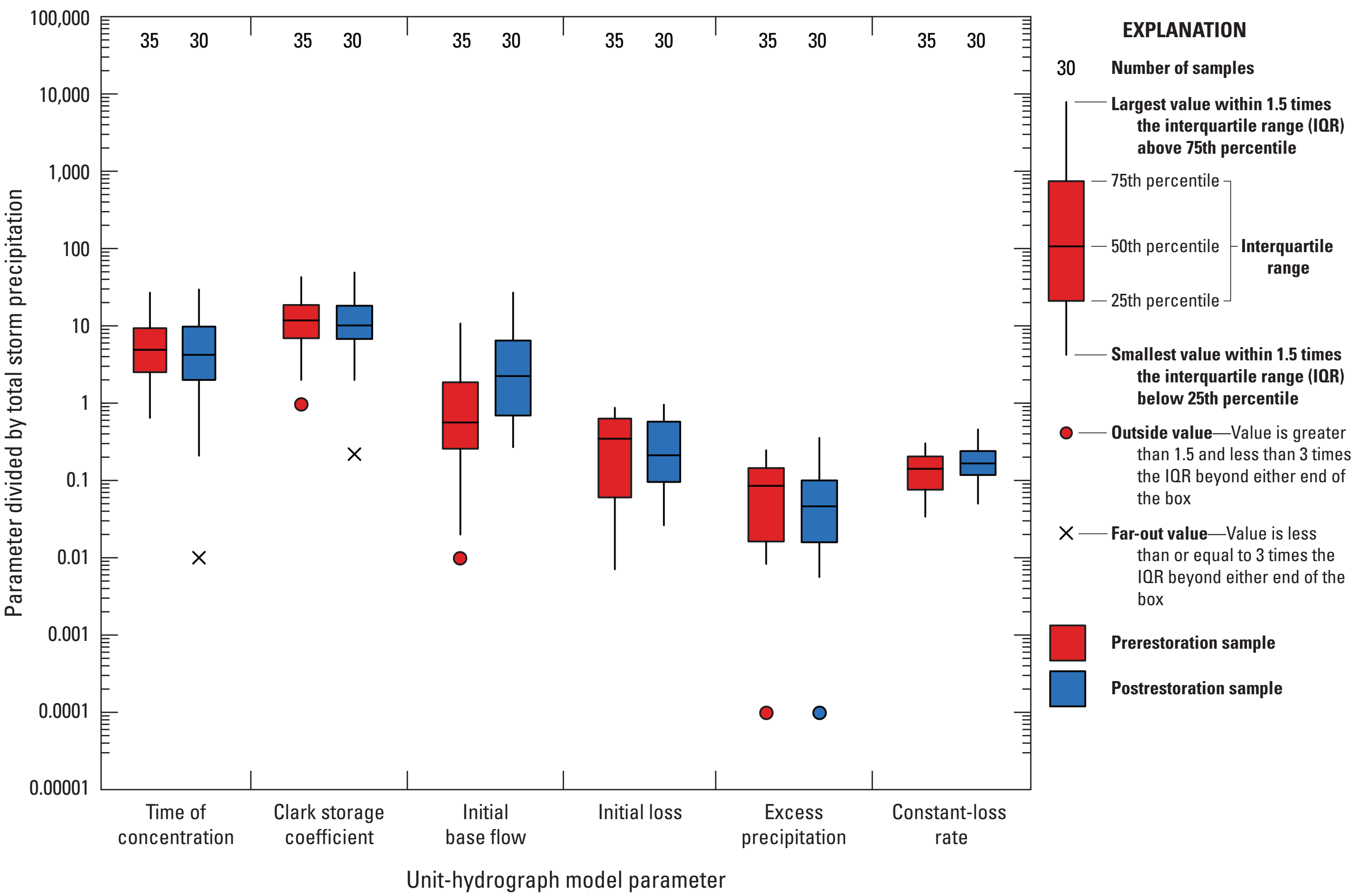


Figure 13. Optimized prerestoration and postrestoration storm unit-hydrograph model parameters normalized to precipitation, Glacial Ridge study area, 2003–15.

basins. The increase in the median Clark storage coefficient for basin SW5 may be explained by the net increase in cropland in the basin during the postrestoration period. Increased crop area likely removed more water from the soil and increased storage capacity in basin SW5. Furthermore, basin SW5 is the least restored basin in the study area. Basin SW4 had the highest percentage of wetland area among all basins and the largest increase in wetland area between restoration periods (table 5). Basin SW4 had relatively few miles of ditches abandoned during restoration. The increased wetland area in basin SW4 likely contributed to the observed increase in initial ditch flow (table 7), and maintaining the most connection between wetlands and ditches may have increased time of concentration in basin SW4.

Core-Area Storm Hydrograph Changes

Distributions of prerestoration and postrestoration unit-hydrograph model variables were compared using boxplots (figs. 13 and 14). Unit hydrograph variables were normalized to either total precipitation (fig. 13) or initial ditch flow (fig. 14) and then plotted on a logarithmic axis to facilitate comparison of prerestoration and postrestoration variables with different units and different ranges of observed values. Boxplots indicate that data distributions for most individual unit-hydrograph model variables did not differ substantially between prerestoration and postrestoration periods (figs. 13 and 14). However, differences in median values and distributions of unit-hydrograph variables still provided insights about how restoration activities affected ditch responses to precipitation.

Most unit-hydrograph model variables have subtle differences in medians and interquartile ranges between restoration periods (figs. 13 and 14). The medians and interquartile ranges of the time-of-concentration and Clark-storage-coefficient variables did not change substantially between restoration periods relative to the total precipitation of each storm (fig. 13). Median values for initial loss and excess precipitation decreased slightly from the prerestoration to postrestoration periods, whereas the median constant loss rate increased slightly (fig. 13). However, there was a noticeable increase in median initial ditch flow (base flow) from prerestoration

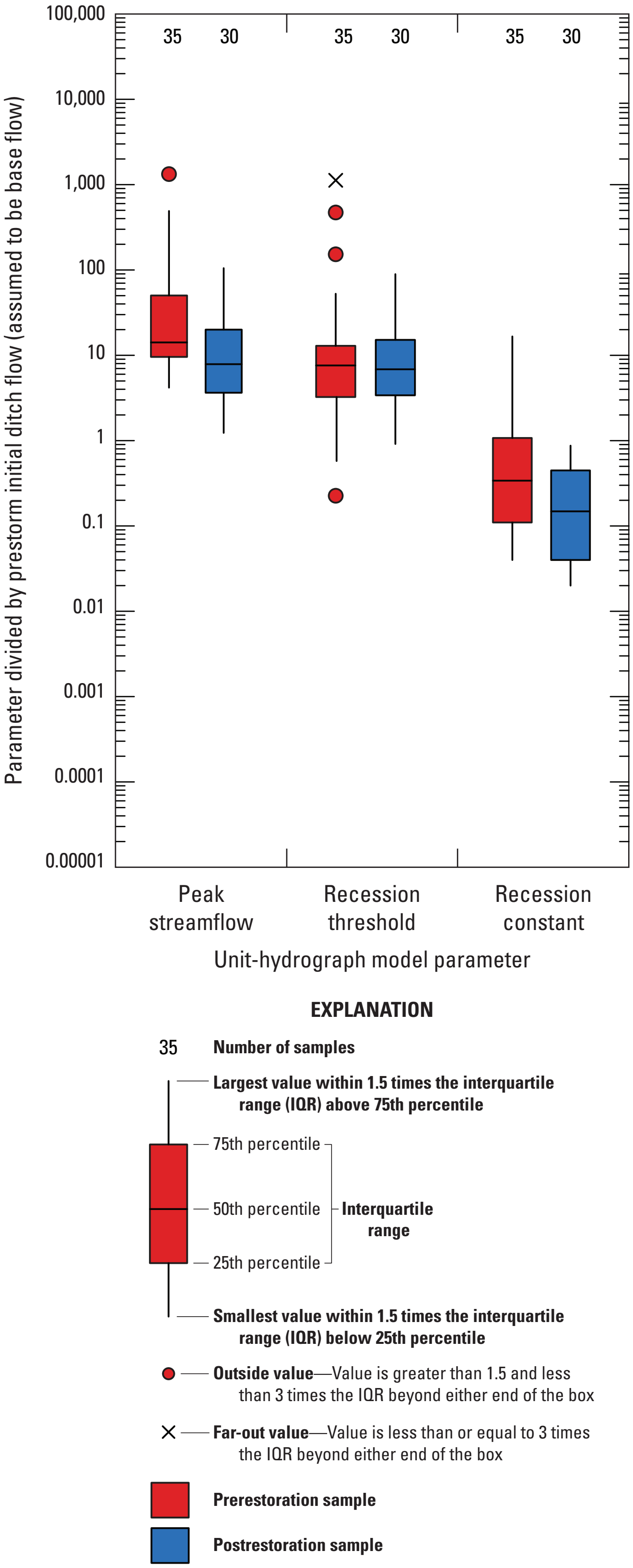


Figure 14. Optimized prerestoration and postrestoration storm unit-hydrograph model parameters normalized to initial ditch flow, Glacial Ridge study area, 2003–15.

to postrestoration periods relative to total precipitation of each storm (fig. 13). The medians of initial-loss and excess-precipitation decreased slightly between restoration periods, whereas the median of constant-loss-rates increased slightly (fig. 13). Furthermore, the median of recession threshold did not change appreciably, but median peak ditch flow and recession constant decreased relative to initial ditch flow (fig. 13). These comparisons generally indicate (1) reduced peak ditch flows on storm hydrographs, (2) increased gradual recession curves, and (3) increased base flows.

Equivalent Storm Comparisons

The results of eight unit-hydrograph models of individual storms during both restoration periods are presented in figure 15 to help illustrate changes in ditch flow in response to precipitation. Each unit-hydrograph model is represented by two graphs in a single panel. The upper graph shows the amount, duration, and intensity of the storm, detailing the amount of loss (red bars) and gain in precipitation (blue bars). The lower graph shows measured and simulated ditch-flow response to the storm. The graphs compare prerestoration and postrestoration ditch-flow response to equivalent storms in four ditches. Data for all storms in this section are provided in table 5.1.

The figure 15 unit-hydrograph models were selected specifically to compare differences in how ditch flows respond to storms. Prerestoration and postrestoration period hydrographs at gage SW6 for storms with similar total precipitation at similar time of year are compared in figures 15*A* and 15*B*. The unit-hydrograph model of storm 5, which started on June 11, 2005, and totaled 1.22 in., is presented in figure 15*A*. The unit-hydrograph model of a similar postrestoration storm, number 12, which started on June 15, 2014, and totaled 1.32 in., is presented in figure 15*B*. Optimized initial-ditch-flow variables were similar for both models, but the postrestoration hydrograph has a reduced peak ditch flow and a more gradual recession compared to the prerestoration hydrograph.

Prerestoration and postrestoration hydrographs at gage SW3 for storms with similar total precipitation but at different times of the year are compared in figures 15*C and 15D*. The unit-hydrograph model of storm 6, which started on August 19, 2005, and totaled 1.13 in., is presented in figure 15*C*. The unit-hydrograph model of storm 12, which started on June 15, 2014, and totaled 1.18 in., is presented in figure 15*D*. The shapes of hydrographs from both storms were similar, but the June hydrograph (postrestoration) initial-ditch flow was higher and base flow represented a smaller proportion of streamflow compared to the August hydrograph (prerestoration). This comparison illustrates the confounding effects of season and the relations among land cover, precipitation, and ET. June is generally wetter than August because precipitation is greater (Smith and Westenbroek, 2015), residual water from spring melt remains, and vegetation is less fully developed in June compared to August. Therefore, June precipitation typically exceeds ET, and surface runoff makes

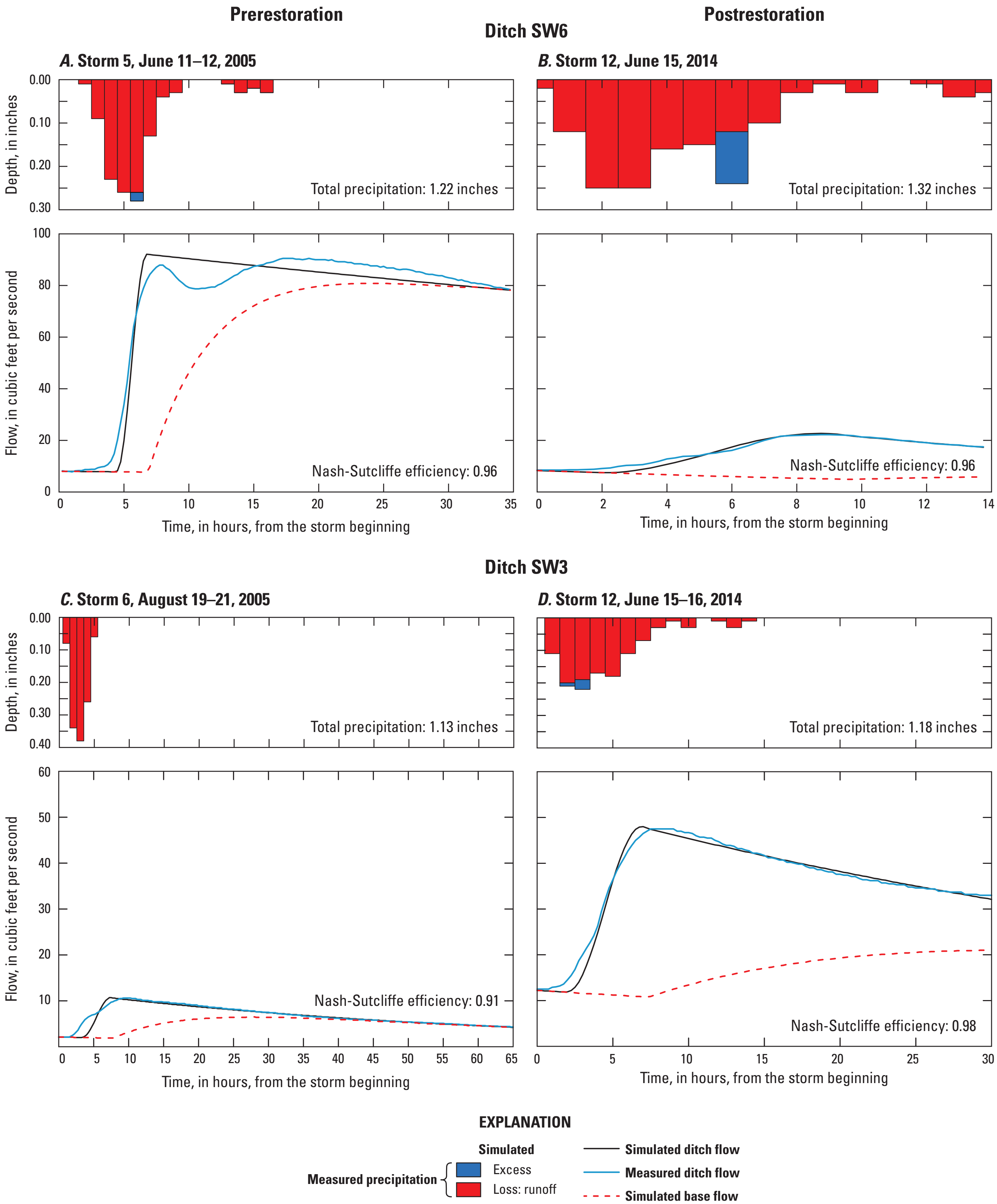


Figure 15. Example storm hydrographs and precipitation, Glacial Ridge study area, 2005 and 2014. *A*, ditch SW6, storm 5, June 11–12, 2005. *B*, ditch SW6, storm 12, June 15, 2014. *C*, ditch SW3, storm 6, August 19–21, 2005. *D*, ditch SW3, storm 12, June 15–16, 2014. *E*, ditch SW2, storm 5, June 11–12, 2005. *F*, ditch SW2, storm 12, June 15–16, 2014. *G*, ditch SW8, storm 8, October 4–6, 2005. *H*, ditch SW8, storm 11, June 25–26, 2014.

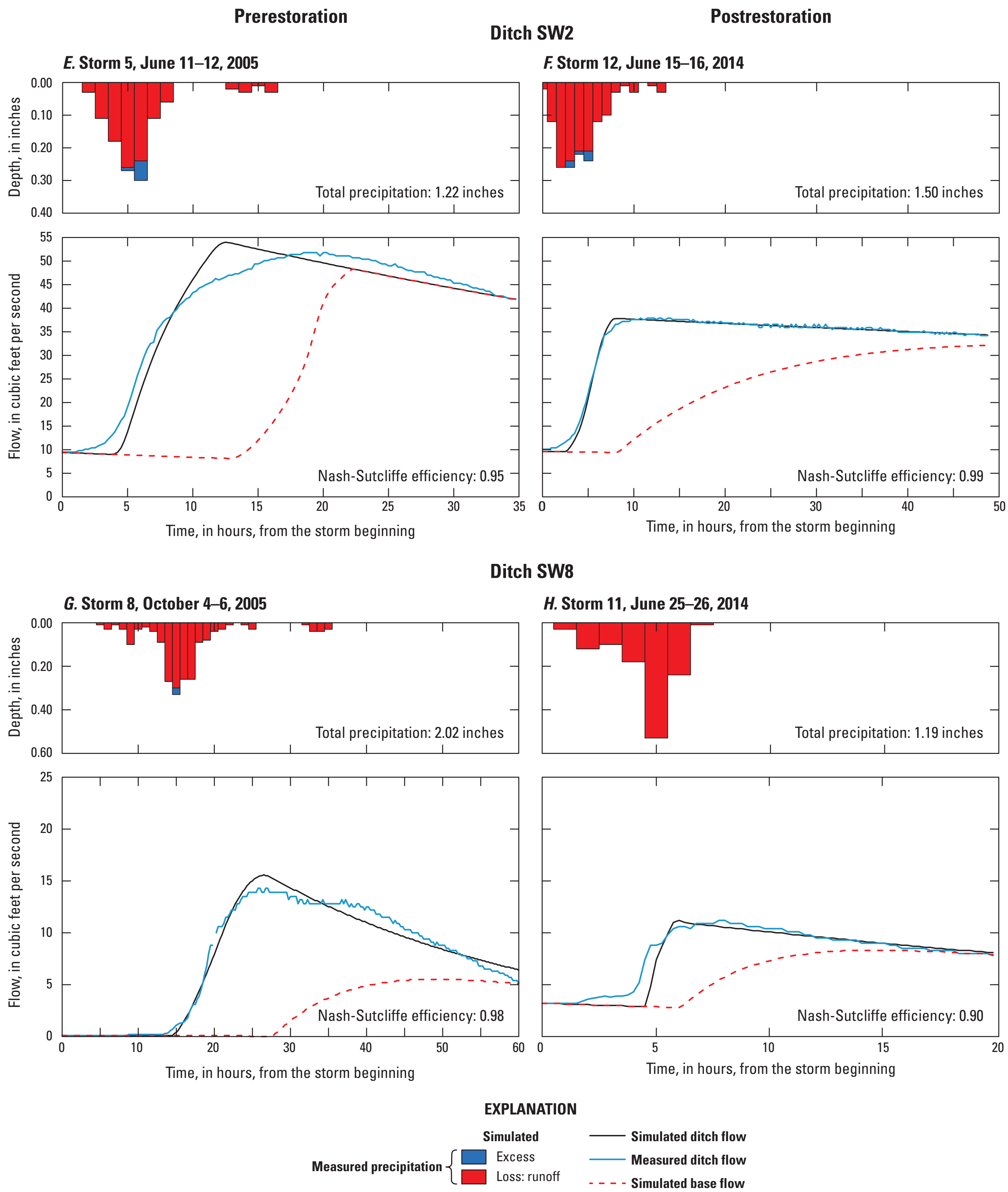


Figure 15. Example storm hydrographs and precipitation, Glacial Ridge study area, 2005 and 2014. *A*, ditch SW6, storm 5, June 11–12, 2005. *B*, ditch SW6, storm 12, June 15, 2014. *C*, ditch SW3, storm 6, August 19–21, 2005. *D*, ditch SW3, storm 12, June 15–16, 2014. *E*, ditch SW2, storm 5, June 11–12, 2005. *F*, ditch SW2, storm 12, June 15–16, 2014. *G*, ditch SW8, storm 8, October 4–6, 2005. *H*, ditch SW8, storm 11, June 25–26, 2014.—Continued

up a higher proportion of the measured flow in a stream. August ET often exceeds precipitation, and a lower proportion of the measured streamflow is surface runoff. August flows are sustained by base flow.

Prerestoration and postrestoration hydrographs at gage SW2 for storms with different precipitation totals at a similar time of the year are compared in figures 15*E* and 15*F*. The unit-hydrograph model of storm 5, which started on June 11, 2005, and totaled 1.22 in., is presented in figure 15*E*. The unit-hydrograph analysis of storm 12, which started on June 15, 2014, and totaled 1.50 in., is presented in figure 15*F*. Initial ditch flow was similar for hydrographs from both restoration periods, but the postrestoration hydrograph had a smaller peak ditch flow despite an increase in total precipitation relative to the prerestoration hydrograph. Furthermore, the simulated base flow contribution increased more gradually for the postrestoration hydrograph, possibly indicating that more precipitation was infiltrating through the soil and reaching the ditch more gradually as groundwater.

Prerestoration and postrestoration hydrographs at gage SW8 for storms with different total precipitation and at different times of the year are compared in figures 15*G* and 15*H*. The unit-hydrograph model of storm 8, which started on October 4, 2005, and totaled 2.02 in., is presented in figure 15*G*. The unit-hydrograph model of storm 11, which started on June 25, 2014, and totaled 1.19 in., is presented in figure 15*H*. Both model hydrographs had similar shapes, but the initial ditch flow was higher in June (postrestoration) than in October (prerestoration). The peak flow of the June (postrestoration) hydrograph was lower despite a higher initial ditch flow. This was probably a result of lower total precipitation relative to the October (prerestoration) storm.

Comparisons of unit-hydrograph models for individual storms from prerestoration and postrestoration periods (fig. 15) cannot be used to make direct conclusions about the effects of restorations; however, comparisons presented in figure 15 do indicate that postrestoration storms generally have lower peak ditch flow. Many factors can affect how ditches respond, including time of the year and antecedent moisture conditions. In addition, the duration, intensity, and volume of storms can affect the ability of the surrounding landscape to absorb precipitation, which then affects how quickly precipitation enters the ditches (Roberson and others, 1988). The response of these ditches to a variety of storms illustrates the importance of examining many storms over periods that include the natural range and variability of ditch flows and weather patterns (Roberson and others, 1988).

Restoration Correlations and Benefits

Although hydrologic responses to restoration activities were highly variable, results of unit hydrograph analyses correlate with wetland and prairie restorations in the study area (table 7). For example, basin SW2 was the only basin in which median initial ditch flow decreased based on unit-hydrograph models. However, basin SW2 had the smallest increase in restored lands, and nearly all restored lands were converted to prairie rather than wetlands. Therefore, the decrease in median initial ditch flow in basin SW2 likely can be attributed to reduced total precipitation and lack of groundwater discharge from wetlands and hence reduced base flow to ditches. In contrast, basins SW8 and SW6 experienced the most restoration and had the two largest increases in medians of the initial-ditch flow (table 7).

Initially, changes in the medians of the peak ditch flows from each restoration period seem variable among basins and difficult to interpret (table 7). However, when peak ditch flows are normalized to (divided by) initial ditch flow, changes from prerestoration to postrestoration become much clearer. Peak flows normalized to initial ditch flows decreased from prerestoration to postrestoration for all basins in the study area, with the largest two decreases in basins SW8 and SW6, respectively (table 7). Basins SW8 and SW6 had the highest percentages of restored lands and the highest percentages of wetlands, demonstrating that increasing percent wetland areas likely helps to sustain higher base flows and reduce peak flows.

Median recession thresholds increased between restoration periods for every basin (table 7). Nonetheless, recession thresholds were normalized to peak ditch flow because peak ditch flow increased between restoration periods. Median normalized recession thresholds also increased between restoration periods for every basin, with the largest increase in basin SW3 (table 7). Increases in normalized recession thresholds indicate that, in the postrestoration period, groundwater base flow is replacing overland flow as the source of water in the ditches at a flow that is much closer to the observed peak flow.

Unit-hydrograph model analyses demonstrate that wetland and prairie restorations in the plains area of western Minnesota provide hydrologic benefits that are measurable at a relatively short time scale (about 10 years). Ditch base flows increased, peak ditch flows decreased, and hydrograph recessions after storm-induced peaks became more gradual in the postrestoration period despite drier conditions with substantial decreases in total precipitation. Unit hydrograph model results indicate that increasing wetlands and prairies could substantially reduce flood risks and severity. Furthermore, increased base flows likely will create more sustainable low flows that provide better and more continuous habitat for aquatic food webs (Poff and others, 1997).

Water Quality

Water quality in samples from the study area greatly and significantly improved after wetland and prairie restoration. The quality of water sampled generally became more suitable for most uses but remained variable after the restorations. Because postrestoration water samples were measured or analyzed for field measurements, nutrients, and suspended sediment (ditch-water samples only), comparisons with prerestoration samples could only be made among these constituents.

As expected, the quality of water from two wells open to buried aquifers did not change. The lack of change may be because land use in the recharge area did not change or because the recharge area is so far away that land use effects on water quality have not yet reached the wells sampled. Data from these wells (E01D and E02D) are not further discussed in this report. Water-quality results from the 10 temporal network wells in surficial aquifers are too few to produce a statistically valid sample of all the water in the surficial aquifers in the study area. However, these wells were sampled for nutrients during a 1994 synoptic sampling of 39 wells, which was a statistically valid representation of the state of water quality in these surficial aquifers. See Cowdery and others (2007) for detailed results of the synoptic sampling. During the 1994 sampling, the median concentrations of nutrients in samples from the 10 temporal network wells in surficial aquifers were similar to the other 29 synoptic samples except for nitrate. The median nitrate concentration in samples from temporal network wells was 1.22 mg/L–N higher than the median nitrate concentrations from all surficial synoptic samples, indicating that samples from the temporal network represent water more affected by nitrate than the usual water from surficial aquifers in the study area. Temporal-network wells were purposefully chosen to include wells with high nutrient concentrations to study how land-use changes affected water quality across the range of concentrations in the study area.

Groundwater

Between restoration periods, the median concentrations of all nitrogen compounds except organic nitrogen decreased significantly in samples from temporal water-quality network surficial wells (fig. 16; Wilcoxon rank-sum test *p*-value [hereinafter, *p*-value]: less than 0.005; table 12). Strikingly, the median nitrate as nitrogen (N) concentration decreased by more than 7 mg/L or 78.5 percent. Median phosphorus concentrations in samples from surficial aquifers were not significantly different (hereinafter, significantly means a *p*-value less than 0.05). Median total dissolved phosphorus concentrations were nearly unchanged, but median dissolved orthophosphate as phosphorus concentrations increased 0.004 mg/L. The median value for all field measurements of samples from surficial aquifers decreased significantly, except for dissolved-oxygen concentration, which increased significantly (*p*-value=0.046). Variability remained about the same between samples collected during each restoration period. This stable variability probably reflects the fact that the 10 wells sampled were chosen to span the range of water quality in the study area. Median nutrient concentrations in the two wells open to buried aquifers were nearly the same between prerestoration and postrestoration periods, reflecting their hydrologic isolation from the land use changes that occurred above them.

Not all median concentrations of water from temporal water-quality network surficial wells changed in the same way, however (for example nitrate; fig. 17). Median nutrient concentrations in samples from well G13, in an area where land use did not change between restoration periods, did not change significantly during the study. Concentrations of nitrogen compounds in samples from all other wells, except E03 and G16, decreased significantly. Median concentrations of nitrate and organic nitrogen increased five- and two-fold, respectively, between restoration periods in samples from well G16; however, only the nitrate increase was statistically significant. Well G16 is on restored land, adjacent to and hydrologically downgradient from land used for row-crop agriculture. Increasing nutrient concentrations in postrestoration samples from well G16 may be caused by an increase in application of agricultural fertilizer on cropland near the well.

Median ammonia and nitrate concentrations in samples from well E03 increased significantly between restoration periods. The median nitrate concentration nearly doubled to 14.5 mg/L–N. Median organic nitrogen and phosphorus concentrations also increased but not significantly. Among temporal network wells, E03 is completed deepest in the surficial aquifer (59–69 ft below land surface). It is possible that water from this deep within the surficial aquifer was recharged before restoration changes or may have recharged beyond the area of land-use change.

Median nutrient concentrations decreased the most in water from wells G08 and G22S (fig. 17). These wells were located in the most intensely agricultural parts of the study area when sampling began in 2002. Well G08 is adjacent to a large confined cattle-feeding area that was removed around 2000. Well G22S is at the top of a sandy beach ridge, adjacent to another well used to supply irrigation water to a row-crop field. This field produced corn, soybeans, and sunflowers during this study (2002–15). Land use around these wells was nutrient-intensive before restoration. Among all samples from the study, nitrate concentrations were greater than 21 mg/L–N only in samples from these wells. Median nitrate concentration decreased from 42 to 2 mg/L–N in samples from well G08 after confined cattle-feeding operation ceased. The decrease occurred within about a decade after the feedlot closed, facilitated by short groundwater flow paths and substantial denitrification (Simmons, 2009) in the aquifer. Median nitrate concentrations also decreased from 81 to 34 mg/L–N in samples from well G22S from the prerestoration to the postrestoration period. This well is in an irrigated row-crop field with no obvious land-use change that can explain the decrease; however, the landowner may have decreased fertilizer applications after he was made aware of the nitrate concentrations in the groundwater beneath his fields. Samples from both wells had the largest decreases in median nitrate concentration (more than 40 mg/L–N) from the prerestoration to the postrestoration period, likely because their prerestoration concentrations were so high.

Changes in the median concentration of phosphorus compounds showed no spatial pattern. Samples from some wells had very small increases, whereas those from others had very small decreases. The absolute values of significant changes in median phosphorus-compound concentrations were less than 0.01 mg/L as phosphorus in samples from the 10 temporal

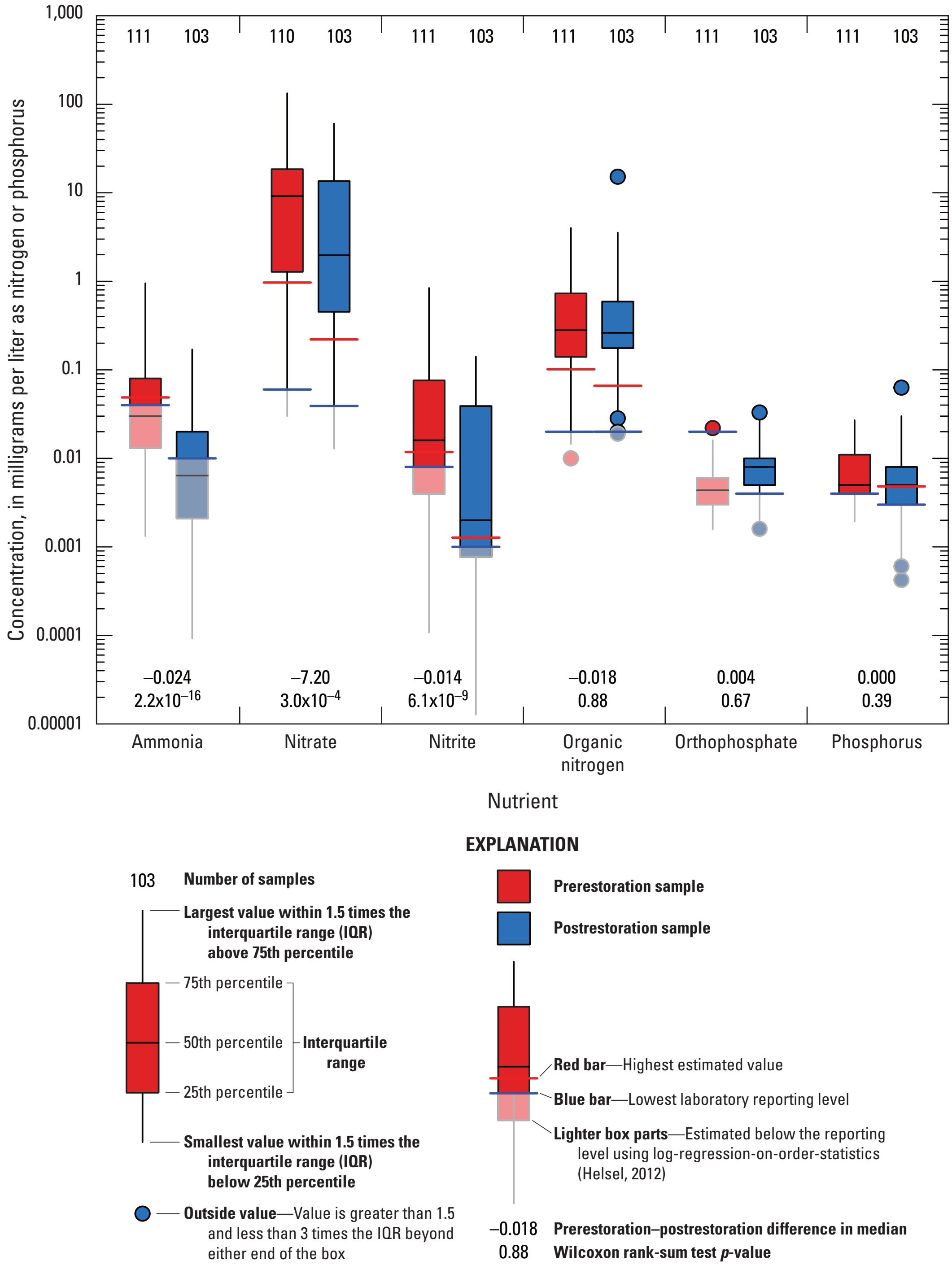


Figure 16. Prerestoration and postrestoration nutrient concentrations in water from surficial aquifers, Glacial Ridge study area, 2003–15.

network wells. The number of wells with significant decreases equaled the number of wells with significant increases for orthophosphate (three each). Wells with significant increases outnumbered those with decreases by 3 times (6 to 2). The lack of spatial phosphorus concentration patterns is probably caused by the small concentration of phosphorus in the surficial aquifers.

Table 12. Change in median measurements in water samples between 2002–6 (prerestoration period) and 2012–15 (postrestoration period), Glacial Ridge study area, northwestern Minnesota.

[Pre, prerestoration period (2003–6); C/N, number of censored values/number of values; Post, postrestoration period (2012–5); RDP, relative percent difference; *p*-value, Wilcoxon rank-sum test *p*-value; BLS, below land surface; °C, degree centigrade; µS/cm at 25 °C, microsiemen per centimeter at 25 degrees Celsius; mg/L, milligram per liter; N, nitrogen; P, phosphorus; ft^3/s, cubic foot per second; NTU, nephelometric turbidity unit; —, no data; blue measurement, dissolved concentration; orange measurement, particulate concentration]

Measurement	Unit	Pre C/N	Post C/N	Pre median	Post median	Pre-post difference	RPD (percent)	Difference *p*-value
Samples from wells open to surficial aquifers								
Water level	feet, BLS	0/62	0/103	6.60	6.83	0.24	3.6	0.762
Water temperature	°C	0/111	0/103	10.0	9.4	−0.6	−6.0	0.099
Specific conductance	µS/cm at 25 °C	0/111	0/101	727	625	−102	−14.0	2.010^{-5}
pH	Standard units	0/111	0/103	7.3	7.2	−0.1	−1.4	0.005
Dissolved oxygen	mg/L	11/105	6/97	1.7	3.5	1.8	105.9	0.066
Ammonia	mg/L as N	58/111	55/103	0.030	0.006	−0.024	−78.7	2.2×10^{-16}
Nitrate	mg/L as N	17/110	15/103	9.173	1.972	−7.201	−78.5	3.0×10^{-4}
Nitrite	mg/L as N	40/111	34/103	0.016	0.002	−0.014	−87.5	6.1×10^{-9}
Organic nitrogen	mg/L as N	21/111	9/103	0.280	0.262	−0.018	−6.4	0.883
Orthophosphate	mg/L as P	63/111	14/103	0.004	0.008	0.004	83.6	0.672
Total phosphorus	mg/L as P	3/111	26/103	0.005	0.005	0.000	0.0	0.392
Samples from ditches								
Gage height	feet	0/107	0/97	1.48	1.37	−0.11	−7.4	0.197
Discharge	ft^3/s	0/151	0/93	1.00	0.52	−0.48	−48.0	0.003
Water temperature	°C	0/121	0/102	10.4	15.0	4.5	43.7	1.7×10^{-7}
Specific conductance	µS/cm at 25 °C	0/154	0/102	578	617	40	6.8	0.001
pH	Standard units	0/154	0/102	7.9	7.8	−0.1	−1.3	0.007
Dissolved oxygen	mg/L	0/154	0/102	10.1	8.2	−1.9	−18.8	0.022
Turbidity	NTU	0/0	0/102	—	3	—	—	—
Suspended sediment	mg/L	0/81	0/101	66	24	−42	−63.6	9.6×10^{-8}
Ammonia	mg/L as N	86/154	23/102	0.031	0.020	−0.011	−34.9	1.3×10^{-18}
Nitrate	mg/L as N	72/154	58/102	0.087	0.041	−0.046	−52.9	1.7×10^{-8}
Nitrite	mg/L as N	79/154	39/102	0.006	0.002	−0.004	−66.7	1.9×10^{-21}
Organic nitrogen	mg/L as N	0/154	0/102	0.755	0.820	0.065	8.6	0.011
Ammonia	mg/L as N	30/154	30/102	0.085	0.075	−0.010	−11.8	0.206
Orthophosphate	mg/L as P	108/154	12/102	0.011	0.007	−0.004	−37.1	4.7×10^{-25}
Total phosphorus	mg/L as P	1/154	4/102	0.015	0.014	−0.001	−6.7	0.144
Total phosphorus	mg/L as P	2/154	0/102	0.014	0.013	−0.001	−7.1	0.584

Surface Water

Like samples from wells, the median concentrations of all dissolved nutrients except organic nitrogen and total phosphorus in samples of ditch water decreased significantly (fig. 18; *p*-value less than 0.005; table 12) from the prerestoration to the postrestoration period. Median nitrate and nitrite concentrations decreased by more than one-half and median orthophosphate concentrations decreased by more than one-third. Median suspended-sediment concentrations decreased by nearly two-thirds from 66 to 24 mg/L, reflecting the decrease in median ditch flow of nearly 50 percent. Even when normalized for decreased precipitation of 14 percent in the postrestoration period, total ditch flow decreased by an average of 4 percent of precipitation after restoration, reducing the ditches' ability to transport sediment. Decreased overland flow (runoff) and increased groundwater discharge to ditches (base flow) after restorations (fig. 12*B*; table 9) also may account for lower dissolved oxygen and higher specific conductance (characteristics of groundwater quality relative to surface-water quality in the study area) in postrestoration ditch water.

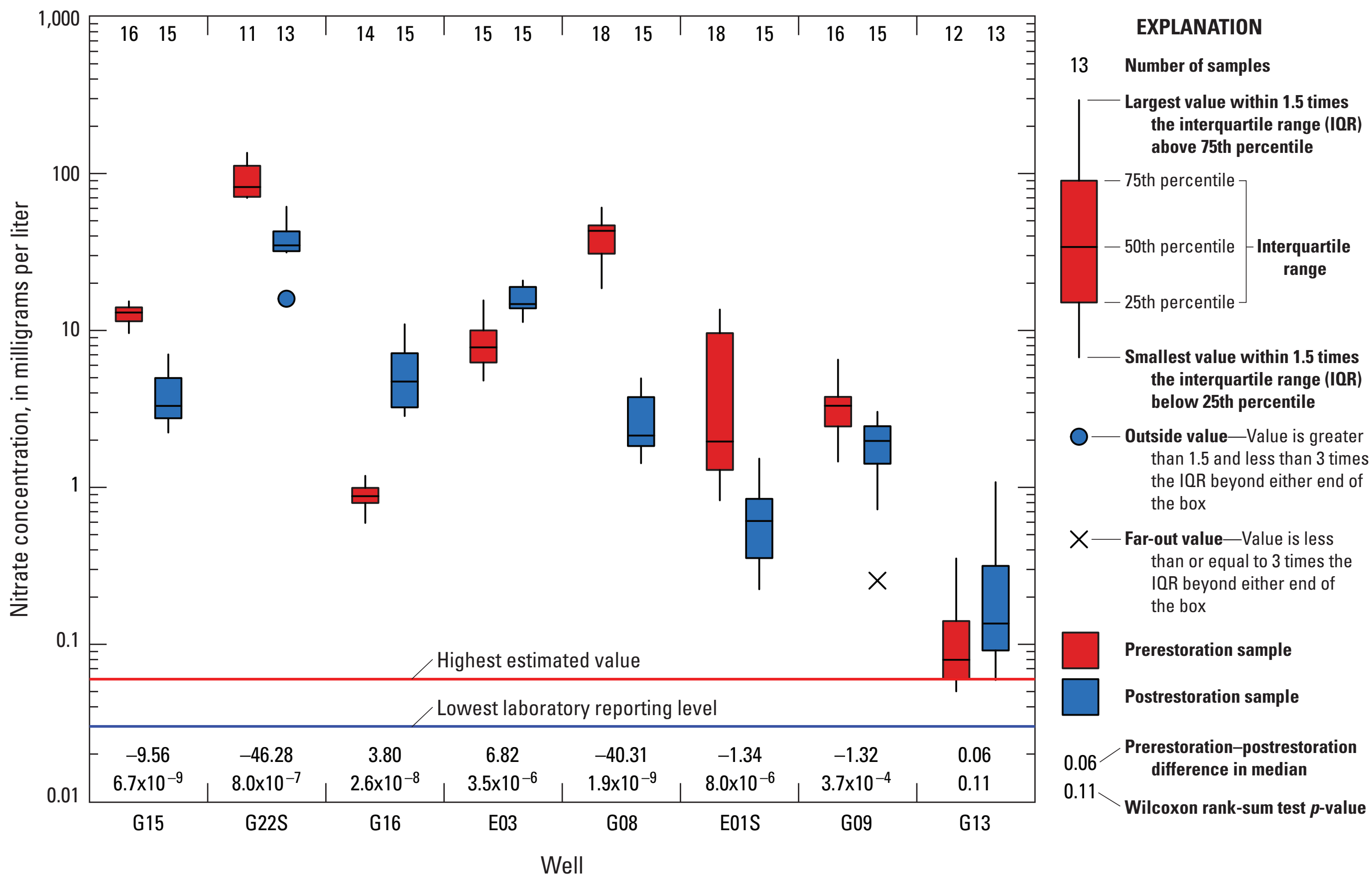


Figure 17. Prerestoration and postrestoration nitrate concentrations in water from surficial aquifers by well, Glacial Ridge study area, 2003–15.

In samples from individual ditches, all significant median nutrient concentration changes between restoration periods were decreases except for dissolved organic nitrogen from ditch SW3, which increased by 0.034 mg/L–N, and dissolved ammonia from SW8, which increased by 0.012 mg/L–N. Median nitrite concentrations decreased in all ditches, but the decrease was not significant at SW5. The largest significant median nutrient concentration decrease was 0.57 mg/L–N nitrate at ditch SW6. Median concentration changes of particulate ammonia, total phosphorus, and total dissolved phosphorus were not significantly different at any ditch between the restoration periods.

The median suspended-sediment concentration decreased significantly in samples from all ditches except SW2 and combined SW1 and SW8. Decreases in suspended-sediment concentrations ranged from −32 to −68 mg/L and were largest in ditch SW5 (fig. 19). A large decrease in median suspended-sediment concentration occurred in samples from ditch SW8, but this difference is anecdotal because only two prerestoration samples were collected. The decrease in suspended-sediment concentration in ditch SW5 is difficult to explain by land-use change alone because the area of cropland in the basin increased 13 percent at the expense of fallow land, tame grass, and noncropland. Prairie land use did increase 8 percent in the basin, but this was again at the expense of fallow land, tame grass, and noncropland, a land-use group with runoff and erosive characteristics similar to prairie. In fact, there does not seem to be an obvious correlation between land-use change and changes in the median concentration of ditch water nutrients and sediment when the data are disaggregated into individual ditch basins. This lack of correlation may reflect a complex interaction of water among many factors, including precipitation amount and intensity, landscape characteristics, land use, and ditch water quality; however, suspended-sediment concentration in ditch water likely is sensitive to precipitation. During the postrestoration period, precipitation in the study area decreased and occurred in more frequent but less intense storms. These precipitation characteristics would entrain less sediment in overland flow, which also decreased. Less overland flow produced lower peak flows in ditches, which would be less likely to entrain sediment from ditch channels. The reduced amount and intensity of precipitation during the postrestoration period could explain much of the decrease in suspended-sediment concentration in study area ditches.

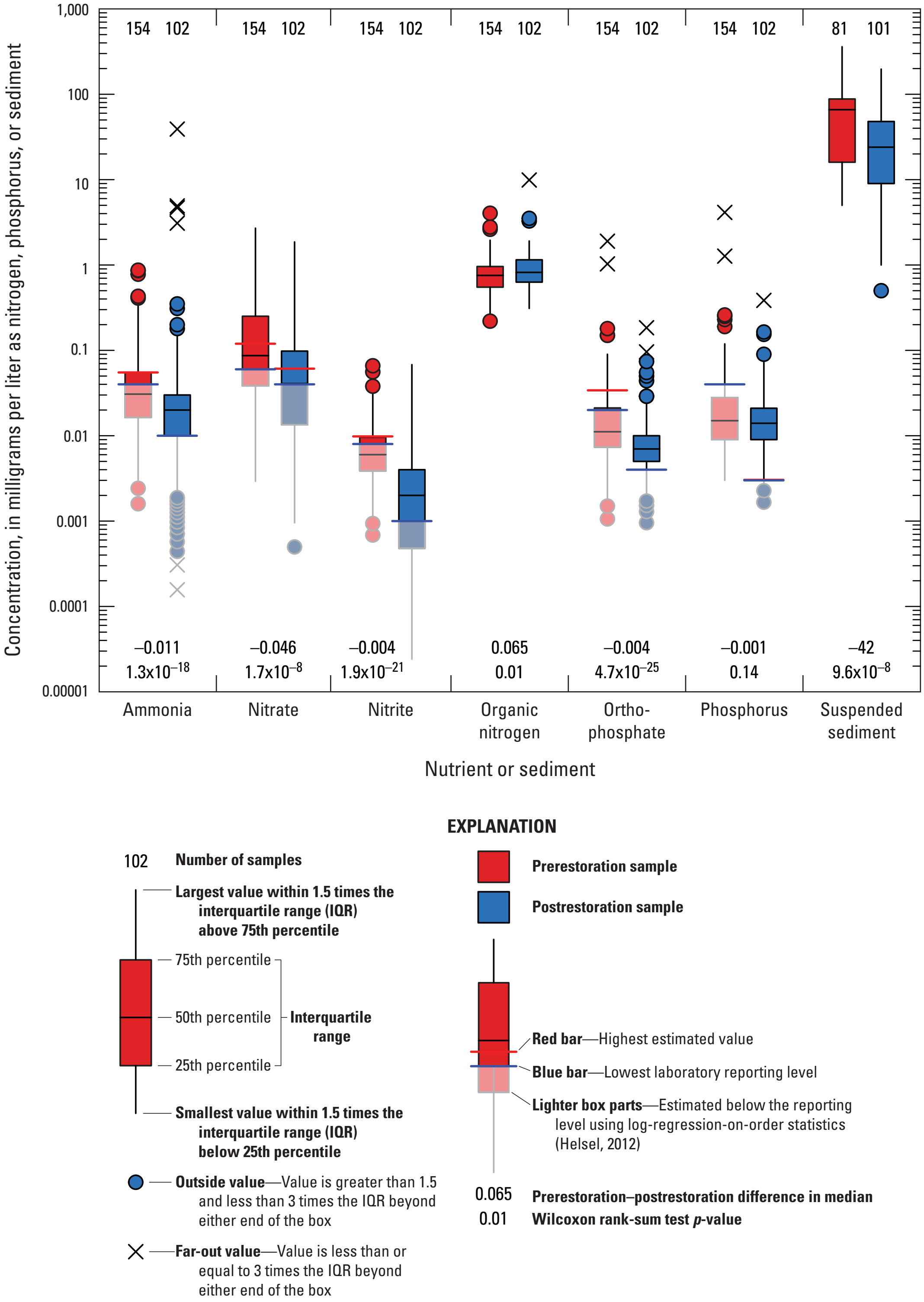


Figure 18. Prerestoration and postrestoration dissolved nutrient and suspended-sediment concentrations in water from ditches, Glacial Ridge study area, 2003–15.

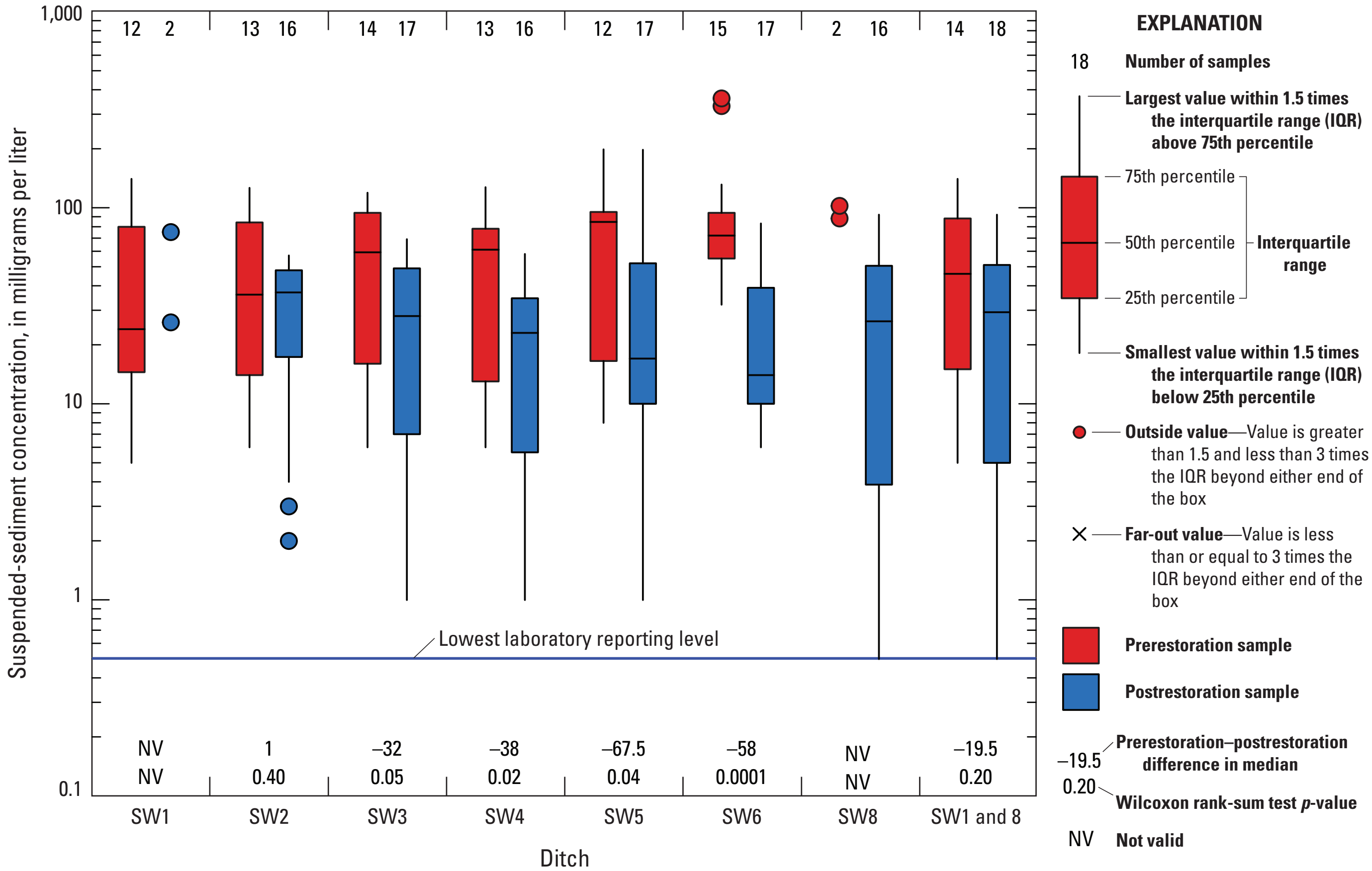


Figure 19. Prerestoration and postrestoration suspended-sediment concentrations in water by ditch, Glacial Ridge study area, 2003–15.

Hydrologic Benefits of Wetland and Prairie Restoration and Implications for Western Minnesota

The six ditches examined in the Glacial Ridge study area are unusual because their headwaters are contained within the study area. Each basin provides a small example of what kind of hydrologic benefits can result from wetland and prairie restorations. The ditch basins received varying amounts of restoration and have different landscape characteristics. The basins also exhibited different amounts of hydrologic change. To explore if restorations and landscape characteristics related to hydrologic change, selected measures of basin restorations and landscape characteristics were plotted against selected hydrologic benefits for each basin (fig. 20; table 13). These measures were selected because restorations are the focus of this study and landscape characteristics are easily mappable across western Minnesota. Changes in groundwater recharge, overland runoff, and total ET are the components of the hydrologic cycle that changed most from the prerestoration to the postrestoration period (fig. 12) and each change was a hydrologic benefit. Increased groundwater recharge reduces overland runoff into ditches, runoff that contributes to flooding. Similarly, increased recharge increases base flow to ditches and discharge to ponds and wetlands, keeping these surface-water bodies wet longer during dry periods and providing better habitat. Decreased overland runoff reduces flood peaks in ditches. Increased ET reduces the amount of water flowing from the basin, which, in combination with decreased overland runoff, reduces the potential for flooding downstream.

Many of the landscape characteristics plotted for correlation with hydrologic benefits are themselves related. Percent area of surficial aquifer and percent area of sand soils are positively related because coarser-grained soils act as aquifers. These characteristics are inversely related with percent area of till, wave-washed till, and organic wetland soils because sand, till, and organic deposits compose all surface materials in the study area. Likewise, many of the areas of land-use change are related. Areas of restoration (both as percent and as total area) are inversely related with areas that were restored, particularly cropland and fallow land.

The landscape characteristics and land-use changes that most related with hydrologic benefits are highlighted in grey in table 13. One group of characteristics relates well to increased recharge (fig. 20*B*). This group consists of percent area of sand soils and surficial aquifers (positively related), and till, wave-washed till, and wetland soils (inversely related). These correlations illustrate that more recharge will occur in basins that are underlain by a higher percentage of sandy surficial aquifers. This relation will be called the "sand-soils factor."

Another group of land-use changes is somewhat related to a decrease in the increase of total ET (fig. 20*A*). This group (hereinafter called the restored-wetland factor) consists of wetland area, prairie area, and the sum of wetland and prairie area (negatively related). The mechanisms controlling this correlation are unclear. After restoration, ET increased in all six basins, but, except for basin SW5, ET tended to increase the most in basins with the least amount of restored wetland area. This indicates that there may be a threshold above which more wetlands are not able to increase ET. Alternatively, excluding basin SW2 from the analysis may be justified because this basin contains an unusually high concentration of lakes and wetlands. This concentration may have produced an unusually high increase in ET during the postrestoration period, which was 14 percent drier than the prerestoration period. If basin SW2 is removed, the slope of the relation is very close to zero, indicating the relation between restored wetland area and ET is weak at best. Other landscape characteristics examined, like the ditch channel slope (using various measurement schemes) and average basin slope, were not significantly related with any hydrologic benefit.

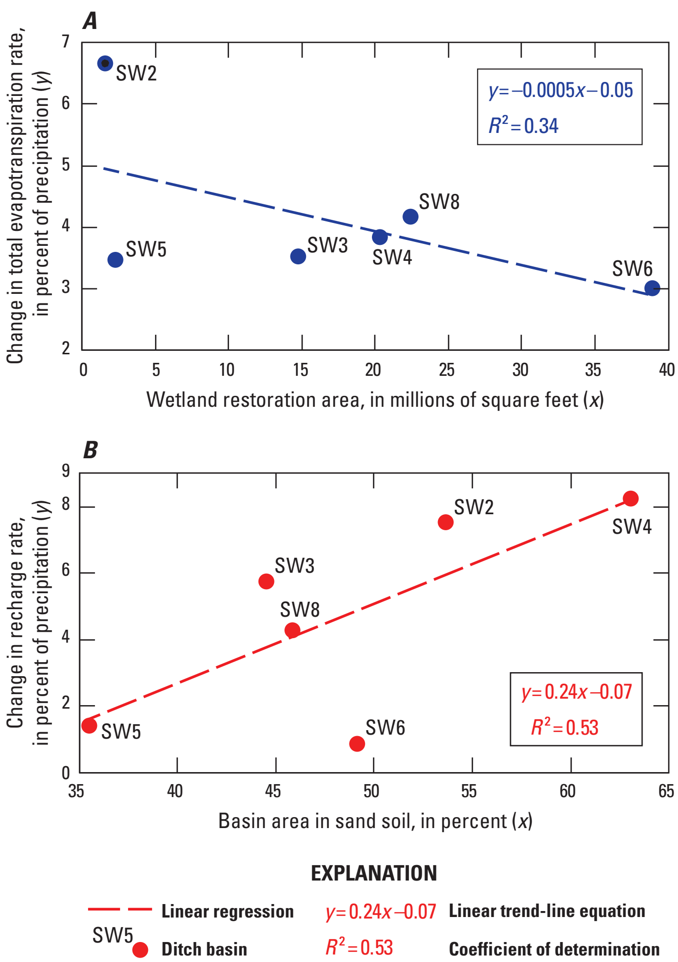


Figure 20. Correlations between restoration change or landscape characteristic and hydrologic change by ditch basin, Glacial Ridge study area, northwestern Minnesota, 2002–15. *A*, change in total evapotranspiration rate by wetland restoration area. *B*, change in recharge rate by basin area in sand soil.

This analysis was limited by having only six landscape/land-use change against hydrologic-benefit pairs with which to deduce a correlation. Also, in many change-benefit plots, one basin often falls far off of a linear trend, causing uncertainty in the relation and lowering the coefficient of determination (SW2 in fig. 20*A* and SW6 in fig. 20*B*). Finally, all six basins in the analysis are adjacent to each other and quite similar in characteristics. Although this is an advantage in eliminating a myriad of confounding factors, resulting data are bunched on the independent axis, confounding efforts to deduce a correlation trend.

The measurements and analyses produced for this study demonstrate that stream basins with larger areas of sandy soils and restorable wetlands will benefit more from wetland and prairie restorations. As restorations occur, runoff from precipitation falling on prairie more easily infiltrates the landscape, especially on sandy soil, and recharges surficial aquifers rather than continuing to streams. The permanence of the vegetation and the very deep roots of many prairie grasses likely contribute to this effect. Likewise, restored wetlands store runoff that cannot infiltrate, further reducing runoff reaching streams. Increased groundwater recharge increases groundwater discharge to streams, but this discharge occurs slowly, providing base flow to keep streams flowing during dry periods. Further, groundwater also discharges to closed subbasins, many of which contain wetlands. The increased groundwater discharge to closed subbasins and the increased wetland storage within basins keep wetlands wet longer, providing habitat for wetland plants and animals, improving water quality (Crumpton, 2001), and, by increasing ET, decreasing water that otherwise would have left a basin as ditch flow. The decrease in total ditch flow from a basin reduces the likelihood of flooding downstream.

The mechanisms of hydrologic benefits derived from wetland and prairie restoration identified in this study likely function everywhere, but the amount of benefit measured at the Glacial Ridge is most relevant to similar landscapes. To identify where wetland and prairie restoration may produce the most hydrologic benefits, the amount of sandy soils and drained wetlands in each of the MNDNR Level-07 watersheds were mapped across western Minnesota (fig. 21). The mapping was restricted to the western one-third of Minnesota because this area is most like the study area. However, the results of this analysis likely also are relevant to the Prairie Pothole Region of eastern North and South Dakota and southern Manitoba, Canada.

Table 13. Linear trend-line direction and coefficient of determination between restoration change or landscape characteristics and hydrologic change in ditch basins, Glacial Ridge study area, northwestern, Minnesota, 2002–15.

[ET, evapotranspiration; R^2, coefficient of determination; Dir., direction of correlation; −, negative; +, positive; shaded factor, those selected for mapping; shaded R^2, values greater than 0.3. The choice of the R^2 value of 0.3 for shading in this table is arbitrary, but highlights relatively high values]

Ditch-basin factor		2002–15 change as a percentage of precipitation					
		Recharge		Runoff		ET	
		R^2	Dir.	R^2	Dir.	R^2	Dir.
Percentage of area	Surficial aquifer	0.45	+	0.17	−	0.17	+
	Sand soils	0.53	+	0.09	−	0.10	+
	Till soils	0.39	−	0.23	+	0.08	−
	Wave-washed till soils	0.60	−	0.01	+	0.27	−
	Wetland soils	0.25	+	0.13	−	0.25	+
Ditch channel slope,[1] in feet per mile	StreamStats	0.04	+	0.22	−	0.02	+
	First report[2]	0.49	+	0.07	−	0.01	−
	This report[2]	0.04	−	0.04	+	0.00	−
	Mean basin slope, in percent	0.02	+	0.00	+	0.00	−
2002–15 percent change in area	Wetland	0.01	−	0.01	+	0.26	−
	Total restorations	0.02	−	0.00	+	0.25	−
	Cropland	0.05	−	0.02	+	0.09	+
	Fallow land	0.11	+	0.50	−	0.14	+
2002–15 change in area, in square feet	Restored wetlands	0.11	−	0.02	+	0.34	−
	Restored prairie	0.23	−	0.03	+	0.34	−
	Total restorations	0.20	−	0.03	+	0.34	−

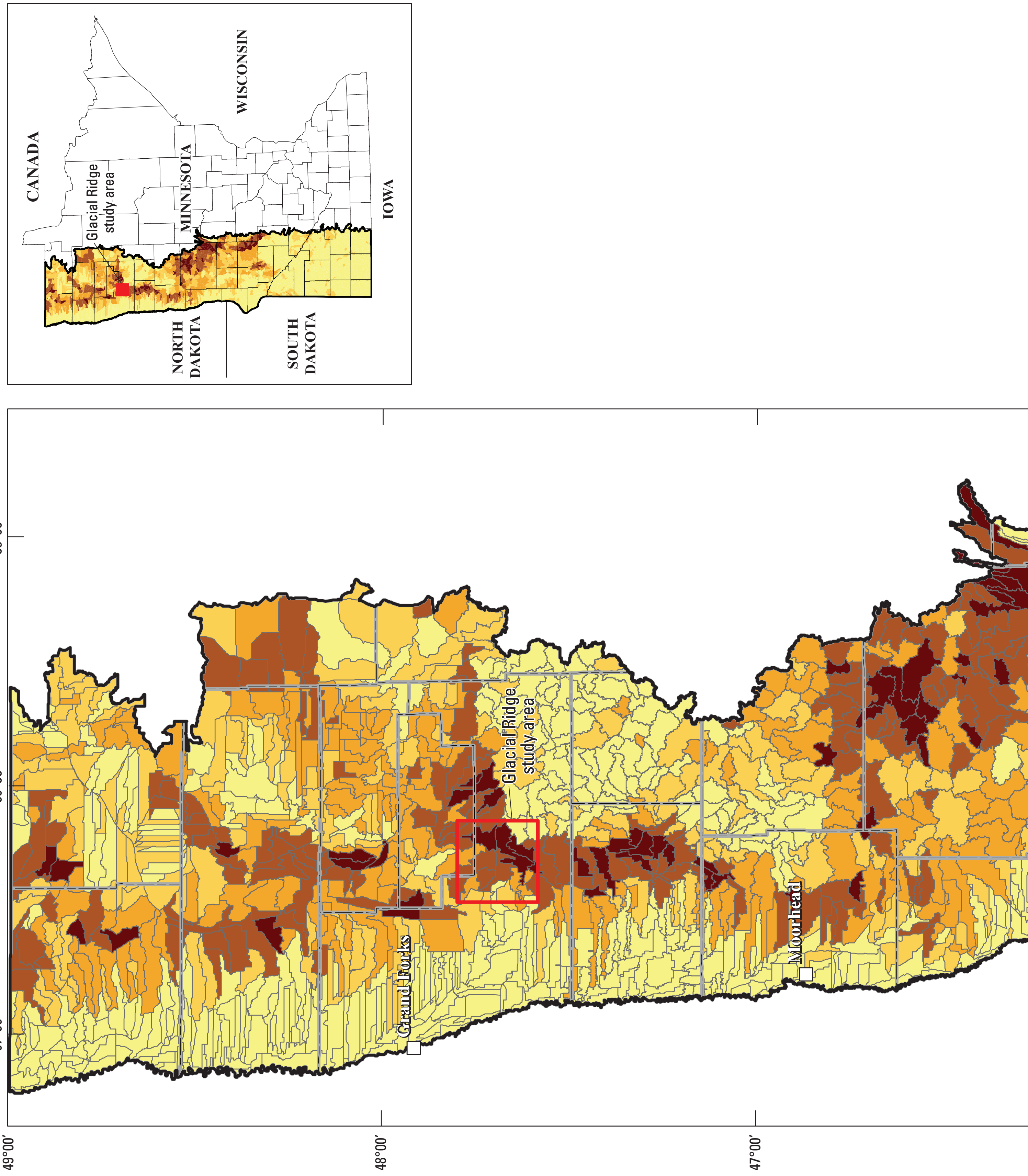
[1]10th–85th percentile method used in all three measurements.

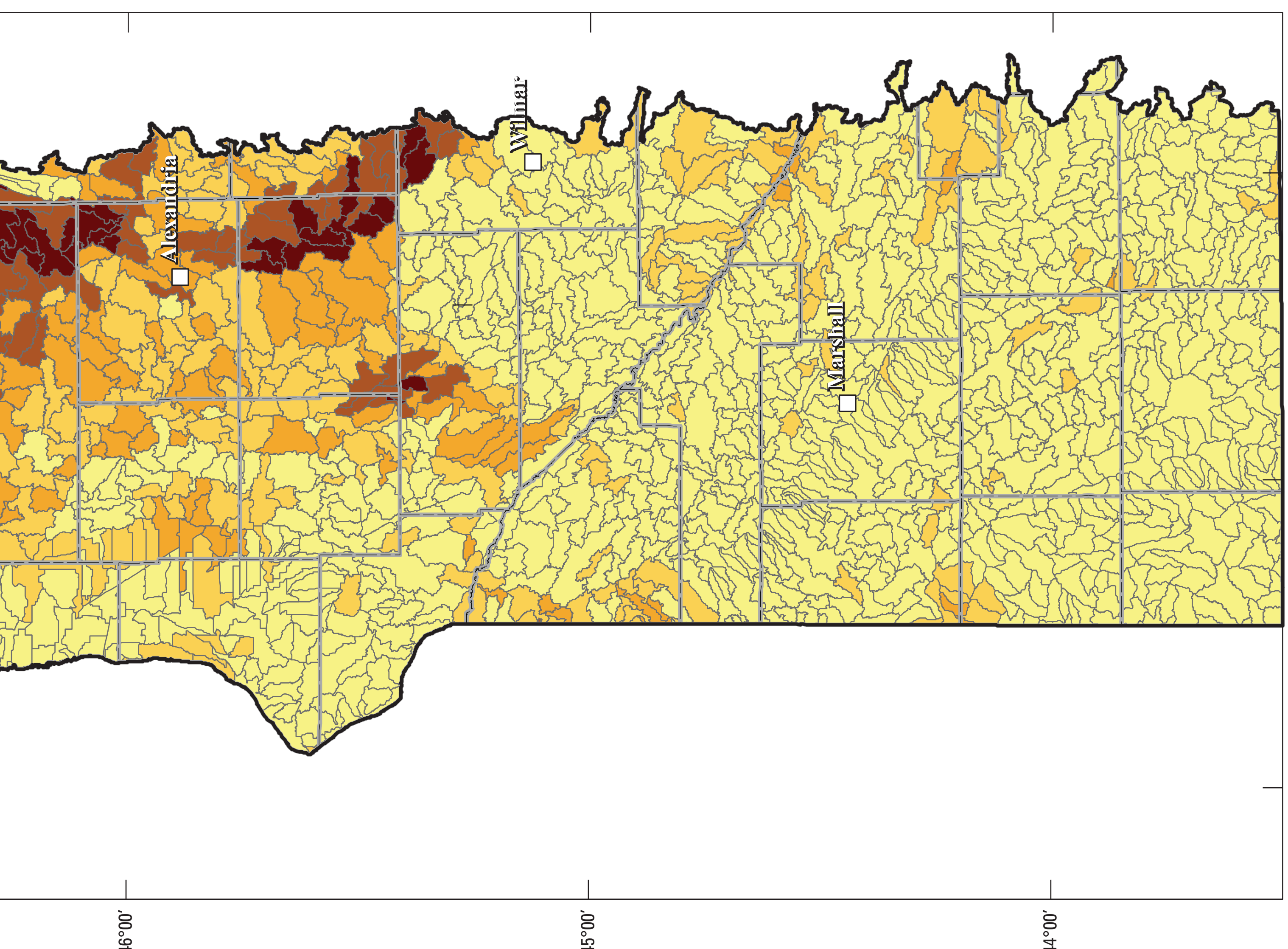
[2]The two report measurements rely on the authors' local knowledge of the basin hydrology to define the main channel at the time of the report.

The darker areas in figure 21 are watersheds where we would expect greater hydrologic benefits from wetland and prairie restoration. Darker areas have a higher percentage of sandy-soil and drained-wetland area. These areas occur north of Wilmar, Minn., and are the beaches of glacial Lake Agassiz and the Alexandria Moraine Complex (not mapped in fig. 21), especially in upland areas. The Lake Agassiz beaches are the same geological landforms in which surficial aquifers occur in the study area. Outside the area of figure 21, restorations in the western beaches of Lake Agassiz in North and South Dakota likely would produce benefits like those documented in this study because the geology and hydrology of the two areas are very similar.

The Alexandria Moraine Complex is a highland in western Minnesota formed as glacial lobes of the Laurentide Ice Sheet crossed the area many times (Wright, 1972). The complex is formed of overlapping lateral- and end-moraines, which were deposited by ice lobes from the west and east sides. The surface of the north-south axis of the complex is hummocky and rugged, characterized by typical features like ice-block lakes and wetlands, coarse-grained ice-contact stratified deposits, and small coarse-grained outwash deposits. More extensive coarse-grained outwash deposits drape the complex on the west and east.

The Alexandria Moraine Complex is most like the study area's basins SW2 and SW3, which are part of the Erskine Moraine (not shown). Parts of the Alexandria Moraine Complex contain extensive areas of sandy soils and drained wetlands that likely function hydrologically like the study area. However, the difference in formation of the complex may make wetland and prairie restoration produce somewhat different hydrologic benefits than those documented in this study. That said, restorations in the eastern part of the Alexandria Moraine Complex likely would produce similar benefits to those in the western part. These findings provide resource managers with information that can help focus restoration resources in areas where the greatest hydrologic benefits can be realized.


CANADA
WISCONSIN
Glacial Ridge study area
MINNESOTA
IOWA
NORTH DAKOTA
SOUTH DAKOTA
95°00′
96°00′
97°00′
Glacial Ridge study area
Grand Forks
Moorhead
49°00′
48°00′
47°00′



EXPLANATION

Watershed area covered in surficial aquifer material and drained wetland, in percent

- 0 to 7
- >7 to 19
- >19 to 36
- >36 to 60
- >60 to 100

Base from U.S. Geological Survey digital data 1:100,000 and 1:24,000, 1972
Transverse Mercator projection
Central meridian –96°15'W

0 10 20 30 40 50 MILES
0 10 20 30 40 50 KILOMETERS

Figure 21. Watersheds showing percent of area covered in surficial aquifers and drained wetlands; larger percentage indicates increasing potential for hydrologic benefit from wetland and prairie restoration, western Minnesota.

Summary

The Nation's largest wetland and prairie restoration at the Glacial Ridge National Wildlife Refuge provided an unparalleled opportunity to identify and quantify the hydrologic changes produced by these restorations. The U.S. Geological Survey cooperated with the Minnesota Environment and Natural Resources Trust Fund, the U.S. Fish and Wildlife Service, and the Red Lake Watershed District to investigate changes between prerestoration (water years 2003–6) and postrestoration (water years 2012–15) hydrology resulting from restorations in the Glacial Ridge area.

The hydrologic changes compared between restoration periods were flows in the water cycle, storm-overland runoff behavior, and nutrient and sediment concentrations in water. Because the study area contains six separate ditch basins, all of which head in the study area, restoration and hydrologic changes were computed for each basin and for all six basins as a whole (called the core area). These six basins compose 33 percent of the study area. Precipitation decreased by 14 percent over the whole study area between restoration periods. All flows were normalized to precipitation and compared as flow rates to make water-cycle flow components comparable between periods. Changes in flow rates and those changes relative to the initial flows (relative increase in flow rates [RIFRs]) reveal important features of the hydrologic response to restorations.

Land use changed substantially between 2002 and 2015. Within the core area, wetland area increased by 6 percent, native prairie area increased by 19 percent, cropland area decreased by 14 percent, and fallow, tame grass, and noncrop land area decreased by 7 percent between 2002 and 2015 because of restorations. Basin SW6 changed the most (37-percent increase in restored lands) and basin SW2 changed the least (9-percent increase in restored lands). In basin SW5 restoration land increased 9 percent but cropland increased 13 percent. The percentage of ditches abandoned ranged from 25 (basin SW5) to 97 (basin SW8), with 64 percent of all ditches being abandoned in the core area. Ditch density in the core area decreased from 1.9 to less than 0.7 mi of ditch per square mile of basin.

Between prerestoration to postrestoration periods, potential for downstream flooding decreased and water quality improved markedly in the Glacial Ridge study area. In the core area, average annual total ditch-flow rate and runoff rate from the core area decreased by 4 percent of total precipitation, or by 23 and 33 percent RIFR, respectively. This resulted in 206 million cubic feet (Mft^3) less water leaving the basin in ditches annually. Had average annual precipitation been the same as the prerestoration period, 141 Mft^3 less water would have left the core part of the study area annually. The decrease in total water leaving the basin through ditch flow was balanced by an increase in total evapotranspiration rate of 3 percent. Areal groundwater recharge rate increased from 30 to 35 percent (16 percent RIFR). Base flow as a proportion of total ditch flow increased from 25 to 35 percent (a 40-percent relative change). During storms, median peak ditch flows decreased when normalized to initial ditch flow. After storms, hydrograph postpeak recessions were more gradual, with generally decreasing median recession constants. Each of these changes reduces the amount of ditch water leaving the study area, reducing the likelihood of downstream flooding, either in total amount (less ditch flow) or lower flood peaks (more ditch base flow and less overland runoff). Increased base flow means that ditches will flow more days throughout the year benefiting aquatic ecosystems. Median groundwater-sample nitrogen concentrations generally decreased by nearly an order of magnitude. Median ditch-water-sample nitrogen and suspended-sediment concentrations decreased, though not by as much as those in groundwater samples.

Neither the density of restorations nor the beneficial changes in hydrology were evenly distributed in the study area. The amount of hydrologic benefits within an individual ditch basin did not relate directly with the amount of restoration in that basin. However, the landscape characteristics that related most closely with hydrologic benefits were the area of a basin underlain by a surficial aquifer and the area of drained wetlands (indicating the potential for wetland restoration). Surficial aquifers provide a groundwater reservoir that can reduce runoff and slowly release water as base flow to streams. The presence of drained wetlands provides the opportunity for their restoration, which increases surface-water storage and reduces streamflow. In western Minnesota, the basins that are underlain by surficial aqufiers and that contain large areas of drained wetlands are the uplands of the Alexandria Moraine Complex and the beaches of glacial Lake Agassiz on the eastern side of the western one-third of Minnesota, north of Wilmar, Minnesota. These findings provide resource managers with information that can help focus restoration resources in areas where the greatest hydrologic benefits can be realized.

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Appendixes

Appendix 1. Gridded Soil Survey Geographic Database (gSSURGO) Parent Group-Material Units

Table 1.1. Gridded Soil Survey Geographic database (gSSURGO) parent-group-material classes interpreted as surficial aquifer deposits.

Parent-group-material class
Alluvium over sandy and gravelly outwash
Beach deposits
Beach glaciofluvial deposits
Beach sand
Course-loamy alluvium
Coarse-loamy alluvium over sandy alluvium
Coarse-loamy eolian deposits over fine-loamy till
Coarse-loamy glaciofluvial deposits
Coarse-loamy glaciofluvial deposits and/or coarse-loamy glacialacustrine deposits
Coarse-loamy glaciolacustrine deposits and/or loamy till
Coarse-loamy glaciofluvial deposits over sandy and gravelly outwash
Coarse-loamy glaciolacustrine deposits over sandy and loamy outwash
Coarse-loamy glaciolacustrine deposits
Coarse-loamy glaciolacustrine desposits and/or outwash
Coarse-loamy outwash over fine/loamy till
Coarse-loamy outwash over sandy and gravelly outwash
Coarse-loamy outwash over sandy outwash
Eolian and lacustrine sands
Eolian sands
Gravelly and sandy outwash deposits
Loamy alluvium
Loamy alluvium over outwash
Loamy alluvium over sandy alluvium
Loamy alluvium over sandy and gravelly outwash
Loamy and sandy glaciolacustrine deposits
Loamy and sandy glaciolacustrine deposits over loamy glacial till
Loamy and sandy glaciolacustrine deposits over glacial till
Loamy and sandy outwash over loamy glacial till
Loamy and sandy outwash over loamy lacustrine deposits
Loamy glaciofluvial deposits over sandy and gravelly outwash
Loamy glaciofluvial deposits over sandy outwash
Loamy lake beach sediments
Loamy lakeshore deposits
Loamy mantle over sandy and gravelly outwash
Loamy mantle over sandy and gravelly outwash deposits
Loamy mantle over sandy and gravelly outwash over loamy glacial till
Loamy mantle over sandy glaciolacustrine deposits
Loamy mantle over sandy outwash deposits
Loamy mantled outwash deposits
Loamy mantled over sandy outwash deposits
Loamy or sandy material
Loamy outwash sediments over sandy and gravelly outwash
Loamy over sandy alluvium
Loamy over sandy and gravelly outwash deposits

Table 1.1. Gridded Soil Survey Geographic database (gSSURGO) parent-group-material classes interpreted as surficial aquifer deposits.—Continued

Parent-group-material class
Loamy over sandy and gravelly outwash over loamy glacial till
Loamy over sandy glaciolacustrine deposits
Loamy over sandy lacustrine deposits
Loamy over sandy outwash deposits
Sandy alluvium
Sandy alluvium over gravelly glaciolacustrine deposits
Sandy and gravelly deposits
Sandy and gravelly glaciofluvial deposits
Sandy and gravelly glaciolacustrine deposits
Sandy and gravelly lakebeach deposits
Sandy and gravelly outwash
Sandy and gravelly outwash deposits
Sandy and gravelly outwash lake beach deposits
Sandy and gravelly outwash or beach deposits
Sandy and loamy lake beach deposits
Sandy and silty glaciolacustrine deposits
Sandy and silty glaciolacustrine deposits over loamy till
Sandy deposits
Sandy eolian outwash deposits
Sandy eolian deposits
Sandy eolian deposits over loamy glacial till
Sandy glaciofluvial deposits
Sandy glaciofluvial deposits and/or sandy glaciolacustrine deposits
Sandy glaciofluvial deposits over clayey glaciolacustrine deposits
Sandy glaciofluvial deposits over loamy glaciolacustrine deposits
Sandy glaciofluvial deposits over loamy lacustrine deposits and/or loamy till
Sandy glaciolacustrine deposits
Sandy glaciolacustrine deposits or outwash over loamy glacial till
Sandy glaciolacustrine deposits over calcareous loamy lacustrine deposits
Sandy glaciolacustrine deposits over clayey till
Sandy glaciolacustrine deposits over fine-loamy till
Sandy glaciolacustrine deposits over loamy glacial till
Sandy glaciolacustrine deposits over loamy till
Sandy glaciolacustrine deposits over till
Sandy lacustrine deposits over loamy glacial till
Sandy lake beach sediments
Sandy lakeshore deposits
Sandy mantled loamy glacial till
Sandy outwash
Sandy outwash deposits
Sandy outwash deposits over loamy glacial till
Sandy outwash deposits over silty glaciolacustrine sediments or glacial till
Sandy outwash over dense basal till
Sandy outwash over fine-loamy till
Sandy outwash over loamy glacial till
Sandy outwash over till
Variable sand and gravel
Variable sandy material

Appendix 2. Site Names, Numbers, and Types

Table 2.1. Site names, numbers, and types.

[MUN, Minnesota unique well number; GW-G, well drilled for the Glacial Ridge study; GW-E, existing well; GW-L, well drilled for an earlier U.S. Geological Survey project by Lindgren (1996); GW-C, Crookston Water Department observation well; SW, ditch gage; L, lake gage; WL, wetland gage; —, not applicable or not available; S, surficial; B, buried; depths in feet below land surface]

Short name	Agency code	Site number	MUN	Type	Aquifer type	Well depth (ft BLS)	Screened-interval depth (ft BLS)
G01	USGS	474135096203001	620661	GW–G	S	10.42	5.58–9.88
G02	USGS	473849096202101	620662	GW–G	S	14.49	9.65–13.95
G03	USGS	473914096195401	620663	GW–G	S	14.61	1.33–10.64
G04	USGS	474242096194701	620664	GW–G	S	9.85	5.01–9.31
G05	USGS	474229096185701	620665	GW–G	S	9.43	0.77–5.07
G06	USGS	474119096190901	620666	GW–G	S	12.94	8.1–12.4
G07D	USGS	474300096172602	620667	GW–G	S	36.05	31.21–35.51
G07S	USGS	474300096172601	620657	GW–G	S	15.58	10.65–14.95
G08	USGS	474346096185501	620668	GW–G	S	11.81	6.97–11.27
G09	USGS	474129096145202	620669	GW–G	S	10.60	5.67–9.97
G10	USGS	474109096133501	620670	GW–G	S	10.23	3.01–7.31
G11	USGS	474254096160401	620671	GW–G	S	16.34	3.58–7.88
G12	USGS	474126096165301	620672	GW–G	S	14.94	8.76–13.06
G13	USGS	474128096175501	620673	GW–G	S	13.92	4.14–8.44
G14	USGS	473842096183901	620674	GW–G	S	15.54	5.58–9.88
G15	USGS	473841096153101	620675	GW–G	S	14.87	7.17–11.47
G16	USGS	474221096120901	620676	GW–G	S	14.41	6.7–11
G17	USGS	474350096144101	620677	GW–G	S	13.47	8.63–12.93
G18	USGS	474534096182701	620678	GW–G	S	29.87	14.97–19.27
G19	USGS	474524096203101	620679	GW–G	S	43.53	38.6–42.9
G20	USGS	474310096121801	620680	GW–G	S	15.01	6.34–10.64
G21	USGS	474420096104901	620681	GW–G	S	12.33	7.49–11.79
G22	USGS	474125096120602	620682	GW–G	S	29.77	24.93–29.23
G23	USGS	474721096232201	620683	GW–G	S	24.56	13.86–18.16
G24	USGS	474220096171801	620684	GW–G	S	11.70	6.86–11.16
G25	USGS	473933096243701	620685	GW–G	S	30.35	20.38–24.68
G26	USGS	474133096245901	620686	GW–G	S	14.89	10.05–14.35
G27	USGS	473901096164901	620687	GW–G	S	10.11	5.27–9.57
G30	USGS	473855096141301	620690	GW–G	S	10.10	3.43–7.73
G32	USGS	474300096204901	620692	GW–G	S	11.66	4.96–9.26
G33	USGS	474201096132501	620693	GW–G	S	25.25	20.32–24.62
G34	USGS	474443096171801	620694	GW–G	S	12.64	7.71–12.01
G35	USGS	474043096155901	620695	GW–G	S	19.88	12.18–16.48
G36	USGS	474135096204501	620696	GW–G	S	10.01	5.17–9.47
G38	USGS	474444096183101	620698	GW–G	S	14.61	2.91–7.21

Table 2.1. Site names, numbers, and types.—Continued

[MUN, Minnesota unique well number; GW-G, well drilled for the Glacial Ridge study; GW-E, existing well; GW-L, well drilled for an earlier U.S. Geological Survey project by Lindgren (1996); GW-C, Crookston Water Department observation well; SW, ditch gage; L, lake gage; WL, wetland gage; —, not applicable or not available; S, surficial; B, buried; depths in feet below land surface]

Short name	Agency code	Site number	MUN	Type	Aquifer type	Well depth (ft BLS)	Screened-interval depth (ft BLS)
G39	USGS	474055096150301	620699	GW–G	S	14.08	7.41–11.71
E01S	USGS	473945096202402	249810	GW–E	S	19.77	14.5–19.5
E03	USGS	474436096140801	654754	GW–E	S	69.00	59–69
E05	USGS	474719096163100	—	GW–E	S	18.06	12.7–17.7
E09	USGS	474353096164401	—	GW–E	S	—	—
E13	USGS	474506096205901	221630	GW–E	S	55.42	52–56
E19	USGS	474305096172401	—	GW–E	S	39.16	—
E23	USGS	474535096204201	—	GW–E	S	64.27	—
E49	USGS	474347096165701	—	GW–E	S	40.00	—
L012	USGS	473042096151800	249806	GW–E	S	10.25	5–10
L032	USGS	474629096210801	—	GW–E	S	14.47	—
L043	USGS	474708096261801	—	GW–E	S	24.26	18–23
L057	USGS	474628096180101	—	GW–E	S	13.48	9.5–14.5
L061	USGS	474629096193901	—	GW–E	S	29.84	24–29
S1	USGS	474539096205101	125721	GW–C	S	53.59	41–56
S2	USGS	474539096203302	105665	GW–C	S	50	46–50
E01D	USGS	473945096202401	516287	GW–E	B	171	168–171
E02	USGS	474129096145201	—	GW–E	B	173.58	—
E04D	USGS	474309096122001	654760	GW–E	B	102	98–102
E06D	USGS	474455096250601	249807	GW–E	B	44.84	40–45
E07	USGS	474255096155601	107932	GW–E	B	80	67–80
E10	USGS	474541096174001	649189	GW–E	B	115	111–115
E14	USGS	474256096222001	—	GW–E	B	64	—
E15	USGS	474207096171101	221063	GW–E	B	82	102–105
E21	USGS	474339096191301	—	GW–E	B	56	—
E22	USGS	474331096193301	—	GW–E	B	170	—
E24	USGS	474220096154101	—	GW–E	B	90	—
E25	USGS	474224096160501	—	GW–E	B	174	—
E27	USGS	473941096151801	—	GW–E	B	126	—
E28	USGS	473905096153101	—	GW–E	B	124	—
E36	USGS	474340096191301	—	GW–E	B	71	—
E37	USGS	474125096120601	—	GW–E	B	65	—
E38	USGS	474251096131201	—	GW–E	B	114	98–102
E39	USGS	474422096111301	—	GW–E	B	82	—

Table 2.1. Site names, numbers, and types.—Continued

[MUN, Minnesota unique well number; GW-G, well drilled for the Glacial Ridge study; GW-E, existing well; GW-L, well drilled for an earlier U.S. Geological Survey project by Lindgren (1996); GW-C, Crookston Water Department observation well; SW, ditch gage; L, lake gage; WL, wetland gage; —, not applicable or not available; S, surficial; B, buried; depths in feet below land surface]

Short name	Agency code	Site number	MUN	Type	Aquifer type	Well depth (ft BLS)	Screened-interval depth (ft BLS)
E40	USGS	474424096101901	—	GW–E	B	—	—
E41	USGS	474334096111601	—	GW–E	B	48	—
E45	USGS	474251096131201	—	GW–E	B	162	—
L101	USGS	474537096160300	513018	GW–E	B	172	169.6–172.6
L102	USGS	474720096150201	516274	GW–E	B	172	170–173
L103	USGS	474210096203101	516278	GW–E	B	190	187–190
L109	USGS	474536096134401	516273	GW–E	B	162	162–165
D1	USGS	474547096210501	105666	GW–C	B	147	123–147
D2	USGS	474540096210401	147234	GW–C	B	172	135–145
D3	USGS	474559096203302	—	GW–C	B	158	135–157
D4	USGS	474634096202601	147242	GW–C	B	97	87–97
SW1	USGS	05078730	—	SW	—	—	—
SW2	USGS	05079250	—	SW	—	—	—
SW3	USGS	05079200	—	SW	—	—	—
SW4	USGS	05078470	—	SW	—	—	—
SW5	USGS	05078520	—	SW	—	—	—
SW6	USGS	05078770	—	SW	—	—	—
SW7	USGS	474003096085901	—	L	—	—	—
SW8	USGS	05078720	—	SW	—	—	—
WL01	USGS	474024096124601	—	WL	—	—	—
WL02	USGS	474026096145001	—	WL	—	—	—
WL03	USGS	474139096150301	—	WL	—	—	—
WL04	USGS	474137096154101	—	WL	—	—	—
WL05	USGS	474127096164701	—	WL	—	—	—
WL06	USGS	474139096165401	—	WL	—	—	—
WL07	USGS	474129096180001	—	WL	—	—	—
WL08	USGS	474120096185001	—	WL	—	—	—
WL09	USGS	474228096171901	—	WL	—	—	—
WL10	USGS	474328096144201	—	WL	—	—	—
WL11	USGS	474205096110401	—	WL	—	—	—
WL12	USGS	474330096175701	—	WL	—	—	—
WL13	USGS	474258096210702	—	WL	—	—	—

Appendix 3. Water Balance

Annual water balances were calculated separately for surficial groundwater and surface water using the same equations presented in the prerestoration study report (Cowdery and others, 2007) with the addition of an explicit ET term in each equation. Water balances were calculated on ditch-basin areas assuming that all water enters the basin as precipitation and leaves the basin either as ET or as ditch flow at the basin's gage. The groundwater and surface-water balances are intertwined. The following equations were used to calculate the water balances (groundwater balance, eq. 1.1; surface-water balance, eq. 1.2):

$$R = G + \Delta S + ET_g + L_g \quad (1.1)$$

$$P + G = R + D + ET_s + L_s \quad (1.2)$$

where

- R areal recharge to surficial aquifers (calculated from hydrographs at six wells),
- G Groundwater discharge to ditches (calculated by hydrograph separation at six gages),
- ΔS change in groundwater storage (measured at 58 wells and 16 surface-water sites),
- ET_g groundwater evapotranspiration (calculated with a Soil-Water-Balance model),
- L_g unmeasured groundwater losses (residual from the water balance),
- P precipitation (measured at nine study sites and six other sites),
- D flow out of the basin in ditches (measured at six ditch gages),
- ET_s surface-water evapotranspiration (calculated with a Soil-Water-Balance model), and
- L_s unmeasured surface-water losses (residual from the water balance).

Recharge estimates from hydrographs at 4 of 10 wells completed in surficial aquifers were not used in the areal recharge term of water-balance analyses. Recharge at wells G01 and G15 included substantial amounts of nonareal recharge. These wells were adjacent to closed-subbasin wetlands that received substantial overland flow and functioned as an area of focused groundwater recharge. Recharge at well G22 was excluded because water levels at the well may have been affected by pumping and return flow from adjacent irrigation. Recharge at well G25 was excluded because its Thiessen polygon did not coincide with any ditch basin. The loss terms L_s and L_g contain all measurement, water-balance assumption, and modeling errors from all the other terms in the water balances.

Buried aquifers with upward head gradients underlie most of the study area. Only one estimate of the leakage to, and hence leakage from, these aquifers has been made in this study (at well E01D). This estimate summed the rises in the hydrograph at well E01D; a water-table aquifer method that may be inappropriate for confined aquifers (Cowdery and others, 2007). The accuracy and representativeness of this leakage rate and the area over which this leakage rate operates is unknown. Therefore, the leakage of groundwater from buried aquifers to surface waters and to surficial aquifers was ignored in the water balances calculated in this report. Any leakage from buried aquifers unaccounted for in these water balances would have the effect of increasing the surface-water or groundwater loss terms (L_s and L_g) above.

Reference Cited

Cowdery, T.K., Lorenz, D.L., and Arnston, A.D., 2007, Hydrology prior to wetland and prairie restoration in and around the Glacial Ridge National Wildlife Refuge, northwestern Minnesota, 2002–5: U.S. Geological Survey Scientific Investigations Report 2007–5200, 68 p., accessed November 1, 2016, at https://pubs.usgs.gov/sir/2007/5200/.

Appendix 4. Hydrologic Engineering Center's Hydrologic Modeling System (HEC–HMS) Model Inputs

Table 4.1. Initial values, optimized values, and quality-assurance data for unit-hydrograph modeled storm ditch flow, Glacial Ridge study area, northwestern Minnesota, 2003–5 and 2013–15.

[Storm number, chronological number to identify simulated storm; RMSE, root mean square error; ft^3/s, cubic foot per second, computed; NSE, Nash-Sutcliffe efficiency; precip, precipitation; in., inch; in/hr, inch per hour; hr, hour]

Ditch gage	Storm number	Simulation start	Simulation end	Peak-weighted RMSE (ft^3/s)	NSE (unitless)	Total precip (in.)	Loss precip (in.)
Prerestoration storms							
SW2	1	2003–06–09 18:00	2003–06–20 00:00	2.21	0.97	3.26	2.93
SW2	2	2004–05–10 00:00	2004–05–23 00:00	4.72	0.94	3.31	2.71
SW2	3	2004–05–29 00:00	2004–06–25 00:00	2.04	0.97	3.15	2.72
SW2	4	2004–10–29 06:00	2004–11–01 00:00	2.98	0.99	3.42	2.96
SW2	5	2005–06–11 13:00	2005–06–13 00:00	3.04	0.95	1.22	1.17
SW2	6	2005–08–19 00:00	2005–08–23 10:00	0.28	0.95	1.15	1.14
SW3	1	2003–06–09 18:00	2003–06–20 00:00	2.92	0.81	2.73	2.53
SW3	2	2004–05–10 00:00	2004–05–24 00:00	2.72	0.94	3.23	2.90
SW3	3	2004–05–29 00:00	2004–06–25 00:00	1.85	0.93	2.92	2.44
SW3	6	2005–08–19 05:00	2005–08–22 00:00	0.61	0.91	1.13	1.12
SW3	7	2005–09–05 01:00	2005–09–09 05:00	0.84	0.93	1.83	1.81
SW4	1	2003–06–09 18:00	2003–06–20 00:00	1.32	0.96	2.20	2.00
SW4	2	2004–05–10 00:00	2004–05–23 00:00	1.76	0.98	3.86	3.43
SW4	3	2004–05–29 00:00	2004–06–25 00:00	0.41	1.00	2.69	2.41
SW4	5	2005–06–11 13:00	2005–06–12 14:00	2.35	0.98	1.21	1.18
SW4	6	2005–08–19 05:00	2005–08–20 02:00	0.14	0.90	1.18	1.18
SW4	8	2005–10–04 16:00	2005–10–09 12:00	0.22	0.95	2.39	2.37
SW5	1	2003–06–09 18:00	2003–06–20 00:00	1.27	0.96	2.23	2.06
SW5	2	2004–05–10 00:00	2004–05–23 00:00	6.63	0.87	4.07	3.72
SW5	3	2004–05–29 00:00	2004–06–25 00:00	3.52	0.97	2.70	2.08
SW5	4	2004–10–29 03:00	2004–10–31 12:00	8.19	0.97	2.70	2.31
SW5	5	2005–06–11 14:00	2005–06–13 06:00	3.85	0.97	1.35	1.12
SW5	6	2005–08–19 05:00	2005–08–24 00:00	0.40	0.96	1.23	1.21
SW5	7	2005–09–05 17:00	2005–09–08 03:00	1.33	0.97	1.32	1.22
SW6	1	2003–06–09 18:00	2003–06–20 00:00	1.53	0.96	2.12	2.03
SW6	2	2004–05–10 00:00	2004–05–23 00:00	4.18	0.96	3.34	3.01
SW6	3	2004–05–29 00:00	2004–06–25 00:00	5.36	0.92	2.66	2.00
SW6	5	2005–06–11 13:00	2005–06–13 01:00	5.42	0.96	1.22	1.20
SW6	6	2005–08–19 05:00	2005–08–21 09:00	1.64	0.94	1.32	1.30
SW8	4	2004–10–29 14:00	2004–11–01 00:00	8.22	0.99	2.68	2.22
SW8	7	2005–09–05 00:00	2005–09–07 00:00	1.09	0.98	1.82	1.77
SW8	8	2005–10–04 13:00	2005–10–07 02:00	0.84	0.98	2.02	1.99

Table 4.1. Initial values, optimized values, and quality-assurance data for unit-hydrograph modeled storm ditch flow, Glacial Ridge study area, northwestern Minnesota, 2003–5 and 2013–15.—Continued

[Storm number, chronological number to identify simulated storm; RMSE, root mean square error; ft^3/s, cubic foot per second, computed; NSE, Nash-Sutcliffe efficiency; precip, precipitation; in., inch; in/hr, inch per hour; hr, hour]

Ditch gage	Storm number	Simulation start	Simulation end	Peak-weighted RMSE (ft^3/s)	NSE (unitless)	Total precip (in.)	Loss precip (in.)
Postrestoration storms							
SW2	9	2013–05–19 00:00	2013–05–25 00:00	0.79	0.96	2.56	2.43
SW2	10	2013–05–29 00:00	2013–06–04 00:00	1.35	0.93	2.02	1.91
SW2	11	2013–06–25 00:00	2013–06–30 00:00	1.19	0.91	1.60	1.52
SW2	12	2014–06–15 07:00	2014–06–17 08:00	0.54	0.99	1.50	1.44
SW2	13	2014–06–19 00:00	2014–06–21 15:00	0.98	0.97	1.39	1.35
SW2	14	2015–06–06 08:00	2015–06–11 00:00	1.03	0.86	1.20	1.13
SW3	9	2013–05–19 00:00	2013–05–24 03:00	1.26	0.98	2.54	2.39
SW3	10	2013–05–29 00:00	2013–06–03 15:00	1.69	0.95	1.95	1.90
SW3	11	2013–06–25 17:00	2013–06–30 00:00	0.13	0.99	1.50	1.47
SW3	12	2014–06–15 07:00	2014–06–16 14:00	1.14	0.98	1.18	1.13
SW3	14	2015–06–06 12:00	2015–06–11 00:00	0.50	0.94	1.39	1.38
SW4	9	2013–05–19 00:00	2013–05–24 03:00	6.36	0.91	2.68	2.27
SW4	10	2013–05–29 00:00	2013–06–04 00:00	5.84	0.94	2.00	1.89
SW4	11	2013–06–25 00:00	2013–06–30 00:00	1.40	0.92	1.48	1.43
SW4	14	2015–06–06 00:00	2015–06–11 00:00	4.09	0.94	1.50	1.22
SW4	15	2015−07−16 00:00	2015−07−22 00:00	2.20	0.76	2.18	2.05
SW5	9	2013−05−19 00:00	2013−05−24 00:00	9.65	0.80	2.98	2.40
SW5	10	2013−05−29 00:00	2013−06−04 00:00	4.77	0.97	2.12	1.65
SW5	12	2014−06−15 07:00	2014−06−17 08:00	3.55	0.99	1.21	0.91
SW5	13	2014−06−19 07:00	2014−06−21 12:00	3.78	0.98	1.01	0.65
SW5	14	2015−06−06 08:00	2015−06−11 00:00	9.71	0.83	1.39	1.25
SW5	15	2015−07−16 00:00	2015−07−21 00:00	2.75	0.98	1.91	1.69
SW6	9	2013−05−19 18:00	2013−05−24 00:00	1.55	0.81	1.25	1.23
SW6	11	2013−06−25 00:00	2013−06−30 00:00	1.29	0.87	1.28	1.27
SW6	12	2014−06−15 07:00	2014−06−15 21:00	0.92	0.96	1.32	1.31
SW6	14	2015−06−06 12:00	2015−06−08 07:00	0.82	0.94	1.40	1.39
SW6	15	2015−07−16 05:00	2015−07−16 21:00	1.76	0.91	1.79	1.78
SW8	11	2013−06−25 21:00	2013−06−26 17:00	0.81	0.90	1.19	1.19
SW8	12	2014−06−15 07:00	2014−06−15 19:30	4.44	0.85	1.50	1.48
SW8	14	2015−06−06 13:00	2015−06−07 00:00	2.31	0.87	1.03	1.01

Table 4.1. Initial values, optimized values, and quality-assurance data for unit-hydrograph modeled storm ditch flow, Glacial Ridge study area, northwestern Minnesota, 2003–5 and 2013–15.—Continued

[Storm number, chronological number to identify simulated storm; RMSE, root mean square error; ft^3/s, cubic foot per second, computed; NSE, Nash-Sutcliffe efficiency; precip, precipitation; in., inch; in/hr, inch per hour; hr, hour]

Ditch gage	Excess precip (in.)	Peak ditch flow (ft^3/s)		Initial loss (in.)			Constant loss rate (in/hr)		
		Simulated	Measured	Initial	Optimized	Sensitivity	Initial	Optimized	Sensitivity
Prerestoration storms									
SW2	0.33	43.5	41.0	0.200	0.200	0.00	0.540	0.540	−0.72
SW2	0.60	69.2	75.6	0.200	0.200	0.00	0.280	0.275	−3.07
SW2	0.43	42.2	44.4	0.240	0.244	−0.02	0.260	0.266	−2.94
SW2	0.46	103	99.0	0.434	0.437	−0.11	0.272	0.273	−5.07
SW2	0.05	54.0	51.8	0.582	0.581	−1.08	0.279	0.280	−1.91
SW2	0.01	4.00	3.90	0.719	0.719	0.92	0.351	0.351	−0.49
SW3	0.20	27.8	31.9	1.31	1.32	−2.11	0.250	0.253	−1.05
SW3	0.33	39.9	37.5	1.87	1.91	−3.36	0.240	0.244	−1.44
SW3	0.48	25.5	23.6	0.720	0.721	−0.13	0.100	0.100	−0.28
SW3	0.01	10.7	10.6	0.896	0.895	2.38	0.315	0.315	29.3
SW3	0.02	12.3	12.0	1.514	1.514	68.8	0.312	0.306	−0.07
SW4	0.21	29.7	28.1	0.740	0.740	0.00	0.470	0.443	−3.17
SW4	0.43	50.7	50.3	0.100	0.100	0.00	0.290	0.279	0.16
SW4	0.28	25.0	25.1	0.070	0.070	0.00	0.190	0.186	−3.88
SW4	0.03	53.6	53.7	0.652	0.652	0.52	0.255	0.256	0.02
SW4	0.00	1.50	1.60	1.027	1.027	−8.90	0.303	0.303	−6.65
SW4	0.02	3.30	3.60	1.385	1.383	0.51	0.346	0.346	1.03
SW5	0.16	23.6	24.5	1.19	1.20	−7.02	0.260	0.248	1.46
SW5	0.35	84.8	80.2	0.100	0.100	0.00	0.440	0.444	−1.39
SW5	0.61	94.9	90.9	0.100	0.098	−0.03	0.160	0.161	−1.82
SW5	0.39	141	139	0.310	0.310	−0.15	0.190	0.190	−0.54
SW5	0.23	89.5	89.0	0.296	0.294	0.02	0.203	0.203	0.32
SW5	0.02	4.90	5.50	0.985	0.985	−1.58	0.206	0.206	−0.16
SW5	0.10	26.9	27.4	0.998	0.998	−3.14	0.315	0.315	−0.94
SW6	0.09	34.7	33.1	0.850	0.850	−0.45	0.520	0.515	−0.34
SW6	0.33	73.5	66.7	0.200	0.200	0.00	0.440	0.423	−0.13
SW6	0.66	65.9	66.9	0.020	0.019	0.01	0.110	0.103	0.00
SW6	0.02	92.1	90.5	0.763	0.763	11.4	0.247	0.248	1.58
SW6	0.02	22.7	21.0	1.026	1.026	−0.10	0.271	0.271	0.08
SW8	0.46	255	264	0.718	0.718	−1.05	0.122	0.122	−1.35
SW8	0.05	21.1	21.3	1.557	1.557	−3.15	0.543	0.543	−0.34
SW8	0.03	15.6	14.3	0.702	0.703	−1.04	0.321	0.321	−1.24

Table 4.1. Initial values, optimized values, and quality-assurance data for unit-hydrograph modeled storm ditch flow, Glacial Ridge study area, northwestern Minnesota, 2003–5 and 2013–15.—Continued

[Storm number, chronological number to identify simulated storm; RMSE, root mean square error; ft^3/s, cubic foot per second, computed; NSE, Nash-Sutcliffe efficiency; precip, precipitation; in., inch; in/hr, inch per hour; hr, hour]

Ditch gage	Excess precip (in.)	Peak ditch flow (ft^3/s)		Initial loss (in.)			Constant loss rate (in/hr)		
		Simulated	Measured	Initial	Optimized	Sensitivity	Initial	Optimized	Sensitivity
Postrestoration storms									
SW2	0.13	16.7	16.4	0.19	0.20	−0.10	0.297	0.298	−4.95
SW2	0.11	21.3	17.3	0.22	0.22	0.00	0.329	0.329	−4.01
SW2	0.08	13.3	11.6	1.22	1.22	−1.49	0.382	0.383	−1.24
SW2	0.06	37.8	37.9	0.49	0.49	5.71	0.253	0.253	59.8
SW2	0.04	36.2	35.2	1.09	1.09	13.1	0.355	0.356	−0.22
SW2	0.07	10.7	10.1	0.20	0.20	0.00	0.292	0.292	−0.72
SW3	0.15	32.0	30.8	0.07	0.07	−0.01	0.321	0.321	−0.23
SW3	0.05	28.3	28.2	0.18	0.18	0.00	0.316	0.316	314
SW3	0.03	9.20	9.10	0.39	0.38	−2.62	0.677	0.679	−20.6
SW3	0.05	48.0	47.5	0.11	0.11	0.00	0.190	0.190	−5.10
SW3	0.01	18.8	18.7	0.81	0.81	−1.97	0.256	0.256	18.7
SW4	0.41	87.1	91.0	0.20	0.21	−0.15	0.207	0.209	−0.55
SW4	0.11	90.3	74.3	0.27	0.27	0.00	0.239	0.239	−3.34
SW4	0.05	17.2	14.5	1.36	1.36	−1.86	0.182	0.183	−0.09
SW4	0.28	88.5	79.0	0.20	0.20	0.00	0.189	0.188	0.13
SW4	0.13	16.1	17.9	1.39	1.39	−1.15	0.186	0.188	−0.04
SW5	0.58	68.3	71.3	0.48	0.48	−0.13	0.150	0.151	−0.16
SW5	0.47	94.1	84.0	0.37	0.37	0.05	0.191	0.191	−1.19
SW5	0.30	116	115	0.11	0.12	−0.28	0.131	0.131	−3.25
SW5	0.36	96.5	89.5	0.39	0.39	−0.06	0.057	0.058	−0.07
SW5	0.14	105	98.5	0.11	0.11	0.00	0.203	0.303	−0.35
SW5	0.22	71.6	65.4	1.09	1.09	−2.97	0.321	0.323	−0.47
SW6	0.02	46.8	46.5	0.44	0.44	0.33	0.119	0.119	−0.07
SW6	0.01	34.0	32.3	1.23	1.23	−2.35	0.249	0.249	−0.05
SW6	0.01	22.7	22.2	0.20	0.20	0.00	0.298	0.298	−2.30
SW6	0.01	33.8	34.6	0.55	0.55	0.00	0.408	0.409	−7.62
SW6	0.01	15.8	15.8	1.59	1.59	−8.27	0.478	0.481	−0.86
SW8	0.00	11.2	11.2	0.86	0.86	42.4	0.208	0.308	129
SW8	0.02	49.1	49.7	0.09	0.09	0.00	0.302	0.302	0.76
SW8	0.02	29.6	28.8	0.53	0.53	−0.09	0.340	0.340	−1.21

Table 4.1. Initial values, optimized values, and quality-assurance data for unit-hydrograph modeled storm ditch flow, Glacial Ridge study area, northwestern Minnesota, 2003–5 and 2013–15.—Continued

[Storm number, chronological number to identify simulated storm; RMSE, root mean square error; ft³/s, cubic foot per second, computed; NSE, Nash-Sutcliffe efficiency; precip, precipitation; in., inch; in/hr, inch per hour; hr, hour]

Ditch gage	Initial ditch flow (ft³/s)			Time of concentration (hr)			Clark storage coefficient (hr)		
	Initial	Optimized	Sensitivity	Initial	Optimized	Sensitivity	Initial	Optimized	Sensitivity
Prerestoration storms									
SW2	4.00	4.05	−0.13	10.0	9.61	−0.01	50.0	50.3	−0.40
SW2	1.00	0.94	0.05	14.0	13.2	−0.05	51.0	46.1	0.21
SW2	4.00	3.76	−0.02	17.0	17.2	−0.32	55.0	55.9	−1.79
SW2	7.73	7.82	−0.16	10.2	9.9	0.07	30.3	30.4	−0.88
SW2	9.34	9.44	−0.21	14.8	14.9	−1.31	1.38	1.17	0.06
SW2	0.30	0.31	−0.09	2.72	2.72	0.00	28.0	28.0	−0.16
SW3	2.00	1.98	−0.04	2.00	1.88	0.21	50.0	50.9	−0.89
SW3	1.00	0.94	−0.01	3.00	2.82	0.13	55.0	55.9	−0.84
SW3	1.00	0.94	0.00	17.0	17.1	−0.05	94.0	95.1	−0.47
SW3	2.10	2.13	−0.48	4.07	4.07	0.01	10.2	10.2	−0.12
SW3	1.01	1.02	−0.17	8.50	7.69	−0.04	22.5	21.6	−0.14
SW4	3.50	3.55	0.00	8.00	7.53	0.72	47.0	44.3	
SW4	1.00	1.01	0.00	5.00	3.20	0.09	52.0	50.0	−0.46
SW4	2.50	2.35	0.19	27.0	25.4	−0.03	62.0	60.6	−1.56
SW4	12.8	12.9	−0.25	5.89	5.96	−2.09	4.80	4.79	−0.22
SW4	0.080	0.081	−0.05	6.61	6.68	−0.98	8.90	8.65	−0.03
SW4	0.084	0.085	0.00	37.7	38.0	−1.14	25.3	25.5	−0.22
SW5	1.00	1.01	−0.01	24.0	23.7	0.34	28.0	28.4	−0.72
SW5	1.00	0.941	0.01	12.0	11.3	0.31	24.0	24.2	−0.23
SW5	1.00	1.02	−0.02	20.0	18.5	−0.21	32.0	31.5	−1.05
SW5	18.0	18.2	−0.51	21.9	21.9	−0.31	5.35	5.35	−0.02
SW5	11.0	11.1	−0.51	23.5	23.6	−1.53	5.46	5.49	−0.27
SW5	0.000	0.000	0.00	32.8	33.1	−1.59	15.4	15.2	0.00
SW5	0.018	0.018	0.00	28.8	28.9	0.06	9.13	9.19	−0.26
SW6	3.00	3.04	−0.20	4.00	3.76	0.01	35.0	23.6	−1.17
SW6	1.00	1.10	−0.02	7.00	6.79	−0.04	40.0	38.5	−0.28
SW6	3.00	3.04	−0.07	21.0	19.8	0.06	69.0	64.9	−0.08
SW6	7.96	8.04	−0.10	2.29	2.24	0.06	4.75	4.82	0.09
SW6	2.90	2.94	−0.16	7.78	7.89	−1.37	15.0	15.1	−0.20
SW8	11.9	11.8	−0.01	1.82	1.71	0.13	14.6	14.7	−0.71
SW8	0.273	0.277	−0.01	4.53	4.59	−1.07	23.0	23.0	−0.03
SW8	0.096	0.097	0.00	13.4	13.5	−0.39	13.4	13.4	−0.33

Table 4.1. Initial values, optimized values, and quality-assurance data for unit-hydrograph modeled storm ditch flow, Glacial Ridge study area, northwestern Minnesota, 2003–5 and 2013–15.—Continued

[Storm number, chronological number to identify simulated storm; RMSE, root mean square error; ft^3/s, cubic foot per second, computed; NSE, Nash-Sutcliffe efficiency; precip, precipitation; in., inch; in/hr, inch per hour; hr, hour]

Ditch gage	Initial ditch flow (ft^3/s)			Time of concentration (hr)			Clark storage coefficient (hr)		
	Initial	Optimized	Sensitivity	Initial	Optimized	Sensitivity	Initial	Optimized	Sensitivity
Postrestoration storms									
SW2	2.47	2.51	−0.46	61.3	61.8	0.12	36.1	36.3	−0.36
SW2	2.39	2.43	−0.15	8.85	8.49	0.02	36.6	37.1	−0.94
SW2	1.60	1.62	−0.03	5.04	5.10	−0.03	54.8	55.6	−0.62
SW2	9.60	9.61	−3.11	3.89	3.87	0.23	15.7	15.8	2.17
SW2	21.5	21.5	−3.03	3.59	3.62	−0.06	17.3	17.5	−0.20
SW2	1.41	1.42	−0.02	7.61	7.72	−0.21	58.6	58.9	−0.21
SW3	1.06	1.08	−0.14	56.1	55.9	0.15	48.9	48.9	−0.16
SW3	2.45	2.30	0.04	3.68	3.68	0.01	24.4	24.3	−0.29
SW3	1.05	1.03	0.06	2.92	2.75	0.18	52.9	53.3	−2.89
SW3	12.1	12.3	−1.48	4.65	4.66	−0.44	18.9	19.0	−0.99
SW3	7.70	7.80	−1.33	2.17	2.04	0.05	11.1	11.3	−0.49
SW4	0.991	1.01	−0.02	49.6	49.8	−0.25	17.9	18.0	−0.08
SW4	6.36	6.45	−0.10	9.78	9.78	−0.02	4.97	4.97	−0.05
SW4	2.52	2.56	−0.10	4.69	4.67	0.00	27.7	27.9	−0.20
SW4	30.0	30.3	−0.70	8.89	8.75	−0.04	28.0	28.4	−1.20
SW4	1.17	1.19	−0.08	64.1	64.1	−0.02	46.1	46.1	0.00
SW5	0.795	0.807	−0.01	42.4	42.7	−0.25	34.9	34.4	0.00
SW5	1.45	1.40	0.00	8.87	8.99	−1.68	18.0	18.3	−1.60
SW5	4.33	4.07	0.10	19.0	18.9	0.15	6.79	6.80	−0.45
SW5	4.74	4.79	−0.01	7.99	8.00	−0.07	18.5	18.5	−0.30
SW5	21.5	21.8	−0.42	13.7	13.7	−0.05	0.303	0.288	0.02
SW5	0.685	0.695	0.00	11.6	11.5	0.12	15.2	15.4	−0.73
SW6	33.9	34.0	−2.05	22.9	23.1	−0.46	10.7	10.8	−0.15
SW6	17.7	17.9	−2.01	2.53	2.38	0.01	7.38	7.46	−0.08
SW6	8.25	8.46	−2.34	7.02	7.04	−1.11	10.7	10.6	−1.10
SW6	27.69	27.68	0.56	2.76	2.77	−0.12	13.8	13.6	0.02
SW6	1.22	1.23	−0.03	0.017	0.017	0.00	9.31	9.20	−0.02
SW8	3.18	3.22	−0.94	0.249	0.249	0.00	3.87	3.57	0.15
SW8	13.34	13.52	−0.64	3.48	3.50	−0.44	3.04	3.04	−0.17
SW8	5.78	5.86	−0.81	0.734	0.703	0.00	7.53	7.53	−0.12

Table 4.1. Initial values, optimized values, and quality-assurance data for unit-hydrograph modeled storm ditch flow, Glacial Ridge study area, northwestern Minnesota, 2003–5 and 2013–15.—Continued

[Storm number, chronological number to identify simulated storm; RMSE, root mean square error; ft^3/s, cubic foot per second, computed; NSE, Nash-Sutcliffe efficiency; precip, precipitation; in., inch; in/hr, inch per hour; hr, hour]

Ditch gage	Recession threshold (ft^3/s)			Recession constant (unitless)		
	Initial	Optimized	Sensitivity	Initial	Optimized	Sensitivity
Prerestoration storms						
SW2	5.00	5.07	−0.12	0.800	0.811	−0.74
SW2	3.00	3.04	−0.02	1.00	1.00	0.12
SW2	4.00	3.86	−0.02	0.910	0.856	−0.21
SW2	99.9	99.6	0.18	0.938	0.944	−4.29
SW2	53.9	53.9	−0.43	0.751	0.759	−1.98
SW2	3.70	3.76	−0.05	0.464	0.464	−0.10
SW3	5.00	4.71	0.45	1.00	1.00	0.82
SW3	3.00	2.82	0.00	0.800	0.753	0.02
SW3	1.20	0.53	0.00	0.820	0.784	0.00
SW3	10.5	10.6	−1.24	0.679	0.681	−0.53
SW3	11.8	11.9	−1.45	0.743	0.747	−0.95
SW4	18.0	18.3	−0.78	0.730	0.848	−4.08
SW4	19.0	19.1	−0.10	0.860	0.861	0.02
SW4	21.0	20.9	−0.76	0.810	0.809	−4.40
SW4	53.3	53.6	−1.70	0.799	0.808	−2.43
SW4	0.41	0.41	0.00	0.104	0.105	0.00
SW4	2.91	2.86	−0.01	0.639	0.642	−0.52
SW5	11.0	11.0	0.00	0.040	0.041	0.00
SW5	22.0	20.7	0.21	0.610	0.796	−0.16
SW5	47.0	46.3	−0.07	0.630	0.626	−0.24
SW5	138	139	−1.46	0.800	0.809	−1.63
SW5	87.9	88.2	−0.61	0.734	0.729	−0.07
SW5	4.84	4.84	−0.04	0.020	0.020	0.00
SW5	22.5	22.4	0.00	0.329	0.332	−0.25
SW6	14.0	14.2	−1.28	0.760	0.767	−1.77
SW6	10.0	10.1	−0.01	0.890	0.892	−0.05
SW6	0.700	0.700	0.00	0.950	0.958	−0.04
SW6	93.0	92.4	−0.14	0.860	0.869	−3.16
SW6	20.7	21.0	−0.65	0.324	0.322	0.00
SW8	140	141	−0.32	0.424	0.424	−0.07
SW8	16.6	14.8	0.00	0.352	0.352	0.37
SW8	15.4	15.4	−0.16	0.522	0.527	−1.37

Table 4.1. Initial values, optimized values, and quality-assurance data for unit-hydrograph modeled storm ditch flow, Glacial Ridge study area, northwestern Minnesota, 2003–5 and 2013–15.—Continued

[Storm number, chronological number to identify simulated storm; RMSE, root mean square error; ft^3/s, cubic foot per second, computed; NSE, Nash-Sutcliffe efficiency; precip, precipitation; in., inch; in/hr, inch per hour; hr, hour]

Ditch gage	Recession threshold (ft^3/s)			Recession constant (unitless)		
	Initial	Optimized	Sensitivity	Initial	Optimized	Sensitivity
Postrestoration storms						
SW2	14.9	15.0	−0.42	0.667	0.667	−1.06
SW2	17.0	17.1	−0.17	0.652	0.656	−0.78
SW2	10.4	10.6	−0.62	0.732	0.737	−0.75
SW2	37.7	37.8	−6.90	0.940	0.944	−6.22
SW2	36.0	36.1	2.34	0.883	0.883	−4.06
SW2	10.4	10.5	−0.25	0.771	0.771	−0.48
SW3	31.1	31.2	−1.09	0.840	0.840	−1.20
SW3	26.9	27.2	−1.96	0.870	0.876	−3.71
SW3	7.38	7.38	3.00	0.895	0.902	−4.82
SW3	47.4	47.5	−2.24	0.663	0.660	0.03
SW3	18.3	18.3	0.07	0.916	0.916	−4.41
SW4	72.7	72.7	−0.02	0.665	0.666	−0.19
SW4	68.1	68.1	−0.05	0.645	0.646	−0.30
SW4	14.6	14.8	−0.91	0.650	0.651	−0.20
SW4	72.0	72.1	−0.18	0.686	0.686	−0.53
SW4	17.9	17.9	0.00	0.594	0.594	0.07
SW5	70.0	70.0	0.00	0.474	0.481	0.00
SW5	38.2	38.5	−0.03	0.425	0.430	−0.31
SW5	96.6	97.3	−0.94	0.324	0.324	−0.14
SW5	78.9	79.9	−0.65	0.393	0.391	0.02
SW5	84.2	83.9	0.00	0.387	0.390	−0.16
SW5	61.0	61.7	−0.99	0.411	0.416	−1.64
SW6	46.7	46.7	−1.36	0.957	0.958	−5.41
SW6	25.5	25.4	−0.02	0.886	0.887	−2.99
SW6	21.6	21.7	−0.15	0.260	0.263	−0.18
SW6	25.3	25.3	−0.10	0.722	0.725	−2.77
SW6	10.5	10.5	0.00	0.073	0.071	0.00
SW8	11.0	11.0	−0.43	0.581	0.579	0.01
SW8	49.0	48.9	−0.07	0.463	0.468	−0.23
SW8	15.8	15.8	−0.03	0.212	0.215	−0.08

Appendix 5. Blank Sample Analysis

Concentrations above the laboratory reporting level (RL) were present in at least one field blank-water sample for four constituents analyzed during both restoration periods from sites in the temporal water-quality network. Contamination by these constituents was small and did not affect the analyses that compared water quality before and after restorations.

Filtered ammonia plus organic nitrogen.—Only postrestoration filtered ammonia-plus-organic-nitrogen blank ditch-water samples had evidence of contamination. Five of nine ditch-water blank samples had quantified filtered ammonia-plus-organic-nitrogen concentrations ranging from 0.10 to 0.18 milligram per liter as nitrogen (mg/L–N). Postrestoration ditch-water environmental samples had a minimum filtered ammonia-plus-organic-nitrogen concentration of 0.32 mg/L–N, nearly twice as high as the highest blank sample concentration; however, it is possible that low-concentration environmental samples may contain substantial ammonia-plus-organic-nitrogen contamination. Using a safety factor of three times the highest blank-sample concentration, any postrestoration ditch-water sample with a concentration less than 0.54 mg/L–N may be contaminated with substantial ammonia-plus-organic nitrogen. Using this threshold, 11 of 123 (9 percent) postrestoration ditch-water environmental samples may be affected. If a similar proportion of environmental samples were contaminated as were blank samples, as many as six low concentration filtered ammonia-plus-organic-nitrogen results may be slightly high.

Filtered ammonia plus organic nitrogen was not analyzed in groundwater blank samples but was analyzed in 51 groundwater environmental samples during 2003. Eight of 51 groundwater environmental samples had filtered ammonia-plus-organic-nitrogen concentrations in the range found in the postrestoration ditch-water blank samples (0.10–0.18 mg/L–N). All groundwater blank samples had total-nitrogen concentrations less than the RL of 0.03–0.06 mg/L–N, one-half or less of the concentration of the minimum groundwater environmental filtered ammonia-plus-organic-nitrogen concentration of 0.12 mg/L–N. There were no changes in groundwater sampling procedures during the study. Therefore, we assume that prerestoration groundwater samples were not affected by contamination, just as prerestoration ditch-water samples were not.

Filtered ammonia.—Filtered ammonia results from blank ditch-water samples also had evidence of contamination. No groundwater blank sample had quantified filtered ammonia concentrations. During the prerestoration period, the filtered ammonia RL was 0.04 mg/L–N. One of nine ditch-water blank samples had an estimated concentration of 0.02 mg/L–N. Nine of 158 (6 percent) ditch-water environmental samples had a quantified filtered ammonia concentration of 0.02 mg/L–N or less. During the postrestoration period, the filtered ammonia RL was 0.01 mg/L–N. Two of eight ditch-water blank samples had a concentration of 0.01 mg/L–N. During the postrestoration period, 24 of 123 (20 percent) ditch-water environmental samples contained 0.01 mg/L–N of ammonia. Using a safety factor of three times the highest blank-sample concentration, any ditch-water sample with an ammonia concentration less than 0.06 mg/L–N may be contaminated with substantial ammonia. Using this threshold, 33 of 158 (21 percent) of prerestoration and 80 of 123 (65 percent) postrestoration ditch-water environmental samples may be affected. If a similar proportion of ditch-water environmental samples were contaminated as were blank samples, as many as 4 samples from the prerestoration period and 25 samples from the postrestoration period may be contaminated with low concentrations of ammonia.

Filtered nitrate-plus-nitrite.—Filtered nitrate-plus-nitrite results from postrestoration blank ditch-water samples showed evidence of minor nitrogen contamination. One of nine (11 percent) of these blank samples had a concentration of 0.045 mg/L–N, which is 1.1 times the RL of 0.04 mg/L–N. During the postrestoration period, 6 of 212 (5 percent) ditch-water environmental samples contained 0.04–0.045 mg/L–N of nitrate-plus-nitrite. No groundwater blank samples or prerestoration ditch-water blank samples had nitrate-plus-nitrite concentrations above the RL. Prerestoration RL was 0.06 mg/L–N. Using a safety factor of three times the highest blank-sample concentration, any postrestoration ditch-water sample with a nitrate-plus-nitrate concentration less than 0.135 mg/L–N may be contaminated with substantial nitrogen. Using this threshold, 72 of 123 (59 percent) postrestoration ditch-water environmental samples may be affected. If the proportion of environmental samples contaminated is similar to the proportion of blank samples contaminated, as many as eight of these very low concentration filtered nitrate-plus-nitrite results may be slightly high.

Filtered phosphorus.—Filtered phosphorus results from post-restoration groundwater blank samples had minor evidence of phosphorus contamination. One of eight (13 percent) of these blank samples had a concentration of 0.005 milligram per liter mg/L as phosphorus (mg/L–P), which is 1.7 times the RL of 0.003 mg/L–P. During the postrestoration period, 56 of 211 (27 percent) ditch-water environmental samples contained 0.003–0.005 mg/L–P of phosphorus. Ditch-water blank samples and post-restoration groundwater blank samples did not have phosphorus concentrations above the RL. Prerestoration RL was 0.006 mg/L–P. The source of the phosphorus found in this blank sample is unknown. Using a safety factor of three times the highest blank-sample concentration, any postrestoration ditch-water sample with a phosphorus concentration less than 0.015 mg/L–P may be contaminated with substantial phosphorus. Using this threshold, 89 of 211 (42 percent) postrestoration groundwater environmental samples may be affected. If the proportion of environmental samples contaminated is similar to the proportion of blank samples contaminated, as many as 11 of these very low concentration filtered-phosphorus results may be biased slightly high.

Suspended sediment.—Suspended-sediment results from postrestoration ditch-water blank samples had minor evidence of sediment contamination. Two of nine (22 percent) of these blank samples had concentrations of 1 mg/L, which is twice the RL of 0.5 mg/L. During the postrestoration period, 6 of 122 (5 percent) ditch-water environmental samples contained 0.5–1 mg/L of suspended sediment. Prerestoration ditch-water blank samples did not have suspended-sediment concentrations above the RL. The source of the sediment seems to be inadequate decontamination or sample handling. Using a factor of 3, any postrestoration ditch-water sample with a suspended-sediment concentration less than 3 mg/L may be contaminated with substantial suspended sediment. Using this threshold, 13 of 122 (11 percent) postrestoration groundwater environmental samples may be affected. If the proportion of environmental samples contaminated is similar to the proportion of blank samples contaminated, as many as three of these low concentration suspended-sediment results may be biased slightly high.

Appendix 6. Groundwater and Surface-Water Annual Balances

Table 6.1. Net groundwater balance, Glacial Ridge study area, northwestern Minnesota, water years 2003–6 and 2012–15.

[GW, groundwater; ET, evapotranspiration]

Basin	SW2	SW3	SW4	SW5	SW6	SW8	Core area
Basin yield, in inches							
Prerestoration period							
Water year 2003							
Areal GW recharge	6.90	5.52	6.34	3.33	4.45	5.24	5.15
− Base flow	1.05	0.37	1.12	0.35	0.85	0.18	0.65
− GW storage	−0.89	−1.65	−1.99	−4.34	−3.88	−1.47	−2.56
− Modeled GW ET	6.66	6.13	7.19	6.04	6.20	6.65	6.42
= Unmeasured losses	0.08	0.67	0.02	1.28	1.28	−0.11	0.64
Water year 2004							
Areal GW recharge	12.28	7.54	8.64	8.30	9.70	9.27	9.24
− Base flow	1.22	1.41	0.61	0.52	0.90	1.04	0.95
− GW storage	1.75	2.12	2.10	7.37	5.55	3.34	3.96
− Modeled GW ET	9.13	3.85	6.08	0.57	4.33	5.80	4.70
= Unmeasured losses	0.18	0.15	−0.14	−0.17	−1.08	−0.91	−0.37
Water year 2005							
Areal GW recharge	8.74	5.70	6.76	5.68	8.19	6.63	6.98
− Base flow	1.75	2.09	1.95	0.90	1.40	1.66	1.59
− GW storage	−0.53	−0.57	−0.28	−3.44	−1.27	−1.11	−1.28
− Modeled GW ET	7.03	4.29	6.02	7.39	8.22	6.24	6.64
= Unmeasured losses	0.49	−0.10	−0.93	0.83	−0.16	−0.15	0.02
Water year 2006							
Areal GW recharge	6.68	4.95	6.40	4.71	6.47	5.08	5.72
− Base flow	0.77	0.53	1.09	0.85	1.12	0.98	0.89
− GW storage	−0.86	−1.72	−1.46	−2.76	−3.83	−2.18	−2.29
− Modeled GW ET	6.44	5.42	6.29	5.77	7.81	6.52	6.45
= Unmeasured losses	0.32	0.71	0.47	0.85	1.36	−0.24	0.67

Table 6.1. Net groundwater balance, Glacial Ridge study area, northwestern Minnesota, water years 2003–6 and 2012–15.—Continued

[GW, groundwater; ET, evapotranspiration]

Basin	SW2	SW3	SW4	SW5	SW6	SW8	Core area
Basin yield, in inches							
Postrestoration period							
Water year 2012							
Areal GW recharge	5.89	3.66	3.19	1.82	3.41	4.44	3.64
− Base flow	0.39	0.12	0.28	0.10	0.36	0.29	0.26
− GW storage	−1.01	−1.77	−1.31	−1.34	−4.61	−3.14	−2.36
− Modeled GW ET	5.32	4.26	3.56	2.55	5.59	5.55	4.49
= Unmeasured losses	1.18	1.05	0.67	0.52	2.06	1.75	1.25
Water year 2013							
Areal GW recharge	10.18	7.18	9.18	6.07	7.32	7.69	7.79
− Base flow	0.77	0.60	1.29	0.24	0.80	0.99	0.75
− GW storage	1.68	2.08	1.72	0.91	2.72	3.69	2.13
− Modeled GW ET	7.73	4.66	7.31	4.97	4.16	3.58	5.26
= Unmeasured losses	0.00	−0.15	−1.15	−0.05	−0.35	−0.57	−0.35
Water year 2014							
Areal GW recharge	8.83	7.45	10.59	5.77	7.34	6.71	7.64
− Base flow	1.68	2.55	2.87	0.50	1.80	1.95	1.85
− GW storage	−0.35	−0.55	−0.58	1.76	−0.57	−1.80	−0.28
− Modeled GW ET	8.42	6.76	12.75	4.98	6.93	10.25	7.99
= Unmeasured losses	−0.92	−1.31	−4.44	−1.47	−0.82	−3.68	−1.90
Water year 2015							
Areal GW recharge	8.99	6.56	8.11	5.76	8.41	6.84	7.44
− Base flow	0.64	1.08	0.73	0.23	0.98	1.15	0.80
− GW storage	−0.18	−0.32	−0.42	−0.98	−0.48	−0.34	−0.47
− Modeled GW ET	7.81	5.45	7.36	6.01	8.53	5.79	6.91
= Unmeasured losses	0.72	0.35	0.44	0.50	−0.63	0.25	0.21
Prerestoration period average							
Areal GW recharge	8.65	5.93	7.03	5.50	7.20	6.56	6.77
− Base flow	1.20	1.10	1.19	0.66	1.07	0.96	1.02
− GW storage	−0.13	−0.45	−0.41	−0.79	−0.85	−0.36	−0.54
− Modeled GW ET	7.32	4.92	6.39	4.94	6.64	6.30	6.05
= Unmeasured losses	0.27	0.36	−0.15	0.69	0.35	−0.35	0.24
Postrestoration period average							
Areal GW recharge	8.47	6.21	7.77	4.86	6.62	6.42	6.63
− Base flow	0.87	1.09	1.29	0.27	0.99	1.09	0.91
− GW storage	0.03	−0.14	−0.15	0.09	−0.74	−0.40	−0.25
− Modeled GW ET	7.32	5.28	7.75	4.63	6.31	6.29	6.16
= Unmeasured losses	0.25	−0.01	−1.12	−0.12	0.06	−0.56	−0.20
Basin area, in square miles	9.41	11.49	8.67	11.64	15.00	8.69	64.91

Table 6.2. Net surface-water balance, Glacial Ridge study area, northwestern Minnesota, water years 2003–6 and 2012–15.

[SW, surface water; ET, evapotranspiration]

Basin	SW2	SW3	SW4	SW5	SW6	SW8	Core area
Basin yield, in inches							
Prerestoration period							
Water year 2003							
Total precipitation	20.43	18.55	17.51	17.70	18.05	18.21	18.37
− Areal GW recharge	6.90	5.52	6.34	3.33	4.45	5.24	5.15
= Available precipitation	13.53	13.03	11.17	14.37	13.60	12.96	13.22
+ Base flow	1.05	0.37	1.12	0.35	0.85	0.18	0.65
− Ditch flow	3.21	1.24	3.10	1.33	1.78	2.79	2.12
− Modeled SW ET	11.22	10.96	9.17	11.05	10.51	10.53	10.61
= Unmeasured losses	0.14	1.19	0.02	2.33	2.16	−0.18	1.13
Water year 2004							
Total precipitation	28.45	26.72	26.41	27.75	25.03	25.61	26.58
− Areal GW recharge	12.28	7.54	8.64	8.30	9.70	9.27	9.24
= Available precipitation	16.17	19.18	17.77	19.45	15.33	16.34	17.33
+ Base flow	1.22	1.41	0.61	0.52	0.90	1.04	0.95
− Ditch flow	5.92	3.93	5.14	5.72	5.14	5.90	5.25
− Modeled SW ET	11.25	16.02	13.56	20.24	14.75	13.62	15.14
= Unmeasured losses	0.22	0.64	−0.32	−5.98	−3.67	−2.14	−2.11
Water year 2005							
Total precipitation	27.61	23.96	21.21	24.23	22.08	24.43	23.80
− Areal GW recharge	8.74	5.70	6.76	5.68	8.19	6.63	6.98
= Available precipitation	18.87	18.26	14.45	18.55	13.89	17.80	16.82
+ Base flow	1.75	2.09	1.95	0.90	1.40	1.66	1.59
− Ditch flow	4.64	4.12	5.46	3.88	4.50	5.31	4.58
− Modeled SW ET	14.94	16.63	12.94	14.01	11.00	14.50	13.84
= Unmeasured losses	1.04	−0.39	−2.00	1.57	−0.21	−0.35	0.00
Water year 2006							
Total precipitation	22.94	21.03	21.52	20.95	18.22	19.48	20.50
− Areal GW recharge	6.68	4.95	6.40	4.71	6.47	5.08	5.72
= Available precipitation	16.26	16.08	15.12	16.23	11.75	14.39	14.78
+ Base flow	0.77	0.53	1.09	0.85	1.12	0.98	0.89
− Ditch flow	4.88	3.47	5.23	2.68	3.41	5.82	4.07
− Modeled SW ET	11.57	11.61	10.21	12.57	8.07	9.91	10.54
= Unmeasured losses	0.58	1.52	0.77	1.84	1.40	−0.36	1.06
Postrestoration period							
Water year 2012							
Total precipitation	19.32	18.22	17.61	17.19	17.24	17.93	17.85
− Areal GW recharge	5.89	3.66	3.19	1.82	3.41	4.44	3.64
= Available precipitation	13.43	14.56	14.42	15.37	13.83	13.49	14.21
+ Base flow	0.39	0.12	0.28	0.10	0.36	0.29	0.26
− Ditch flow	0.67	0.42	0.48	0.24	0.87	0.42	0.54
− Modeled SW ET	10.77	11.44	11.96	12.66	9.73	10.17	11.07
= Unmeasured losses	2.38	2.82	2.26	2.56	3.59	3.20	2.86

Table 6.2. Net surface-water balance, Glacial Ridge study area, northwestern Minnesota, water years 2003–6 and 2012–15.—Continued

[SW, surface water; ET, evapotranspiration]

Basin	SW2	SW3	SW4	SW5	SW6	SW8	Core area
			Basin yield, in inches				
			Postrestoration period—Continued				
			Water year 2013				
Total precipitation	20.01	19.15	18.96	19.24	18.41	18.55	19.02
− Areal GW recharge	10.18	7.18	9.18	6.07	7.32	7.69	7.79
= Available precipitation	9.83	11.97	9.78	13.17	11.09	10.86	11.23
+ Base flow	0.77	0.60	1.29	0.24	0.80	0.99	0.75
− Ditch flow	1.93	1.87	4.09	2.17	1.72	1.88	2.20
− Modeled SW ET	8.67	11.05	8.29	11.36	11.11	11.84	10.51
= Unmeasured losses	0.01	−0.36	−1.30	−0.11	−0.94	−1.87	−0.72
			Water year 2014				
Total precipitation	20.18	18.94	18.06	18.24	18.22	18.84	18.70
− Areal GW recharge	8.83	7.45	10.59	5.77	7.34	6.71	7.64
= Available precipitation	11.35	11.49	7.47	12.47	10.88	12.13	11.05
+ Base flow	1.68	2.55	2.87	0.50	1.80	1.95	1.85
− Ditch flow	4.14	4.91	7.18	3.03	2.82	8.79	4.80
− Modeled SW ET	9.99	11.32	4.84	14.08	11.20	8.25	10.32
= Unmeasured losses	−1.09	−2.19	−1.69	−4.14	−1.33	−2.96	−2.22
			Water year 2015				
Total precipitation	20.94	20.81	21.14	21.59	21.14	20.40	21.03
− Areal GW recharge	8.99	6.56	8.11	5.76	8.41	6.84	7.44
= Available precipitation	11.94	14.25	13.02	15.83	12.73	13.56	13.59
+ Base flow	0.64	1.08	0.73	0.23	0.98	1.15	0.80
− Ditch flow	1.09	2.20	3.29	3.02	5.21	2.17	3.02
− Modeled SW ET	10.52	12.32	9.87	12.04	9.16	12.01	10.91
= Unmeasured losses	0.97	0.80	0.60	1.00	−0.67	0.52	0.46
			Prerestoration period				
Total precipitation	24.86	22.56	21.66	22.66	20.84	21.93	22.31
− Areal GW recharge	8.65	5.93	7.03	5.50	7.20	6.56	6.77
= Available precipitation	16.20	16.64	14.63	17.15	13.64	15.37	15.54
+ Base flow	1.20	1.10	1.19	0.66	1.07	0.96	1.02
− Ditch flow	4.66	3.19	4.73	3.40	3.71	4.96	4.00
− Modeled SW ET	12.25	13.80	11.47	14.47	11.08	12.14	12.53
= Unmeasured losses	0.49	0.74	−0.38	−0.06	−0.08	−0.76	0.02
			Postrestoration period				
Total precipitation	20.11	19.28	18.94	19.07	18.75	18.93	19.15
− Areal GW recharge	8.47	6.21	7.77	4.86	6.62	6.42	6.63
= Available precipitation	11.64	13.07	11.17	14.21	12.13	12.51	12.52
+ Base flow	0.87	1.09	1.29	0.27	0.99	1.09	0.91
− Ditch flow	1.96	2.35	3.76	2.12	2.66	3.31	2.64
− Modeled SW ET	9.99	11.53	8.74	12.53	10.30	10.56	10.70
= Unmeasured losses	0.57	0.27	−0.03	−0.17	0.16	−0.28	0.09
Basin area, in square miles	9.41	11.49	8.67	11.64	15.00	8.69	64.91

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