## *Articles*

# A Case Study Examining the Efficacy of Drainage Setbacks for Limiting Effects to Wetlands in the Prairie Pothole Region, USA

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## Abstract

The enhancement of agricultural lands through the use of artificial drainage systems is a common practice throughout the United States, and recently the use of this practice has expanded in the Prairie Pothole Region. Many wetlands are afforded protection from the direct effects of drainage through regulation or legal agreements, and drainage setback distances typically are used to provide a buffer between wetlands and drainage systems. A field study was initiated to assess the potential for subsurface drainage to affect wetland surface-water characteristics through a reduction in precipitation runoff, and to examine the efficacy of current U.S. Department of Agriculture drainage setback distances for limiting these effects. Surface-water levels, along with primary components of the catchment water balance, were monitored over 3 y at four seasonal wetland catchments situated in a high-relief terrain (7–11% slopes). During the second year of the study, subsurface drainage systems were installed in two of the catchments using drainage setbacks, and the drainage discharge volumes were monitored. A catchment water-balance model was used to assess the potential effect of subsurface drainage on wetland hydrology and to assess the efficacy of drainage setbacks for mitigating these effects. Results suggest that overland precipitation runoff can be an important component of the seasonal water balance of Prairie Pothole Region wetlands, accounting on average for 34% (19–49%) or 45% (39–49%) of the annual (includes snowmelt runoff) or seasonal (does not include snowmelt) input volumes, respectively. Seasonal (2014–2015) discharge volumes from the localized drainage systems averaged 81 $m^3$ (31–199 $m^3$), and were small when compared with average combined inputs of 3,745 $m^3$ (1,214–6,993 $m^3$) from snowmelt runoff, direct precipitation, and precipitation runoff. Model simulations of reduced precipitation runoff volumes as a result of subsurface drainage systems showed that ponded wetland surface areas were reduced by an average of 590 $m^2$ (141–1,787 $m^2$), or 24% (3–46%), when no setbacks were used (drainage systems located directly adjacent to wetland). Likewise, wetland surface areas were reduced by an average of 141 $m^2$ (23–464 $m^2$), or 7% (1–28%), when drainage setbacks (buffer) were used. In totality, the field data and model simulations suggest that the drainage setbacks should reduce, but not eliminate, impacts to the water balance of the four wetlands monitored in this study that were located in a high-relief terrain. However, further study is required to assess the validity of these conclusions outside of the limited parameters (e.g., terrain, weather, soils) of this study and to examine potential ecological effects of altered wetland hydrology.

Keywords: catchment, ecosystem services, model, precipitation runoff, subsurface drainage, water balance

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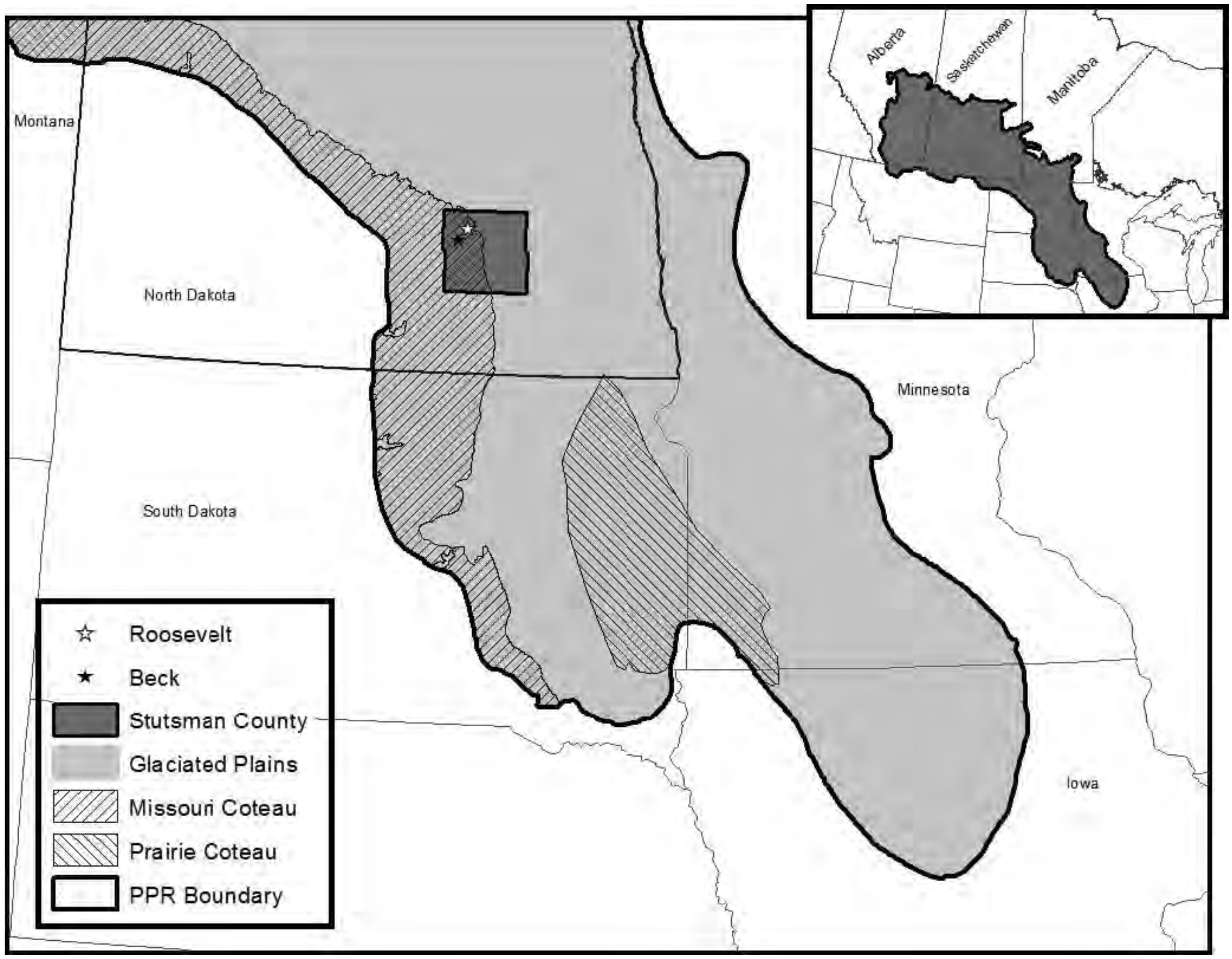


**Figure 1.** Location of Roosevelt and Beck study sites in the Prairie Pothole Region (PPR) of Stutsman County, North Dakota. Study sites were located within the portion of Stutsman County that overlies the Missouri Coteau physiographic region and the primary components of the seasonal water balance and the discharge volumes from the drainage systems were monitored (May/June–November) of 2013–2015.

## Introduction

The use of artificial drainage systems to decrease soil water content or drain wetlands for the purpose of enhancing agricultural production has been a common practice throughout the history of the United States (Pavelis 1987; Dahl 1990, 2014; Dahl and Johnson 1991; Johnson et al. 2008). Traditionally, the purpose of agricultural drainage has been to lower the water table of poorly drained soils with the goal of improving soil aeration. Recently, advanced drainage systems have been promoted as a way to manipulate soil water content during the growing season (NRCS 2001). Surface ditches drain water through altered natural channels or constructed ditches, whereas subsurface drainage systems typically remove water through perforated pipe (commonly referred to as tile) placed below the soil surface. Both types of drainage systems are used to drain localized areas (e.g., wetlands), as well as large tracts of land. Under certain environmental conditions drainage affords several benefits for agricultural production, including potential of earlier planting, better soil conditions for seed germination and plant growth, and reduced soil compaction and erosion (Skaggs et al. 1982; Kandel et al. 2013; Kumar et al. 2015; Streeter and Schilling 2015). Conversely, agricultural drainage has been linked to negative downstream effects associated with increased nutrients and agrichemicals, streamflows, habitat degradation, and effects on adjacent land use and properties (Robinson and Rycroft 1999; Schilling and Libra 2003; Blann et al. 2009; Schilling et al. 2012; Schottler et al. 2014).

The Prairie Pothole Region (PPR) is located in the north-central United States and south-central Canada (Figure 1), and is characterized by millions of isolated wetlands interspersed among a landscape mosaic of agricultural fields and grasslands (Dahl 2014). Prairie Pothole Region wetland catchments, defined as a wetland basin and the surrounding uplands or contributing area (Gleason et al. 2008; Finocchiaro et al. 2014), provide numerous ecosystem services that are linked to their unique and variable surface-water characteristics and biotic communities (Stewart and Kantrud 1972; Swanson et al. 1988; Batt et al. 1989; Kantrud et al. 1989a,b; Murkin 1998; Euliss et al. 2004, 2006; MEA 2005; Zedler and Kercher 2005; Gleason et al. 2008, 2009, 2011; Brinson and Eckles 2011). Because of variable factors such as regional climate, soils, and agriculture practices, the southeast part of the U.S. portion of the PPR (Iowa, Minnesota) has been extensively drained with tile, whereas the western and northern parts (North and South Dakota and Montana) generally have remained unaffected by subsurface drainage. However, high crop demands in recent years have led to a rapid expansion of land-use conversion and subsurface drainage into the eastern portions of North and South Dakota (e.g., Jia et al. 2012; Johnston 2013; Kandel et al. 2013; Wright and Wimberly 2013; Karki et al. 2014; USGS 2015a,b; Werner et al. 2016). This expansion has been associated with changes in cropping practices and greater utilization of wetland catchments and other low-production agricultural areas. There has also been increased conversion of native and restored grasslands, such as those enrolled in the U.S. Department of Agriculture's (USDA) Conservation Reserve Program, to cropland. The Conservation Reserve Program is the predominant conservation program in the PPR, and according to USDA statistics, enrolled acreage has decreased from 2006 to 2013 by roughly 53% (6,437 $km^2$) and 64% (2,197 $km^2$) in North Dakota and South Dakota, respectively. Moreover, greater than 90% of the approximately 11,142 $km^2$ of remaining Conservation Reserve Program land (circa 2014) is up for contract expiration by 2028 (http://www.fsa.usda.gov/FSA/). Thus, the extensive area of wetlands in the Dakotas, including existing cropland wetlands, has great potential to be affected by increased agricultural drainage.

## Catchment water balance and potential effects of subsurface drainage systems

The overall water balance of prairie pothole wetland catchments is primarily driven by direct precipitation onto the wetland, precipitation runoff (i.e., surface or overland flow and near-surface or interflow), and evapotranspiration (Hayashi et al. 2016). Other components include groundwater inputs (discharge) and losses (recharge) and surface outflows (Shjeflo 1968; Kantrud et al. 1989a; Winter 1989). Snowmelt runoff and direct precipitation generally account for the greatest proportion of annual water inputs; however, precipitation runoff (surface and near-surface) generated by long or intense rain events can play an important role, especially in cropland catchments where runoff generally is greater in amount and frequency than in grassland catchments (Poiani and Johnson 1993; Winter and Rosenberry 1995; Euliss and Mushet 1996; Su et al. 2000; van der Kamp et al. 2003; Carroll et al. 2005; Voldseth et al. 2007; Roth and Capel 2012).

The use of subsurface drainage in wetland catchments has the potential to affect the water balance and overall surface-water characteristics of a wetland, as well as associated ecosystem services. Results of model simulations by Werner et al. (2016) suggested that subsurface drainage positioned adjacent to wetlands could result in reduced hydroperiods (period of inundation) depending on several factors such as depth of tile in relation to the wetland. The amount and timing of precipitation intercepted by subsurface drainage systems will vary depending on soil properties, topography (low/high topographic relief), placement of tile relative to the wetland (horizontal distance, elevation), and the relation between the wetland and groundwater (i.e., recharge, discharge) (Winter 1989; Euliss et al. 2004). Direct drainage of a wetland by placing perforated tile and surface inlet pipes through (beneath) the wetland would have a detrimental effect on wetland hydrology regardless of other factors (Blann et al. 2009). Drainage systems positioned adjacent to a wetland in low-relief terrain have the potential to indirectly affect the wetland through lateral drainage (lateral effect) (Figures 2A and 2B). The lateral effect is defined as the perpendicular distance on either side of a tile pipe where soil water can be drained by the tile. Drainage systems positioned to completely or partially encircle a wetland in high-relief terrain (Figures 2C and 2D) can intercept groundwater and precipitation runoff to the wetland depending on the previously mentioned factors.

For scenarios described above, the effects of a drainage system on wetland hydrology also will vary with time. For instance, drainage systems will have little effect on precipitation runoff if the soils are frozen during spring snowmelt because water cannot infiltrate the frozen soil. However, drainage may affect the depth of the soil frost seal and the duration that soils are frozen. Further, the amount of water removed from a catchment has the potential to be greater during years with high precipitation. Potential effects of a drainage system also would vary among precipitation events because of variability in antecedent soil water content (e.g., saturated soils vs. soils at field capacity) and the intensity and duration of an event.

## Drainage setbacks

Agricultural producers who participate in USDA Farm Bill programs generally are prohibited from directly draining or altering wetlands and must adhere to prescribed protective setback distances around wetlands when installing drainage systems to ensure no effects to the ecological processes of the wetland. Guidance for protective drainage setbacks is provided to landowners by the USDA Natural Resources Conservation Service (NRCS). The NRCS typically determines setbacks using scope and effect equations, which essentially estimate the effect of a drainage system on the surrounding soil water table (NRCS 1997). In North and South Dakota, the NRCS typically relies on the van Schilfgaarde equation

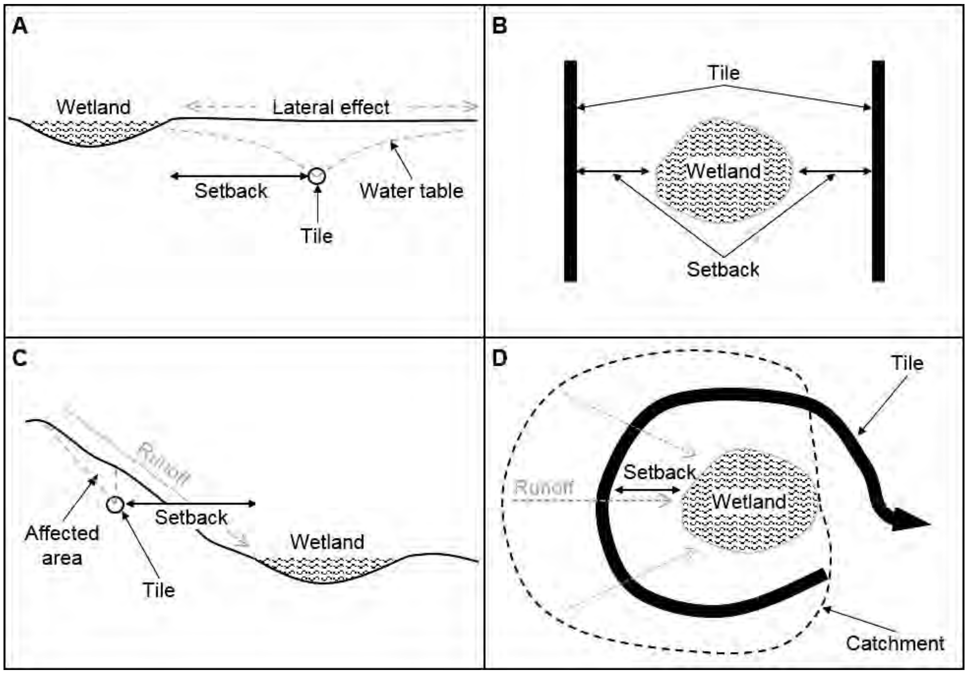


**Figure 2.** Profile and overhead views of common drainage system (tile) placement scenarios in low-relief (panels A and B) and high-relief terrain (panels C and D). Panels A and B represent the concept of lateral effect area and panels C and D represent an example of encirclement intercepting runoff. Drainage systems are shown with generalized setback distances from the wetland.

combined with site-specific soil and landscape characteristics (NRCS 2004, 2009). Calculated setbacks are based on the assumption that a specified water-table drawdown (e.g., 0.3 m over 2 wk) will have a negligible effect on wetlands and their associated functions and values. Models and equations such as the van Schilfgaarde, however, generally were developed to calculate drain spacing on nearly level terrain, and may not be optimal for determining wetland setback distances in the PPR, which is characterized by variable topography and soils (Kantrud et al. 1989a; NRCS 1997; Bluemle 2000). Further, most drainage equations were developed to estimate effects on the subsurface water table or soil water, not on ponded surface waters such as wetlands (NRCS 1997; Werner et al. 2016). The distinction between surface and subsurface water is important because the water balance of PPR wetlands is dominated by surface processes, the underlying soils often have a restrictive layer of high clay content, and they often are characterized by low soil water transmission rates ($< 3$ m·y$^{-1}$) (Shjeflo 1968; Sloan 1972; Hendry 1982; Winter and Rosenberry 1995). Thus, water movement and hydraulic conductivity could differ greatly between typical agricultural soils and wetlands.

In addition to wetlands protected by USDA regulations (e.g., drainage setbacks) and conservation programs, the U.S. Fish and Wildlife Service (USFWS) protects hundreds of thousands of wetlands in North and South Dakota through conservation easements where private landowners agree not to disturb wetlands (e.g., drain, fill, level, burn) in exchange for financial compensation. Uncertainties with regard to the indirect effects of adjacent drainage systems on wetlands, and the efficacy of prescribed setback distances, has prompted the USFWS to conditionally adapt the NRCS methodology for determining setbacks on easement lands. To increase the likelihood that subsurface drainage will not affect wetland water levels, the USFWS has decreased the allowable amount of water-table decline or reduction in soil saturation at the wetland edge in the scope-and-effect equation from 0.3 m to 0.03 m. The rationale for not relying on the standard permissible water-table/soil saturation loss to protect wetlands on easement lands is that there is little to no information pertaining to the efficacy of various scope-and-effect equations. Further, even if setbacks are properly applied, there still is potential for indirect drainage or interruption of precipitation runoff from the catchment area upslope of the drainage system. Thus, agencies such as the USFWS require information on the utility of scope-and-effect equations to support policies of conservation programs focused on protecting wetland resources. The objectives of this study were to provide an initial assessment of prescribed setback distances for limiting effects to wetland hydrology and to assess the potential effects of reduced precipitation runoff on wetland surface-water characteristics resulting from subsurface drainage.

## Methods

### Study sites

Study sites consisted of two parcels of land located within approximately 13 km of each other in the Missouri Coteau physiographic region of Stutsman County, North

**Table 1.** Characteristics of the four wetland catchments located in Stutsman County, North Dakota. Surface areas, maximum depth and volume, and slope characteristics were determined using data from detailed topographic surveys of each wetland catchment conducted during 2013. The spill-point elevation was used to delineate the upland and wetland zones (see Figure 3), as well as to calculate maximum depths and volumes. Wetlands Beck 5 and 6 were located at the Beck site, whereas wetlands Roos 3 and Roos 8 were located at the Roosevelt site.

| | Surface area, $m^2$ | | | | Mean upland slope | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Wetland | Wetland zone | Upland zone | Maximum depth, m | Maximum volume, $m^3$ | Grade, % | Length, m | Catchment soil mapping units[a] | Setback[b] distance, m | Upland zone area upslope of tile setback, $m^2$ (%)[c] |
| Beck 5 | 5,500 | 24,500 | 0.9 | 1,611 | 7 | 89 | C132B, C132C | 38 | 9,123 (37%) |
| Beck 6 | 20,800 | 46,600 | 1.7 | 19,296 | 10 | 67 | C132C, C132B, C135D | 43 | 10,182 (22%) |
| Roos 3 | 7,900 | 20,060 | 0.6 | 2,109 | 8 | 61 | C132C | 43 | 3,067 (15%) |
| Roos 8 | 1,400 | 16,700 | 0.6 | 407 | 11 | 58 | C165F, C156F | 39 | 4,654 (28%) |

[a] Soil mapping units from U.S. Department of Agriculture, Natural Resources Conservation Service, Soil Survey Geographic (SSURGO) database. Definition of mapping units: C132B, Williams–Zahl loams; C132C, Williams–Zahl–Zahill complex; C135D, Zahl–Williams loams; C156F, Zahl–Max–Bowbells loams; C165F, Zahl–Max–Parnell complex.

[b] Setback distance is the minimal linear surface distance that the tile can be installed near the wetland and is prescribed by the U.S. Department of Agriculture, Natural Resources Conservation Service on the basis of standard protocols and criteria for North Dakota.

[c] Percentage of the total upland zone surface area represented by the area upslope of the tile setback.

Dakota (Figure 1). Two wetland catchments were selected on each parcel that were comparable in regard to wetland classification, size, soils, topography, and land-management history (Table 1). The wetlands are located in a relatively high-relief terrain (7–11% slopes) (Table 1) and generally considered groundwater recharge or flow-through systems on the basis of characteristics such as seasonal water permanence, vegetation, soils, and water chemistry (e.g., Stewart and Kantrud 1971, 1972; NRCS 2010; Euliss et al. 2014). The sites were managed as grasslands for nearly 40 y and were converted to crop production during this study. The sod was broken and soil tilled in July of 2012. Throughout this study the wetlands contained ponded water in the spring; thus, the catchments only were tilled and cropped to the approximate wetland edge as defined by ponded water, saturated soils, and hydrophytic vegetation. In the spring (May, June) of 2013, the uplands of all catchments were planted to soybeans (*Glycine max*) using minimal tillage practices, and perforated drainage tile was installed in two of the four wetland catchments (Beck 5, Beck 6) in November of 2013. Both drained catchments were located at the Beck study site because of the considerable time and labor required to install the drainage systems. The 15.24-cm-diameter tile was professionally installed at an average depth ranging from 76 to 107 cm and according to site-specific NRCS setback distances (Table 1). As a result of the setback distances, the perforated tile was positioned in the upland zone of each catchment (e.g., Figure 3), and did not extend outside the catchment. On average, the tile was positioned 5 m or more above the wetland boundaries. The tile water outlets were located outside the catchments, and were connected to the localized drainage systems with nonperforated pipe to allow for measurement of drainage discharge only from the catchments. The placement of tile in areas that could directly contribute runoff to the wetland facilitated the quantification of water discharge from the catchment through the tile outlet. All catchments were planted to wheat (*Triticum aestivum*) using minimal tillage practices during 2014 and soybeans during 2015.

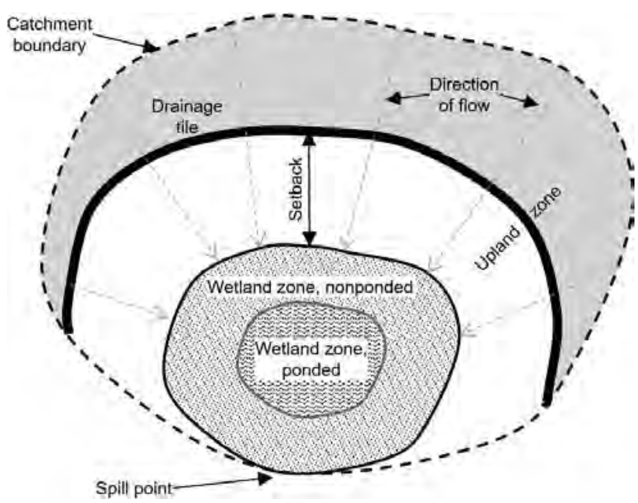


**Figure 3.** Overhead view of wetland catchment showing the upland zone and dynamic ponded and nonponded portions of the wetland zone. The thick black line depicts an example of wetland encirclement by a drainage system (tile) using a setback. The shaded area upslope of the tile represents the area where precipitation runoff can be intercepted by the drainage system. Dashed arrows show direction of surface and near-surface flow of precipitation runoff in the upland zone.

### Catchment instrumentation and monitoring and water volume calculations

The wetland catchments were instrumented during the approximate ice-free season (May/June–November) of 2013–2015 to monitor the primary components of the seasonal water balance and the discharge volumes from the drainage systems. Air temperature, solar radiation, and precipitation were monitored at each site using a weather station (Watchdog 2900ET, Spectrum Technologies, Aurora, IL) and two tipping-bucket rain gauges

(Hobo RG3-M, Onset, Bourne, MA) that were placed in each catchment. Wetland surface-water levels were monitored continuously using pressure transducers (Solinst LTC Levellogger Junior, Georgetown, Ontario, Canada). Average daily precipitation was calculated for each site using data from the weather station and rain gauges. Temperature and solar radiation data were used in the water-balance model described below. Additionally, detailed topographic surveys were conducted on each catchment using a high-accuracy global positioning system (Trimble 5700, Trimble, Sunnyvale, CA). Surveys included the locations and elevations of all monitoring equipment and drainage tile lines, as well as wetland water levels. The topographic and water-level data were used to determine catchment surface areas, volumes, and depths, as well as depth–volume–surface area curves. Hereafter, observed depths refer to depths from the pressure transducers, whereas observed ponded surface areas refer to areas calculated using the observed depths and the depth–surface area curves (see *Supplemental Material*).

The contribution of direct precipitation, precipitation runoff, and snowmelt runoff to the seasonal water balance of each wetland was determined using a mass balance approach. The water-level data were used, along with the depth–volume–surface area curves (*Supplemental Material*), to calculate average daily wetland water volumes and ponded and nonponded surface areas. Change in daily water volume was calculated by subtracting the volume of the previous day, and daily volume of direct precipitation to the wetland was calculated by multiplying precipitation amount (depth) by the ponded wetland surface area. Similarly, daily volume of evapotranspiration was calculated by multiplying evapotranspiration (see *Supplemental Material*) by the ponded wetland surface area. Seasonal totals of direct precipitation were subtracted from seasonal volume gains (i.e., positive daily wetland volume changes plus evapotranspiration volumes) to estimate the volume of precipitation runoff from the nonponded portion of the catchment (upland zone and nonponded portion of wetland zone; Figure 3). The volume of snowmelt runoff was approximated by subtracting the previous year's fall volume (final sample date of season) from the current year's spring volume (first sample date of season). Since water depth was not monitored during 2012, snowmelt runoff was not calculated for 2013. Additionally, the volume of precipitation that fell on the nonponded portion of the catchment was calculated by multiplying precipitation depth by the nonponded surface area of the catchment. Results of these calculations were used to assess the contribution of precipitation and runoff (precipitation and snowmelt) to the wetland water balance.

The timing and rate of discharge from the drainage systems were measured by routing the tile outlet through a standard 7.62-cm Parshall flume equipped with a submersible pressure transducer (MEAS KPSI 501, Measurement Specialties, Hampton, VA). The transducer was connected to a data logger (CR1000, Campbell Scientific, Logan, UT) that was programmed to collect a reading every minute. Discharge rate through the flume was determined using the manufacturer-supplied rating curve. Daily discharge volume was calculated by multiplying the discharge rate ($m^3 \cdot s^{-1}$) collected each minute by 60 and summing the resulting volumes by day. To estimate the predominant low-volume flows (i.e., trickle flows) through the flume, which could not be accurately captured with the pressure transducer because of minimal depth limitation, a 208-L water collection tank was installed below the flume outlet. The tank was set up in a manner to capture the trickle flows while allowing the higher-volume flows to overshoot the tank's inlet pipe. Water depth of the tank from manual measurements or pressure transducer data were used to calculate water volumes, which were used to supplement the flume discharge data. Total daily tile discharge volume was calculated by summing daily volumes calculated from the flume data and daily volumes from the low-flow water collection tank, when present. During 2014, the discharge estimates likely are conservative because of minor data gaps associated with equipment failures.

### Approach for assessing drainage setbacks and potential effects of subsurface drainage

A combination of field measurements and wetland hydrologic modeling was used to assess drainage setbacks, as well as potential effects of subsurface drainage systems on the overall water balance of the four wetland catchments. First, the drainage setbacks were assessed by calculating the seasonal volumes of tile discharge and qualitatively relating them to seasonal volumes of precipitation and runoff. The purpose of these general comparisons was to provide context to the drainage system discharge volumes and to relate them to the primary components of the wetland water balance. Second, a water-balance model was calibrated and applied to each wetland catchment to assess the potential effects of drainage systems on ponded surface area, an ecologically important surface-water characteristic. The model calculates daily surface-water characteristics on the basis of the primary components of the catchment water balance (precipitation and runoff, evapotranspiration), and is described in *Supplemental Material*.

The precipitation runoff parameters (i.e., curve number method) for the drained catchments (Beck 5 and 6) were calibrated using data from 2013, which were collected before the installation of the drainage systems. This calibration allows for assessments of model fit among years (i.e., pre- and postdrainage) with the purpose of identifying potential effects of the drainage systems. To do so, the daily difference between predicted and observed ponded wetland surface area (difference = predicted − observed) was calculated and a one-way analysis of variance (ANOVA) was run using PROC MIXED

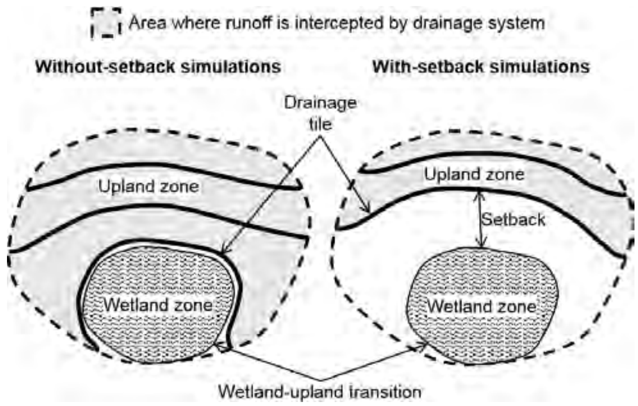


**Figure 4.** Depiction of the without- and with-setback model scenarios. The without-setback simulations are characterized by drainage system tile (thick black lines) placed throughout the upland zone of the catchment with no protective setbacks around the wetland zone (see Figure 3). The with-setback simulations represent the use of drainage setbacks to provide a buffer between the wetland and drainage tile. For the model scenarios, precipitation runoff is excluded from the shaded area of the catchment (upslope of the tile) to simulate the interception of precipitation runoff by the drainage system.

in SAS (version 9.4; SAS Institute Inc., Cary, NC) to test for differences in model fit (difference) among years. The rationale of this analysis was to determine whether model fit varied by year, and if so, did results suggest that differences were attributable to natural factors influencing the water balance of the wetlands, such as precipitation amount and intensity, or did model fit differ only among the pre- and postdrainage years, indicating a potential effect of the drainage systems?

The calibrated water-balance models also were used to simulate the effects of subsurface drainage systems, located in the upland zone of the wetland catchment, on wetland surface-water characteristics. These model scenarios were based on the assumption that drainage systems placed in the upland contributing areas of wetland catchments indirectly drain wetlands by enhancing drainage of the upland soils, thereby effectively reducing water inputs attributed to precipitation runoff. To demonstrate the potential effects of reduced precipitation runoff, as well as to assess the efficacy of drainage setbacks for mitigating this reduction, model simulations were generated using two scenarios. The first scenario simulates the placement of a drainage system without any protective setback distance from the wetland edge; therefore, it is immediately adjacent to the wetland. These model simulations are referred to as without-setback simulations. The second scenario simulates the placement of a drainage system at the NRCS-prescribed setback distance from the wetland edge (with-setback simulations). Both scenarios were compared with a reference scenario of no drainage system.

The without-setback simulations were based on the assumption that the subsurface drainage systems were located at or outside of (upslope of) the wetland zone boundary and in the contributing area of the catchment. For the without-setback simulations, 100% of modeled precipitation runoff from the upland zone of the catchment was eliminated (i.e., maximum potential reduction); precipitation runoff from the nonponded portion of the wetland zone was not affected for these simulations. For the with-setback simulations, modeled precipitation runoff was eliminated as a contributing water source only from the catchment area upslope of the drainage system (Figures 3 and 4). To do this, any daily precipitation runoff was simply reduced on the basis of the percentage of the upland zone surface area located upslope of the drainage system (Table 1). Consequently, daily modeled precipitation runoff from Beck 5, Beck 6, Roos 3, and Roos 8 were reduced by 37, 22, 15, and 18%, respectively. It is, however, unlikely that a drainage system would effectively capture 100% of runoff, so results represent the maximum potential reduction and should be interpreted accordingly. Simulations were based on the assumption that the entire contributing area of the wetland catchment contributes runoff equally and that the drainage system effectively eliminated all runoff from the upland zone (without-setback scenario) or the area upslope of the drainage setback (with-setback scenarios). In reality, however, the generation of runoff and the effectiveness of a drainage system for reducing surface runoff would vary according to factors such as catchment slope length and grade, precipitation amount and intensity, antecedent soil moisture conditions, soil profile characteristics, seasonal vegetative cover, and the characteristics of the drainage system. Further, drainage systems placed directly adjacent to a wetland (without-setback) would have an additional effect on wetland hydrology through the lateral effect of the system, depending on the depth of the tile (Werner et al. 2016).

## Results

### Catchment water inputs

The contribution of snowmelt runoff, direct precipitation to the ponded portion of the catchment, and precipitation runoff from the nonponded portion of the catchment varied by year among the four wetland catchments (Table 2). During the year when snowmelt runoff was not calculated (2013), seasonal water input volumes averaged 3,130 $m^3$ (950–9,400 $m^3$). Likewise, annual volumes averaged 2,530 $m^3$ (877–6,993 $m^3$) for the years when snowmelt runoff was calculated (2014–2015) (Table 2). During 2013, direct precipitation to the ponded portion of the catchment accounted for 55% (51–61%) of the seasonal wetland water input, whereas precipitation runoff accounted for 45% (39–49%). These estimates represent only the approximate ice-free season and do not include snowmelt runoff, which was not calculated during 2013. During 2014 and 2015, snowmelt runoff, direct precipitation, and precipitation runoff accounted for 29 (0–53), 47 (27–61), and 34% (19–49%) of the annual water input, respectively. Moreover, model

**Table 2.** Summary of yearly (2013–2015) precipitation and water input volumes to the four wetland catchments located in Stutsman County, North Dakota. Total wetland volume change represents only positive change in water levels and is attributed to snowmelt runoff, direct precipitation to the ponded portion of the catchment, and precipitation runoff (surface and near-surface) from the nonponded portion of the catchment. Evapotranspiration was incorporated into the total positive change to calculate precipitation runoff volumes (see Methods). Snowmelt runoff volume was not calculated during 2013.

| | | | | Water volume, $m^3$ (%)[b] | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Wetland | Year | Days[a] | Precipitation, cm | Total positive change to ponded portion | Evapo-transpiration | Snowmelt runoff | Precipitation to ponded portion | Precipitation runoff from nonponded portion | Precipitation to nonponded portion of the catchment |
| Beck 5 | 2013 | 181 (0) | 44 | 910 | 160 | —- | 543 (51%) | 528 (49%) | 12,635 |
| | 2014 | 169 (0) | 28 | 1,265 | 137 | 469 (33%) | 578 (41%) | 356 (25%)[c] | 7,723 |
| | 2015 | 229 (57) | 28 | 971 | 243 | 276 (23%) | 564 (46%) | 374 (31%)[c] | 7,973 |
| Beck 6 | 2013 | 181 (0) | 44 | 8,162 | 1,238 | — | 5,257 (56%) | 4,143 (44%) | 24,349 |
| | 2014 | 169 (0) | 28 | 6,125 | 868 | 1,950 (28%) | 3,481 (50%) | 1,562 (22%)[c] | 15,168 |
| | 2015 | 223 (28) | 28 | 4,562 | 808 | 1,251 (23%) | 3,099 (58%) | 1,020 (19%)[c] | 16,082 |
| Roos 3 | 2013 | 181 (82) | 43 | 979 | 122 | — | 673 (61%) | 428 (39%) | 11,586 |
| | 2014 | 165 (87) | 22 | 2,153 | 194 | 925 (39%) | 643 (27%) | 779 (33%) | 5,734 |
| | 2015 | 230 (145) | 34 | 910 | 193 | 0 (0%) | 559 (51%) | 544 (49%) | 9,223 |
| Roos 8 | 2013 | 181 (0) | 43 | 862 | 88 | — | 490 (52%) | 461 (49%) | 7,295 |
| | 2014 | 165 (13) | 22 | 807 | 70 | 469 (53%) | 234 (27%) | 175 (20%) | 3,816 |
| | 2015 | 224 (46) | 34 | 797 | 138 | 276 (30%) | 381 (41%) | 278 (30%) | 5,832 |

[a] Total number of days that water depth and precipitation were measured along with the number of days (in parentheses) that the wetland was dry.
[b] Percentage of total wetland volume change attributed to snowmelt runoff, direct precipitation, and precipitation runoff.
[c] Beck 5 and Beck 6 had drainage tile installed (using setbacks) in November 2013.

calibrations suggested that evapotranspiration estimates may be conservative (*Supplemental Material*); thus, the estimates of precipitation runoff also may be conservative.

## Drainage system discharge

The daily drainage system discharge measurements resulted in total seasonal volumes of 60 and 34 $m^3$ for Beck 5 during 2014 and 2015, respectively. Discharge volumes for Beck 6 were 199 and 31 $m^3$ for 2014 and 2015, respectively (Figure 5). For the same sites and years, the average combined water input from snowmelt runoff, direct precipitation, and precipitation runoff was 3,745 $m^3$ (1,214–6,993 $m^3$) (Table 2). The seasonal drainage system discharge volumes generally were small compared with estimates of precipitation runoff, with discharge representing 3–17% of the runoff volumes (Figure 5; Table 2). The area upslope of the drainage system (e.g., Figure 3) is considered the contributing area for the drainage system discharge and represents approximately 37 and 22% of the upland zone for Beck 5 and Beck 6, respectively (Table 1). The width of the contributing area (distance between drainage tile and catchment boundary) varied within each catchment and was only a few meters in some places.

## Assessment of drainage setbacks

The water-balance model was applied to all four catchments during all years and performed well, with correlations between modeled and observed daily surface areas ranging from 0.89 to 0.99 (Figures S2 and S3, *Supplemental Material*). Results of the ANOVA suggested that the difference between modeled and observed wetland surface area, the measure of model performance, varied by year (Table 3). Nine of the 12 wetland-by-year combinations resulted in an overall negative difference (i.e., model underpredicted ponded surface area), whereas the remaining three resulted in a positive difference (i.e., model overpredicted area). The model for Beck 5 overpredicted slightly during the predrainage year (2013) and underpredicted during the postdrainage years (2014–2015) (Table 3). The model for Beck 6 underpredicted during the predrainage year, and overpredicted and underpredicted for the postdrainage years. Models for the nondrained control sites underpredicted for five of the six wetland-year combinations (Table 3). Overall, the models did not consistently overpredict ponded surface areas for the postdrainage years, suggesting that any drainage effects on surface runoff volumes were minor relative to the accuracy of the models.

## Model simulations

Qualitative visual interpretations of results of with- and without-setback model scenarios generally suggest smaller ponded surface areas for the without-setback scenarios when compared with the calibrated water-balance models (Figure 6). Results of the with-setback model scenarios suggest that ponded surface areas were similar, or slightly smaller, when compared with the calibrated models (Figure 6). These differences, however, vary with time. Overall, average differences in daily ponded surface area between the calibrated models and the without- and with-setback scenarios were approximately 590 $m^2$ (24% reduction) and 141 $m^2$ (7% reduction), respectively (Table 4).

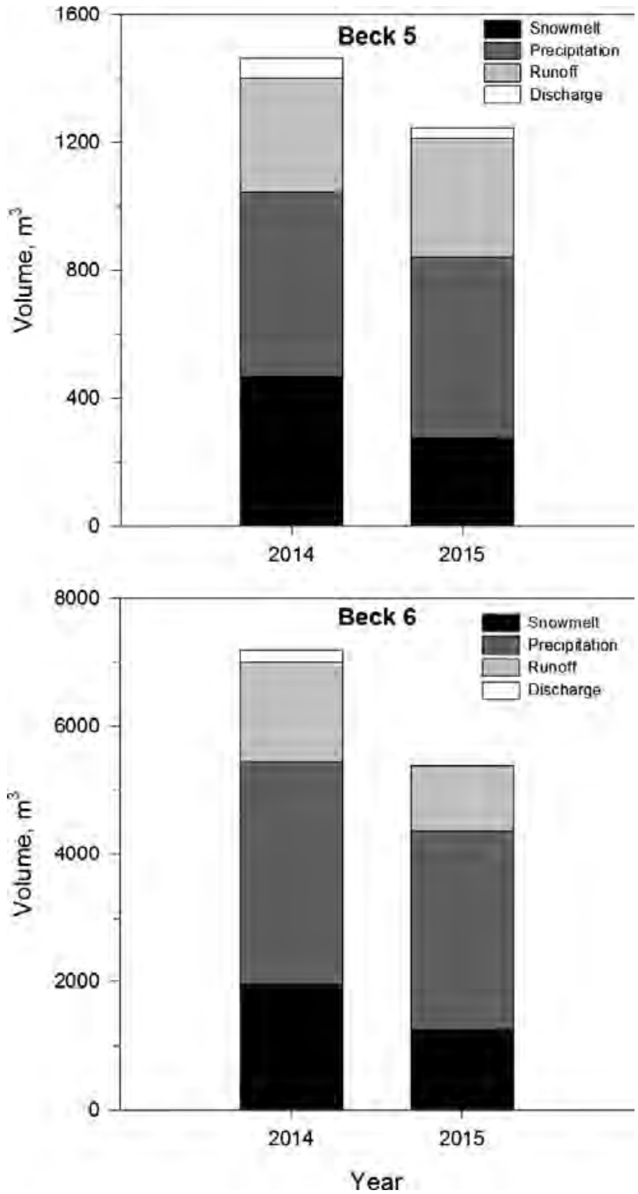


**Figure 5.** Water-volumes during 2014 and 2015 for wetlands Beck 5 and Beck 6, Stutsman County, North Dakota. Volumes were attributed to snowmelt runoff, direct precipitation to the ponded portion of the catchment, precipitation runoff from the nonponded portion of the catchment, and discharge from the subsurface drainage systems.

## Discussion

Ancillary results of this study correspond with previous studies indicating the importance of overland precipitation runoff to the seasonal water balance of PPR wetlands (Shjeflo 1968; Poiani and Johnson 1993; Euliss and Mushet 1996; Su et al. 2000; Carroll et al. 2005; Voldseth et al. 2007; Roth and Capel 2012). Precipitation runoff, although variable, accounted for up to 49% of the seasonal water inputs for the ponded portion of the catchments examined during this study (Table 2). Consequently, a subsurface drainage system placed outside (upslope) of a wetland's boundary, but in the contributing area of the catchment, has the potential to indirectly affect a wetland's water balance through a reduction in the volume of precipitation runoff that would contribute to the wetland's surface-water characteristics. It is important to note, however, that this study was conducted in relatively high-relief terrain where precipitation runoff likely is a greater contributor to the water balance of a wetland compared with flat terrain where direct precipitation, and in some cases groundwater, likely are the dominant contributors. A majority of the lands in the eastern Dakotas that have been targeted for drainage are associated with relatively flat, low-relief terrain compared with the sites associated with this study. The potential effects of subsurface drainage systems to wetland hydrology in this flat terrain are associated primarily with physical characteristics (e.g., drainpipe depth) and the lateral effect of a drainage system (Werner et al. 2016), as opposed to the interception of precipitation runoff from adjacent slopes. Thus, the application of prescribed setbacks in low-relief terrain is fairly straightforward. This study focused on sites with greater topographic relief for a two primary reasons. First, USFWS personnel identified the ongoing expansion of subsurface drainage into high-relief areas as an area of concern associated with several information gaps pertaining to drainage in the adjacent, contributing areas of wetland catchments. Second, precipitation runoff likely is more important to the water balance of wetlands surrounded by steeper slopes compared with those in a low-relief terrain; thus, drainage in the contributing area of a wetland catchment represents a greater potential impact that is not typically accounted for in drainage policy.

Although the potential indirect effects of subsurface drainage are evident, quantifying these effects, along with the efficacy of drainage setbacks, is not straightforward. For example, measuring discharge volumes from

**Table 3.** Results of the analysis of variance testing for differences between modeled and observed ponded surface areas among years (2013–2015) for the four wetland catchments located in Stutsman County, North Dakota. Daily difference was calculated by subtracting observed from modeled ponded surface areas.

| | | | Mean (SE) difference, $m^2$ | | |
|---|---|---|---|---|---|
| **Treatment** | **Wetland** | **Model results** | **2013** | **2014** | **2015** |
| Drained | Beck 5 | $F_{2,503} = 57.66$; $P < 0.0001$ | 57 (13) | −91 (11) | −123 (14) |
| | Beck 6 | $F_{2,479} = 227.06$; $P < 0.0001$ | −117 (23) | 52 (15) | −734 (41) |
| Non-drained | Roos 3 | $F_{2,201} = 13.4$; $P < 0.0001$ | −127 (30) | −419 (62) | −57 (56) |
| | Roos 8 | $F_{2,422} = 81.49$; $P < 0.0001$ | −139 (13) | 54 (9) | −72 (7) |

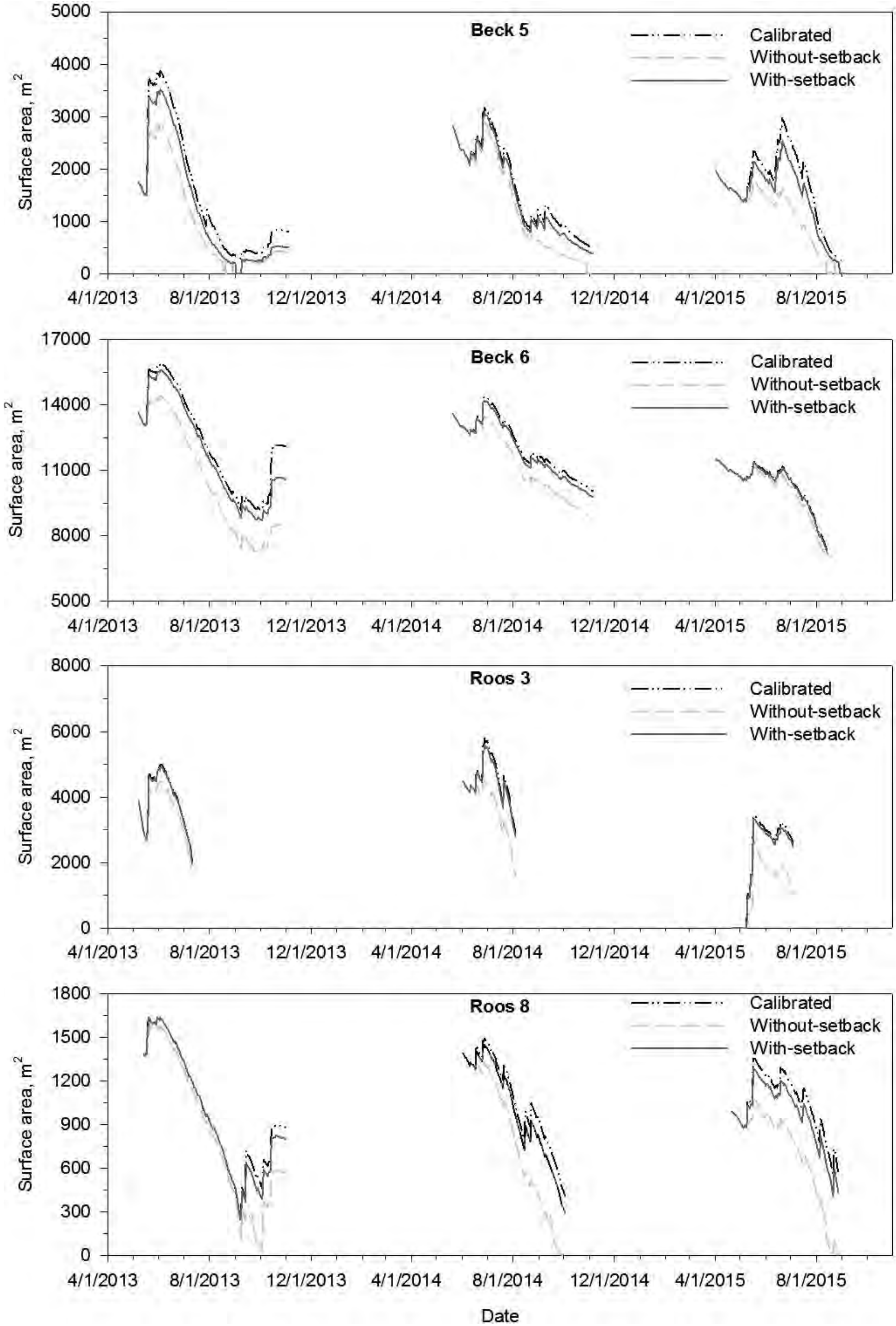


**Figure 6.** Results of the calibrated models (2013–2015) and without- and with-setback model simulations for the four wetland catchments (Beck 5, Beck 6, Roos 3, Roos 8) located in Stutsman County, North Dakota. The without- and with-setback scenarios excluded 100% of the precipitation runoff contributions (water volume) from the area upslope of the simulated drainage systems.

**Table 4.** Differences in daily (2013–2015) mean ponded surface area between the calibrated water-balance models and the with- and without-setback model scenarios for the four wetland catchments located in Stutsman County, North Dakota (see Figure 6). Differences represent days when water was present for the calibrated models. The without-setback simulations excluded 100% of precipitation runoff inputs from the entire upland zone and the with-setback simulations exclude runoff only from the area upslope of the setback distances. Daily difference was calculated by subtracting scenario model results from the calibrated model results. Percent reduction was calculated by dividing daily difference by results of the calibrated models.

| | | Mean (SE) difference, $m^2$ | | Mean reduction, % | |
|---|---|---|---|---|---|
| Wetland | Year | Without setback | With setback | Without setback | With setback |
| Beck 5 | 2013 | 517 (23) | 250 (7) | 46 | 28 |
| | 2014 | 341 (16) | 106 (5) | 33 | 10 |
| | 2015 | 537 (35) | 195 (12) | 40 | 17 |
| Beck 6 | 2013 | 1,787 (57) | 464 (28) | 15 | 4 |
| | 2014 | 871 (32) | 185 (7) | 7 | 2 |
| | 2015 | 247 (16) | 53 (3) | 3 | 1 |
| Roos 3 | 2013 | 359 (23) | 55 (5) | 9 | 1 |
| | 2014 | 834 (66) | 121 (10) | 19 | 3 |
| | 2015 | 835 (61) | 85 (6) | 31 | 3 |
| Roos 8 | 2013 | 141 (11) | 23 (3) | 20 | 3 |
| | 2014 | 290 (17) | 71 (4) | 35 | 9 |
| | 2015 | 325 (16) | 79 (4) | 34 | 8 |
| Mean | | 590 | 141 | 24 | 7 |

existing subsurface drainage systems may not be practical because these systems often cover large parcels of land and the combined drainage discharge typically is routed through common outlets; thus, it may not be feasible to determine water removal at smaller scales such as wetland catchments embedded within these larger parcels. Moreover, the design of drainage systems can be highly variable (e.g., tile size, depth, and spacing) and they often are not well mapped. It also is difficult to examine potential effects of drainage on precipitation runoff because runoff is very difficult to measure or model at the scale of a wetland catchment and the factors that regulate the generation of runoff (e.g., precipitation, antecedent soil conditions, topography, vegetation) are highly variable temporally and spatially.

For this study, small-scale drainage systems were installed within the wetland catchments using drainage setbacks. This design facilitated the quantification of drainage-system discharge from each catchment. Installation of the drainage systems using setbacks resulted in small areas of the catchments (22–37% of the upland zone) located upslope of the systems; thus, small proportions of the catchment had the potential to be directly affected by the drainage system. Correspondingly, the drainage systems yielded relatively small volumes of water in comparison with the contributions of snowmelt, direct precipitation to the ponded portion of the wetland, and precipitation runoff (Figure 5). These small volumes of water, combined with the setback distances between the wetland and the drainage systems (~40 m; Table 1), support a conclusion that these areas likely would not contribute substantial volumes of precipitation runoff to the wetlands. The assessment of model performance between years (e.g., pre- and postdrainage system) lends further credence to this conclusion as the models did not consistently overpredict ponded surface areas for the postdrainage system years. This observation, combined with the fact that model results generally were similar between the drained and nondrained catchments, suggest that any drainage effects on surface runoff volumes were minor relative to the accuracy of the models. Model simulations of the with- and without-setback scenarios clearly show that setbacks reduce the effects of drainage systems to wetland hydrology. In totality, the field data and model simulations suggest that the drainage setbacks should reduce impacts to the water balance of the wetlands monitored for this study.

Thus far, this paper has focused on the potential effects of subsurface drainage to wetland hydrology and the efficacy of setbacks for moderating these effects. However, a broader and perhaps more relevant discussion should focus on the potential ecological effects associated with altered surface-water characteristics (e.g., surface area, depth, hydroperiod). Qualitative comparisons or formal statistical analyses for assessing changes to surface-water characteristics are somewhat limited for determining whether a change is ecologically meaningful, especially when the scale of the effect is small. For example, minimal changes in water depth (e.g., a few centimeters) or seasonal hydroperiod (e.g., a few days) may be statistically significant but not ecologically meaningful. Essentially, assessing impacts to surface-water characteristics requires relating the change to the various ecological functions and societal values attributed to wetlands.

Wetlands are recognized for providing a variety of ecosystem services such as water storage, groundwater recharge, atmospheric carbon sequestration, and most notably wildlife habitat (Batt et al. 1989; Winter 1989; Zedler and Kercher 2005; Euliss et al. 2006; Gleason et al. 2008, 2011; Kayranli et al. 2010; Badiou et al. 2011; Brinson and Eckles 2011). The provisioning of many of these ecosystem services is related to a catchment's surface-water (e.g., surface area, hydroperiod) and habitat (e.g., vegetation and invertebrate community composition) characteristics, which are influenced by the overall water balance. Thus, the overarching question related to artificial drainage and protective setbacks is "what is a significant effect in terms of the delivery of ecosystem services?" For example, the relatively high rate of atmospheric carbon sequestration by wetlands is linked to high biotic productivity and low decomposition rates, which largely are governed by water-level fluctuations (Yu et al. 2008; Gleason et al. 2009; Kayranli et al. 2010; Bernal and Mitsch 2012; Mitsch et al. 2013). Alterations to the water depth and hydroperiod can shift productivity and decomposition rates, and subsequently carbon cycling. Moreover, PPR wetlands are recognized as critical habitats for a large proportion of North America's migratory waterfowl and other waterbirds. Diverting water that otherwise would contribute to the hydrologic cycle of a wetland would affect surface-water characteristics, and in turn, waterfowl habitat. Possible effects to waterfowl habitats include reduced water depths and hydroperiods, which in turn could result in altered vegetation communities or cover types that would diminish food resources, as well as habitat conditions required by waterbirds during mating, brood rearing, molting, and migration. This may be especially relevant in the spring when drainage systems have the greatest impact and wetland habitats are critical for breeding waterfowl.

Subsurface drainage has the potential to affect the water balance of PPR wetland catchments, and standard procedures for mitigating potential effects to wetland water levels and associated ecosystem services have not been well vetted. This initial study suggests that effects of subsurface drainage to the study wetlands were minimal when proper drainage setbacks were used. On average, drainage system discharge was equivalent to only 2% of the overall wetland water inputs, and the modeled reduction in average ponded surface area was 7% when setbacks were considered. However, these results are based on a 3-y study of four wetlands in a relatively high-relief terrain, and further study is required to assess their validity outside of the limited weather and site parameters of this study. Specifically, results should not be applied to other wetland types (e.g., groundwater discharge) or to low-relief areas without further investigation. To build upon this and related studies (e.g., Werner et al. 2016), future research should consider a range of landscapes (low- and high-relief), wetland types (e.g., groundwater discharge and recharge), and soils. Additionally, studies should consider factors such as depth of drainage tile, setback distance, and drainage system design (e.g., encirclement, pattern tiling, random) (NRCS 2001; Blann et al. 2009; Werner et al. 2016). Long-term studies would be ideal to maximize the likelihood of capturing a range of weather (e.g., precipitation) conditions. Last, field data should be collected to support modeling exercises because of the complex nature of wetland hydrology and subsurface drainage systems, along with the variable site and weather conditions that characterize the PPR.

## Supplemental Material

Please note: The *Journal of Fish and Wildlife Management* is not responsible for the content or functionality of any supplemental material. Queries should be directed to the corresponding author for the article.

**Supporting data.** Data and metadata associated with this paper are available online through the U.S. Geological Survey ScienceBase Catalog (see Tangen 2017).

**Text S1.** Description of wetland water-balance model that was applied to monitoring data from the four wetland catchments located in Stutsman County, North Dakota during all years of the study (May/June–November) of 2013–2015.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S1 (32 KB DOCX).

**Table S1.** Relations between wetland water volumes, surface areas, and depths for the four wetland catchments located in Stutsman County, North Dakota that were monitored (May/June–November) of 2013–2015.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S2 (23 KB DOCX).

**Figure S1.** Depth–volume–surface area curves for the four study wetland catchments located in Stutsman County, North Dakota (May/June–November) of 2013–2015).

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S3 (150 KB PDF).

**Figure S2.** Observed and modeled ponded wetland surface areas by date for the four study wetland catchments located in Stutsman County, North Dakota (May/June–November) of 2013–2015).

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S4 (180 KB PDF).

**Figure S3.** Scatter plot showing relations between modeled and observed wetland surface areas by year for the four study wetland catchments located in Stutsman County, North Dakota (May/June–November) of 2013–2015).

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S5 (195 KB PDF).

**Reference S1.** Dahl TE. 1990. Wetland losses in the United States 1780s to 1980s. Washington, D.C.: U.S. Fish and Wildlife Service.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S6; also available at http://www.fws.gov/wetlands/Status-And-Trends/index.html (2.4 MB PDF).

**Reference S2.** Dahl TE. 2014. Status and trends of prairie wetlands in the United States 1997 to 2009. Washington, D.C.: U.S. Fish and Wildlife Service.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S7; also available at http://www.fws.gov/wetlands/Status-And-Trends/index.html (17 MB PDF).

**Reference S3.** Dahl TE, Johnson CE. 1991. Wetlands status and trends in the conterminous United States, mid-1970′s to mid-1980′s. Washington, D.C.: U.S. Fish and Wildlife Service.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S8; also available at http://www.fws.gov/wetlands/Status-And-Trends/index.html (6 MB PDF).

**Reference S4.** Gleason RA, Laubhan MK, Euliss NH Jr, editors. 2008. Ecosystem services derived from wetland conservation practices in the United States Prairie Pothole Region with an emphasis on the U.S. Department of Agriculture Conservation Reserve and Wetlands

Reserve Programs. Reston, Virginia: U.S. Geological Survey. Professional Paper 1745.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S9; also available at http://pubs.usgs.gov/pp/1745/ (4 MB PDF).

**Reference S5.** Kantrud HA, Krapu GL, Swanson GA. 1989. Prairie basin wetlands of the Dakotas: a community profile. Washington, D.C.: U.S. Fish and Wildlife Service. Biological Report 85 (7.28).

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S10; also available at www.nwrc.usgs.gov/techrpt/85-7-28.pdf (14 MB PDF).

**Reference S6.** Natural Resources Conservation Service. 1997. Hydrology tools for wetland determination. Washington, D.C.: U.S. Department of Agriculture. Natural Resources Conservation Service, Engineering Field Handbook, National Engineering Handbook, Part 650, Chapter 19.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S11; also available at http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17556.wba (206 KB PDF).

**Reference S7.** Natural Resources Conservation Service. 2001. Water management (drainage). Washington, D.C.: U.S. Department of Agriculture. Natural Resources Conservation Service, Engineering Field Handbook, National Engineering Handbook, Part 650, Chapter 14.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S12; also available at http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17551.wba (5 MB PDF).

**Reference S8.** Natural Resources Conservation Service. 2004. Hydrology tools for wetland determination: North Dakota Supplement. Washington, D.C.: U.S. Department of Agriculture. Natural Resources Conservation Service, Engineering Field Handbook, National Engineering Handbook, Part 650, Chapter 19.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S13; also available at http://www.nrcs.usda.gov/wps/portal/nrcs/detail/nd/technical/engineering/?cid=stelprdb1269614 (85 KB PDF).

**Reference S9**. Natural Resources Conservation Service. 2009. Tile guidelines for protecting wetland hydrology. Washington, D.C.: U.S. Department of Agriculture. Natural Resources Conservation Service, South Dakota Hydrology Technical Note #4.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S14; also available at http://www.nrcs.usda.gov/wps/portal/nrcs/detail/sd/technical/engineering/?cid=nrcs141p2_036576 (193 KB PDF).

**Reference S10.** Natural Resources Conservation Service. 2010. Field indicators of hydric soils in the United States: a guide for identifying and delineating hydric soils. Version 7.0., 2010. Washington, D.C.: U.S. Department of Agriculture. Natural Resources Conservation Service.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S15; also available at http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1046970.pdf (5 MB PDF).

**Reference S11.** Pavelis GA, editor. 1987. Farm drainage in the United States: history, status, and prospects. Washington, D.C.: U.S. Department of Agriculture. Economic Research Service, Miscellaneous Publication Number 1455.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S16; also available at https://eric.ed.gov/?id=ED295043 (4 MB PDF).

**Reference S12.** Shjeflo JB. 1968. Evapotranspiration and the water budget of prairie potholes in North Dakota. Washington, D.C.: U.S. Geological Survey. Professional Paper 585-B.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S17; also available at http://pubs.er.usgs.gov/publication/pp585B (14 MB PDF).

**Reference S13.** Sloan CE. 1972. Ground-water hydrology of prairie potholes in North Dakota. Washington, D.C.: U.S. Geological Survey. Professional Paper 585-C.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S18; also available at http://pubs.er.usgs.gov/publication/pp585C (12 MB PDF).

**Reference S14.** Stewart RE, Kantrud HA. 1971. Classification of natural ponds and lakes in the glaciated prairie region. Washington, D.C.: U.S. Fish and Wildlife Service. Bureau of Sport Fisheries and Wildlife, Publication 92.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S19; also available at https://pubs.usgs.gov/rp/092/report.pdf (21 MB PDF).

**Reference S15.** Stewart RE, Kantrud HA. 1972. Vegetation of prairie potholes, North Dakota, in relation to quality of water and other environmental factors. Washington, D.C.: U.S. Geological Survey. Professional Paper 585-D.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S20; also available at http://pubs.er.usgs.gov/publication/pp585D (46 MB PDF).

**Reference S16.** Swanson GA, Winter TC, Adomaitis VA, LaBaugh JW. 1988. Chemical characteristics of prairie lakes in south-central North Dakota—their potential for influencing use by fish and wildlife. Washington, D.C.: U.S. Fish and Wildlife Service. Fish and Wildlife Technical Report 18.

Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S421 (25 MB PDF).

**Reference S17**. Cowardin LM, Carter V, Golet FC, LaRoe ET. 1979. Classification of wetlands and deepwater habitats of the United States. Washington, D.C.: U.S.

Department of the Interior. Fish and Wildlife Service, Office of Biological Services, FWS/OBS-79/31. Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S22 (17 MB PDF).

**Reference S18.** Gleason RA, Tangen BA, Laubhan MK, Kermes KE, Euliss NH Jr. 2007. Estimating water storage capacity of existing and potentially restorable wetland depressions in a subbasin of the Red River of the North. Reston, Virginia: U.S. Geological Survey. Open-File Report 2007–1159. Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S23 (8 MB PDF); also available: http://pubs.usgs.gov/of/2007/1159/ (June 2017).

**Reference S19.** McGuinness JL, Bordne EF. 1972. A comparison of lysimeter-derived potential evapotranspiration with computed values. Washington, D.C.: U.S. Department of Agriculture. Agricultural Research Service, Technical Bulletin 1452. Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S24 (2 MB PDF); also available: https://naldc.nal.usda.gov/naldc/download.xhtml?id=CAT87201413&content=PDF (June 2017).

**Reference S20**. Natural Resources Conservation Service. 2004. Estimation of direct runoff from storm rainfall. Washington, D.C.: U.S. Department of Agriculture. Natural Resources Conservation Service, Engineering Field Handbook, National Engineering Handbook, Part 630, Chapter 10. Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S25 (307 KB PDF); also available: https://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/NEHhydrology/ch10.pdf (June 2017).

**Reference S21.** Winter TC, editor. 2003. Hydrological, chemical, and biological characteristics of a prairie pothole wetland complex under highly variable climate conditions–the Cottonwood Lake area, east-central North Dakota. Denver, Colorado: U.S. Geological Survey. Professional Paper 1675. Found at DOI: http://dx.doi.org/10.3996/022017-JFWM-012.S26 (23 MB PDF); also available: http://pubs.er.usgs.gov/publication/pp1675 (June 2017).

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Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

## References

Badiou P, McDougal R, Pennock D, Clark B. 2011. Greenhouse gas emissions and carbon sequestration potential in restored wetlands of the Canadian prairie pothole region. Wetlands Ecology and Management 19:237–256. doi: 10.1007/s11273-011-9214-6

Batt BDJ, Anderson MG, Anderson CD, Caswell FD. 1989. The use of prairie potholes by North American ducks. Pages 204–227 in van der Valk AG, editor. Northern prairie wetlands. Ames, Iowa: Iowa State University Press.

Bernal B, Mitsch WJ. 2012. Comparing carbon sequestration in temperate freshwater wetland communities. Global Change Biology 18:1636–1647. doi: 10.1111/j.1365-2486.2011.02619.x

Blann KL, Anderson JL, Sands GR, Vondracek B. 2009. Effects of agricultural drainage on aquatic ecosystems: a review. Critical Reviews in Environmental Science and Technology 39:909–1001. doi: 10.1080/10643380801977966

Bluemle JP. 2000. The face of North Dakota: the geologic story. 3rd edition. Bismarck, North Dakota: North Dakota Geological Survey. Educational Series 26.

Brinson MM, Eckles SD. 2011. U.S. Department of Agriculture conservation program and practice effects on wetland ecosystem services: a synthesis. Ecological Applications 21:S116–S127.

Carroll R, Pohll G, Tracy J, Winter T, Smith R. 2005. Simulation of a semipermanent wetland basin in the Cottonwood Lake area, east-central North Dakota. Journal of Hydrologic Engineering 10:70–84. doi: 10.1061/(ASCE)1084-0699(2005)10:1(70)

Dahl TE. 1990. Wetland losses in the United States 1780s to 1980s. Washington, D.C.: U.S. Fish and Wildlife Service (see *Supplemental Material*, Reference S1, http://dx.doi.org/10.3996/022017-JFWM-012.S1; also available: http://www.fws.gov/wetlands/Status-And-Trends/index.html (June 2017).

Dahl TE. 2014. Status and trends of prairie wetlands in the United States 1997 to 2009. Washington, D.C.: U.S. Fish and Wildlife Service (see *Supplemental Material*, Reference S2, http://dx.doi.org/10.3996/022017-JFWM-012.S2; also available: http://www.fws.gov/wetlands/Status-And-Trends/index.html (June 2017).

Dahl TE, Johnson CE. 1991. Wetlands status and trends in the conterminous United States, mid-1970′s to mid-1980′s. Washington, D.C.: U.S. Fish and Wildlife Service (see *Supplemental Material*, Reference S3, http://dx.doi.org/10.3996/022017-JFWM-012.S3; also available: http://www.fws.gov/wetlands/Status-And-Trends/index.html (June 2017).

Euliss NH Jr, Gleason RA, Olness A, McDougal RL, Murkin HR, Robarts RD, Bourbonniere RA, Warner BG. 2006.

North American prairie wetlands are important non-forested land-based carbon storage sites. Science of the Total Environment 361:179–188. doi:10.1016/j.scitotenv.2005.06.007

Euliss NH Jr, LaBaugh JW, Fredrickson LH, Mushet DM, Laubhan MK, Swanson GA, Winter TC, Rosenberry DO, Nelson RD. 2004. The wetland continuum: a conceptual framework for interpreting biological studies. Wetlands 24:448–458.

Euliss NH Jr, Mushet DM. 1996. Water-level fluctuation in wetlands as a function of landscape condition in the Prairie Pothole Region. Wetlands 16:587–593.

Euliss NH Jr, Mushet DM, Newton WE, Otto CRV, Nelson RD, LaBaugh JW, Scherff EJ, Rosenberry DO. 2014. Placing prairie pothole wetlands along spatial and temporal continua to improve integration of wetland function in ecological investigations. Journal of Hydrology 513:490–503. doi:10.1016/j.jhydrol.2014.04.006

Finocchiaro R, Tangen B, Gleason R. 2014. Greenhouse gas fluxes of grazed and hayed wetland catchments in the U.S. Prairie Pothole Ecoregion. Wetlands Ecology and Management 22:305–324. doi: 10.1007/s11273-013-9331-5

Gleason RA, Euliss NH Jr, Tangen BA, Laubhan MK, Browne BA. 2011. USDA conservation program and practice effects on wetland ecosystem services in the Prairie Pothole Region. Ecological Applications 21:S65–S81.

Gleason RA, Laubhan MK, Euliss NH Jr, editors.2008. Ecosystem services derived from wetland conservation practices in the United States Prairie Pothole Region with an emphasis on the U.S. Department of Agriculture Conservation Reserve and Wetlands Reserve Programs. Reston, Virginia: U.S. Geological Survey. Professional Paper 1745 (see *Supplemental Material*, Reference S4, http://dx.doi.org/10.3996/022017-JFWM-012.S4; also available: http://pubs.usgs.gov/pp/1745/ (June 2017).

Gleason RA, Tangen BA, Browne BA, Euliss NH Jr. 2009. Greenhouse gas flux from cropland and restored wetlands in the Prairie Pothole Region. Soil Biology & Biochemistry 41:2501–2507. doi:10.1016/j.soilbio.2009.09.008

Hayashi M, van der Kamp G, Rosenberry DO. 2016. Hydrology of prairie wetlands: understanding the integrated surface-water and groundwater processes. Wetlands 36[Supplement 2]:S237–S254.

Hendry MJ. 1982. Hydraulic conductivity of a glacial till in Alberta. Ground Water 20:162–169.

Jia X, DeSutter TM, Lin Z, Schuh WM, Steele DD. 2012. Subsurface drainage and subirrigation effects on water quality in southeast North Dakota. Transactions of the American Society of Agricultural and Biological Engineers 55:1757–1769. doi: 10.13031/2013.42368

Johnson RR, Oslund FT, Hertel DR. 2008. The past, present, and future of prairie potholes in the United States. Journal of Soil and Water Conservation 63:84A–87A.

Johnston CA. 2013. Wetland losses due to row crop expansion in the Dakota Prairie Pothole Region. Wetlands 33:175–182. doi: 10.1007/s13157-012-0365-x

Kandel HJ, Brodshaug JA, Steele DD, Ransom JK, DeSutter TM, Sands GR. 2013. Subsurface drainage effects on soil penetration resistance and water table depth on a clay soil in the Red River of the North Valley, USA. Agricultural Engineering International: CIGR Journal 15:1–10.

Kantrud HA, Krapu GL, Swanson GA. 1989a. Prairie basin wetlands of the Dakotas: a community profile. Washington, D.C.: U.S. Fish and Wildlife Service. Biological Report 85 (7.28) (see *Supplemental Material*, Reference S5, http://dx.doi.org/10.3996/022017-JFWM-012.S5; also available: www.nwrc.usgs.gov/techrpt/85-7-28.pdf (June 2017).

Kantrud HA, Millar JB, van der Valk AG. 1989b. Vegetation of wetlands of the prairie pothole region. Pages 132–187 in van der Valk AG, editor. Northern prairie wetlands. Ames, Iowa: Iowa State University Press.

Karki G, Hay C, Kjaersgaard J, Trooien T. 2014. Design drainage intensity for eastern South Dakota. Montreal, Quebec, Canada: ASABE and CSBE/SCGAB Annual International Meeting, July 13–16, 2014. Paper number 141914059. http://elibrary.asabe.org/abstract.asp?aid=44682&t=2&redir=&redirType= (June 2017).

Kayranli B, Scholz M, Mustafa A, Hedmark Å. 2010. Carbon storage and fluxes within freshwater wetlands: a critical review. Wetlands 30:111–124. doi: 10.1007/s13157-009-0003-4

Kumar S, Nakajima T, Kadono A, Lal R, Fausey N. 2015. Long-term tillage and drainage influences on greenhouse gas fluxes from a poorly drained soil of central Ohio. Journal of Soil and Water Conservation 69:553–563. doi:10.2489/jswc.69.6.553

[MEA] Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: Wetlands and water synthesis. Washington, D.C.: World Resources Institute.

Mitsch WJ, Bernal B, Nahlik AM, Mander Ü, Zhang L, Anderson CJ, Jørgensen SE, Brix H. 2013. Wetlands, carbon, and climate change. Landscape Ecology 28:583–597. doi: 10.1007/s10980-012-9758-8

Murkin HR. 1998. Freshwater functions and values of prairie wetlands. Great Plains Research 8:3–15.

[NRCS] Natural Resources Conservation Service. 1997. Hydrology tools for wetland determination. Washington, D.C.: U.S. Department of Agriculture. Natural Resources Conservation Service, Engineering Field Handbook, National Engineering Handbook, Part 650, Chapter 19 (see *Supplemental Material*, Reference S6, http://dx.doi.org/10.3996/022017-JFWM-012.S6; also available: http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17556.wba (June 2017).

[NRCS] Natural Resources Conservation Service. 2001. Water management (drainage). Washington, D.C.: U.S.

Department of Agriculture. Natural Resources Conservation Service, Engineering Field Handbook, National Engineering Handbook, Part 650, Chapter 14 (see *Supplemental Material*, Reference S7, http://dx.doi.org/10.3996/022017-JFWM-012.S7; also available: http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17551.wba (June 2017).

[NRCS] Natural Resources Conservation Service. 2004. Hydrology tools for wetland determination: North Dakota Supplement. Washington, D.C.: U.S. Department of Agriculture. Natural Resources Conservation Service, Engineering Field Handbook, National Engineering Handbook, Part 650, Chapter 19 (see *Supplemental Material*, Reference S8, http://dx.doi.org/10.3996/022017-JFWM-012.S8; also available: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/nd/technical/engineering/?cid=stelprdb1269614 (June 2017).

[NRCS] Natural Resources Conservation Service. 2009. Tile guidelines for protecting wetland hydrology. Washington, D.C.: U.S. Department of Agriculture. Natural Resources Conservation Service, South Dakota Hydrology Technical Note #4 (see *Supplemental Material*, Reference S9, http://dx.doi.org/10.3996/022017-JFWM-012.S9; also available: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/sd/technical/engineering/?cid=nrcs141p2_036576 (June 2017).

[NRCS] Natural Resources Conservation Service. 2010. Field indicators of hydric soils in the United States: a guide for identifying and delineating hydric soils. Version 7.0., 2010. Washington, D.C.: U.S. Department of Agriculture. Natural Resources Conservation Service (see *Supplemental Material*, Reference S10, http://dx.doi.org/10.3996/022017-JFWM-012.S10; also available: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1046970.pdf (June 2017).

Pavelis GA, editor.1987. Farm drainage in the United States: history, status, and prospects. Washington, D.C.: U.S. Department of Agriculture. Economic Research Service, Miscellaneous Publication Number 1455 (see *Supplemental Material*, Reference S11, http://dx.doi.org/10.3996/022017-JFWM-012.S11; also available: https://eric.ed.gov/?id=ED295043 (June 2017).

Poiani KA, Johnson WC. 1993. A spatial simulation model of hydrology and vegetation dynamics in semi-permanent prairie wetlands. Ecological Applications 3:279–293.

Robinson M, Rycroft DW. 1999. The impact of drainage on streamflow. Pages 767–800 in Skaggs RW, van Schilfgaarde J, editors. Agricultural drainage: agronomy monograph no. 38. Madison, Wisconsin: American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc.

Roth JL, Capel PD. 2012. The hydrology of a drained topographical depression within an agricultural field in north-central Iowa. Transactions of the American Society of Agricultural and Biological Engineers 55:1801–1814.

Schilling KE, Jindal P, Basu NB, Helmers MJ. 2012. Impact of artificial subsurface drainage on groundwater travel times and baseflow discharge in an agricultural watershed, Iowa (USA). Hydrological Processes 26:3092–3100. doi: 10.1002/hyp.8337

Schilling KE, Libra RD. 2003. Increased baseflow in Iowa over the second half of the 20th century. Journal of the American Water Resources Association 39:851–860.

Schottler SP, Ulrich J, Belmont P, Moore R, Lauer JW, Engstrom DR, Almendinger JE. 2014. Twentieth century agricultural drainage creates more erosive rivers. Hydrological Processes 28:1951–1961. doi: 10.1002/hyp.9738

Shjeflo JB. 1968. Evapotranspiration and the water budget of prairie potholes in North Dakota. Washington, D.C.: U.S. Geological Survey. Professional Paper 585-B (see *Supplemental Material*, Reference S12, http://dx.doi.org/10.3996/022017-JFWM-012.S12; also available: http://pubs.er.usgs.gov/publication/pp585B (June 2017).

Skaggs RW, Nassehzadeh-Tabrizi A, Foster GR. 1982. Subsurface drainage effects on erosion. Journal of Soil and Water Conservation 37:167–172.

Sloan CE. 1972. Ground-water hydrology of prairie potholes in North Dakota. Washington, D.C.: U.S. Geological Survey. Professional Paper 585-C (see *Supplemental Material*, Reference S13, http://dx.doi.org/10.3996/022017-JFWM-012.S13; also available: http://pubs.er.usgs.gov/publication/pp585C (June 2017).

Stewart RE, Kantrud HA. 1971. Classification of natural ponds and lakes in the glaciated prairie region. Washington, D.C.: U.S. Fish and Wildlife Service. Bureau of Sport Fisheries and Wildlife, Publication 92 (see *Supplemental Material*, Reference S14, http://dx.doi.org/10.3996/022017-JFWM-012.S14; also available: https://pubs.usgs.gov/rp/092/report.pdf (June 2017).

Stewart RE, Kantrud HA. 1972. Vegetation of prairie potholes, North Dakota, in relation to quality of water and other environmental factors. Washington, D.C.: U.S. Geological Survey. Professional Paper 585-D (see *Supplemental Material*, Reference S15, http://dx.doi.org/10.3996/022017-JFWM-012.S15; also available: http://pubs.er.usgs.gov/publication/pp585D (June 2017).

Streeter MT, Schilling KE. 2015. A comparison of soil properties observed in farmed, restored and natural closed depressions on the Des Moines Lobe of Iowa. Catena 129:39–45. http://dx.doi.org/10.1016/j.catena.2015.02.021

Su M, Stolte WJ, van der Kamp G. 2000. Modelling Canadian prairie wetland hydrology using a semi-distributed streamflow model. Hydrological Processes 14:2405–2422.

Swanson GA, Winter TC, Adomaitis VA, LaBaugh JW. 1988. Chemical characteristics of prairie lakes in south-central North Dakota—their potential for influencing use by fish and wildlife. Washington, D.C.: U.S. Fish and Wildlife Service. Fish and Wildlife Technical Report 18 (see *Supplemental Material*, Reference S16, http://dx.doi.org/10.3996/022017-JFWM-012.S16.

Tangen, BA. 2017. Data release supporting "A case study examining the efficacy of drainage setbacks for limiting effects to wetlands in the Prairie Pothole Region, USA." Jamestown, ND: U.S. Geological Survey ScienceBase data. doi: 10.5066/F7CF9N8C. https://www.sciencebase.gov/catalog/item/5888f562e4b05ccb964c3b99?community=Northern+Prairie+Wildlife+Research+Center (June 2017).

[USGS] U.S. Geological Survey. 2015a. Agricultural subsurface drainage tile locations by permits in North Dakota. Jamestown, North Dakota: U.S. Geological Survey. ScienceBase-Catalog. https://www.sciencebase.gov/catalog/item/54f8bef5e4b02419550d9ae1 (January 2017).

[USGS] U.S. Geological Survey. 2015b. Agricultural subsurface drainage tile locations by permits in South Dakota. Jamestown, North Dakota: U.S. Geological Survey. ScienceBase-Catalog. https://www.sciencebase.gov/catalog/item/5307c127e4b0702cab966d52 (January 2017).

van der Kamp G, Hayashi M, Gallén D. 2003. Comparing the hydrology of grassed and cultivated catchments in the semi-arid Canadian prairies. Hydrological Processes 17:559–575. doi: 10.1002/hyp.1157

Voldseth RA, Johnson WC, Gilmanov T, Guntenspergen GR, Millett BV. 2007. Model estimation of land-use effects on water levels of northern prairie wetlands. Ecological Applications 17:527–540.

Werner B, Tracy J, Johnson WC, Voldseth RA, Guntenspergen GR, Millett B. 2016. Modeling the effects of tile drain placement on the hydrologic function of farmed prairie wetlands. Journal of the American Water Resources Association 1–11. doi: 10.1111/1752-1688.12471

Winter TC. 1989. Hydrologic studies of wetlands in the northern prairie. Pages 193–211 in van der Valk AG, editor. Northern prairie wetlands. Ames, Iowa: Iowa State University Press.

Winter TC, Rosenberry DO. 1995. The interaction of ground water with prairie pothole wetlands in the Cottonwood Lake area, east-central North Dakota, 1979–1990. Wetlands 15:193–211.

Wright CK, Wimberly MC. 2013. Recent land use change in the Western Corn Belt threatens grasslands and wetlands. Proceedings of the National Academy of Sciences of the United States of America 110:4134–4139. www.pnas.org/cgi/doi/10.1073/pnas.1215404110 (January 2017).

Yu K, Faulkner SP, Baldwin MJ. 2008. Effect of hydrological conditions on nitrous oxide, methane, and carbon dioxide dynamics in a bottomland hardwood forest and its implication for soil carbon sequestration. Global Change Biology 14:798–812. doi: 10.1111/j.1365-2486.2008.01545.x

Zedler JB, Kercher S. 2005. Wetland resources: status, trends, ecosystem services, and restorability. Annual Review of Environment and Resources 30:39–74. doi: 10.1146/annurev.energy.30.050504.14424