Environmental Flows and Levels for Groundwater-Dependent Wetlands

Sheyenne National Grasslands, North Dakota

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Cover Page Photo Credit

Leslie Bach of The Nature Conservancy, taken at the Sheyenne National Grasslands, ND.
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Groundwater-dependent ecosystems (GDEs) such as swale wetlands are common across the Sheyenne National Grassland (SNG) in southeastern North Dakota. However, the shallow groundwater dynamics that drive these ecosystems often are disrupted by ditching on private and public land. The goal of this project was to determine the maximum water table depths that will continue to support all species and ecosystem processes, and to use this information to answer the following management question:

How can drainage ditches in the Sheyenne delta be better managed to meet the needs of agriculture while still supporting an acceptable number of groundwater dependent wetlands and species? Specifically, how can the extent, locations, placement, and management of ditches be designed and maintained to enable them to function more like natural drainages across the landscape?

To answer these questions, we measured and modeled the hydrogeologic system supporting these GDEs and used data collected on indicator plant species occurrences to set maximum depth thresholds. By combining this information, we were able to establish ditching conditions that would maintain a hydrologic regime that will support GDEs across the SNG.

Key hydrogeologic results:

• The water table is generally level across the Sheyenne grassland despite the undulating swale-low dune topography due to relatively well-sorted sands that permit rapid equilibration of the water table. However, recharge broadly distributed over the Sheyenne delta creates a slight slope of the water table in all directions outward from the core of the SNG.

• There is a strong vertical component to groundwater dynamics
  ◦ During the wet season, most precipitation and snowmelt lead to a rise in the water table rather than running off, due to the relatively flat topography and the high infiltration capacity.
  ◦ During the dry season, recharge is mostly lost to evapotranspiration; very little incoming precipitation (roughly 1%) ultimately reaches the water table and flows laterally.
  ◦ During the dry season, hydraulic head in the dunes is higher than in the swales, inducing flow from the dunes to the swales and supporting wetland vegetation there.
  ◦ Annual water level fluctuation is about 1.2m (4 ft).
• Ditching leads to lower groundwater levels that extend away from the ditch.

• A near-steady state pattern of drainage and water-table change develops in as few as two or three years after ditching.

• Ditching leads to a decrease in the annual wet-dry water level fluctuation.

Key groundwater-ecology results:

• Seventeen plant species (11 common and 6 rare) were found to be good indicators of water level fluctuation on the SNG.

• Data from 54 publications in the scientific literature were identified, describing relationships between water levels and occurrence of the 17 indicator species. These data were used to supplement the SNG study results.

• Combining data from the study sites and the literature, a drawdown threshold was established at 0.91 m (3ft).

Key management results:

• A methodology is presented for analyzing the effects of ditching and natural channel incision on wetland plant communities in unconsolidated aquifers characterized by a shallow water table.

• The zone of impact is defined as the area affected by drawdown from the ditch, and the goal is to minimize the width of that zone. Differences in sediment texture, average depth to the water table, and rates of evapotranspiration and recharge are the main factors that affect the zone of impact.

• Ditches excavated to 1 m (3.3 ft) (a value just slightly deeper than the ecological threshold) will affect the water table up to approximately 400 m (1,300 ft) away, and ditches 2 m (6.6 ft) deep are expected to have a zone of impact of approximately 1 km (3,300 ft).

• In the ditch system evaluated in this study, 36% of the total wetland area within the watershed is affected by ditch-induced drawdown.
Groundwater-dependent ecosystems (GDEs) include wetlands, lakes, rivers, springs, estuaries and offshore marine environments, subterranean ecosystems, and areas of phreatophytic vegetation that rely on groundwater to meet part or all of its water needs (Brown et al. 2010; Eamus and Froend 2006; Sinclair Knight Merz 2011). For these ecosystems and the species they support, groundwater may provide water with physical and chemical characteristics that differ from available surface water, and this has important consequences for their structure and function.

Groundwater discharging to GDEs often is altered to meet human needs, including drainage to accommodate agriculture. According to the latest measure conducted in the late 1980s, artificial drainage is used on approximately 110 million acres of agricultural land in the U.S. (Pavelis 1987), although accurate estimates are complicated and difficult to make (Jaynes and James 2007). Furthermore, drainage has expanded since that time, especially with the increase in low cost installation of pattern tile in recent years, which has neither been carefully recorded nor mapped (Finocchiaro 2014). Although most U.S. Forest Service administered lands do not lie in regions where agricultural drainage is widely utilized, there are areas scattered throughout the U.S. where the effects of ditching, tiling, and field scrapes may encroach on federal lands, including the Sheyenne National Grassland. When managed properly, agricultural drainage systems can provide ecological benefits within intensely cultivated regions (Herzon and Helenius 2008), but are more often associated with degradation to environmental conditions downstream (Blann et al. 2009) and widespread lowering of groundwater levels that affect GDEs.

A key to protecting groundwater-dependent species and habitats, such as those found on the Sheyenne National Grassland, is to determine the amount, timing, and quality of groundwater needed for GDEs and to establish constraints on activities that impact this discharge (Aldous et al. 2014; Aldous and Bach 2014). This requires a robust methodology for determining the groundwater needs of ecosystems that is straightforward to implement, convenient to monitor, and easy to adapt to a variety of management situations. There are several conceptual frameworks for protecting the groundwater supply to GDEs (Colvin et al. 2004, Sinclair Knight Merz 2011), but a comprehensive, scientifically defensible, field tested methodology is still needed. The Nature Conservancy and the U.S. Forest Service are developing such a method to help make management decisions related to groundwater development that are protective of GDEs and seek to meet societal needs. This method is termed Environmental Flows and Levels (EFL), and is defined as follows:

“Environmental flows and levels describe the quantity, quality, timing and range of variability of water flows and levels required to sustain or restore freshwater and estuarine ecosystems and the functions and services they provide. Environmental flows and levels include in-stream flows, geomorphic and flood flows, groundwater levels, and lake and wetland levels established for environmental purposes”.

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This is based on the definition of environmental flows as described in the Brisbane Declaration (eFlowNet 2014) that states in part: “Environmental flows describe the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems”.

As part of several pilot projects on U.S. Forest Service lands, this report describes our efforts to characterize and analyze the groundwater-dependent ecosystems of the Sheyenne National Grassland of southeastern North Dakota. This site was selected due to the expanding agricultural development immediately adjacent to federal lands that has occurred in response to increasing precipitation over the last two decades. Small wetlands (generally <10 ha (25 acres)) found in swales function as “windows” within a shallow unconfined aquifer consisting of fine aeolian sediments (Figure 1). These wetlands comprise the most extensive groundwater-dependent ecosystem in the area and could be affected by expanded agricultural development. Figure 2 shows the extent of the Sheyenne delta aquifer which is used to describe and model the geological and physical setting of the wetlands; within this boundary is the larger Sheyenne grassland ecophysiological system. The Sheyenne National Grassland (SNG) refers to the area within the US Forest Service Ranger District boundary (Figure 2), and includes public land administered by the US Forest Service as well as private land.

The objective of this project is to quantify the Environmental Flows and Levels (EFL) for swale wetlands found on the Sheyenne National Grassland. EFL refers specifically to the volume and timing of groundwater discharge to groundwater-dependent ecosystems that is essential to support biota, both plants and animals, and ecosystem processes (e.g., soil development, nutrient and microbial cycling). The EFL is expressed in terms of annual patterns of optimal, minimum, and maximum water table (WT) elevations that will support

Figure 1. Photos illustrating the transition from dune crest to swale wetland. Photo credits: Eric Hoff /TNC (left); Allison Aldous/ TNC (right).
species and ecosystem processes. The EFL will be used to inform the following management question for this project:

*How can drainage in the Sheyenne delta be better managed to meet the goals of agriculture while still supporting an acceptable number of groundwater dependent wetlands and species? Specifically, how can the extent, location, placement, and management of ditches and modified natural channels be designed and maintained to enable them to function more like a natural drainage system across the landscape?*

**The steps to setting EFLs for a GDE follow (Figure 3):**

1. Characterize and describe the GDE study area and management context. This step is intended to set the stage for the EFL analysis. Key considerations should include any information necessary for evaluating whether the management activity is likely to affect the GDE(s). Study area information
Figure 3. Flowchart for evaluating Environmental Flows and Levels of GDEs. The bullet points for each step are examples of data sets and analyses; the level of detail required for each step depends on the size and complexity of the GDEs and the extent of the water management effects.
includes the type and boundaries of the GDE(s); climate, physiography, expected hydroperiod or hydrograph; dominant plant communities and any other landscape characteristics. The management context includes information such as current or planned water developments, diversions, contamination, or other hydrologic or water quality alterations that may affect the GDE; endangered or invasive species issues; or any other relevant management issues.

2. Quantify the hydrogeology of the GDE. Data and information at varying levels of complexity are used to investigate the effects of the management activity on the GDE(s), and for developing the EFL recommendations. The initial step is to characterize the hydrogeologic setting. This is followed by a water budget, and finally if deemed necessary, either analytical or numerical models. These data and analyses are used in combination to evaluate potential effects of the management actions.

3. Quantify the groundwater ecohydrology. Species and ecosystem processes dependent on groundwater flow or chemistry are identified and the groundwater-ecology relationships are quantified.

4. Develop thresholds. Combine the information above to determine the groundwater thresholds or “tipping points” beyond which groundwater-dependent species and processes will be impaired.

5. Evaluate groundwater management in relation to thresholds. If the impacts to GDEs as a result of management actions are expected to exceed viability thresholds of species and ecosystem processes, then management or mitigation plans can be used to meet the needs of the GDE and of society. Monitoring is used to test the accuracy of the results if the impacts are not expected to exceed the viability thresholds.

Each of these steps is summarized below for the Sheyenne National Grassland. Much of the data collection, modeling, and analyses are conducted simultaneously so that hydrogeologic results inform ecological analyses, and vice versa. The method allows an EFL to be determined using differing levels of hydrogeologic analysis, depending on site complexity, significance of the management action, and level of uncertainty.
Study Area and Management Context

The Sheyenne National Grassland extends across 54,600 ha (135,000 ac) of southeastern North Dakota (Figure 2), closely corresponding to the extent of an underflow fan deposit that formed in glacial Lake Agassiz roughly 12,000 years ago. At that time, cold, sediment-laden water from the ancestral Sheyenne River flowed into the lake, which at its maximum extended from western Minnesota northwestward into central Saskatchewan. As the dense waters of the river flowed into and under the warmer and less turbid waters of Lake Agassiz, coarse gravels and sands were deposited to the west with finer sediment transported and deposited eastward.

At the end of Wisconsinan glaciation, as continental ice sheets ablated and retreated northward, Lake Agassiz receded and diminished, exposing the broad expanse of the sandy underflow delta deposit. Paleoclimate studies in this mid-continental region suggest that the area of the SNG experienced repeated episodes of warm and dry conditions throughout the Holocene Epoch (e.g. Valero-Garcés et al. 1997; Fritz et al. 2000) and into historically recent times, leading to a loss of vegetation and mobilization of fine sand and silt by wind. This process created the current landscape that is characterized by expansive areas of dunes incised by the present channel of the Sheyenne River, which is fed by short streams that discharge groundwater locally recharged in the delta sediments. Elevations range from about 330 m (1,080 ft) on the highest and largest dunes to 293 m (960 ft) near the point where the Sheyenne River leaves the delta region. Within the dune topography are extensive areas of reticulated low amplitude dunes and swales, which we describe as the dune-swale landscape (Figure 1). The local relief between dune top and adjacent swale is less than about 3 m (10 ft) in all areas except along the Sheyenne River and the largest dunes.

The Sheyenne National Grassland is currently the most important native prairie landscape remaining in the northern Midwestern U.S. In contrast to the organic-rich soils of the Red River Valley to the east and north, the sandy prairie soils that underlie the SNG are droughty, much less productive, and used for primarily grazing and forage production in the dune-swale landscape. Because of this, it is one of the few large blocks of grassland left in the tallgrass prairie region. Although the area of the SNG was settled by ranchers and farmers in the late 19th century, many were forced off the land during the 1930s drought and economic depression. At that time, the federal government bought a portion of the area to help provide financial relief to struggling farmers and ranchers. Today, that land is administered by the U.S. Forest Service as the Sheyenne National Grassland.

i. Sheyenne National Grassland Management

The Sheyenne National Grassland has been identified as an area of high conservation priority by the U.S. Forest Service and The Nature Conservancy because of its unique physiography, which is coupled to its unusual biodiversity. The SNG comprises 28,400 ha (70,180 ac) of public land and 26,211 ha (64,770 ac) of
lands under private ownership, the latter largely in agricultural production. Although the SNG constitutes only a portion of the total grasslands area on the Sheyenne delta, the federally administered area lies within the core of the best remaining native grassland. It is the only National Grassland in the tallgrass prairie region of the United States. Livestock production occurs on both public and private ownership on the SNG. During the last two decades, The Nature Conservancy has acquired more than 1,012 ha (2,500 ac) and has helped build partnerships with neighboring landowners and government agencies, including the U.S. Forest Service.

ii. Water Management and Drainage

Underlying the Sheyenne grassland is an expansive, unconfined aquifer fed mainly by local recharge. This aquifer supports groundwater-dependent wetlands as well as supplying water for municipal and agricultural purposes (Figure 4). As of July 2014, the Cass Rural Water Users District and Southeast Water Users District divert water for municipal/rural water systems from the Sheyenne delta aquifer, with $1.5 \times 10^6$ and $1 \times 10^6$ m$^3$/yr (1,250 and 828 ac-ft/yr) of water appropriated, respectively. The Sheyenne delta aquifer also supports 131 perfected and provisionally approved irrigation permits, for a total appropriation of

![Figure 4](image.jpg)

*Figure 4.* Hydrologic features across the Sheyenne grassland. Map showing the Sheyenne delta aquifer (blue dashed outline), along with areas with appropriated water permits (purple), and state-appropriated surface and tile drains (blue dots). Land ownership features are the same as on Figure 3.
2.31x10^7 m³/yr (18,820 ac-ft/yr) (Figure 4). In addition, roughly 7.4x10^6 m³/yr (6,000 ac-ft/yr) has been appropriated for diversion from the Sheyenne River in the vicinity of the delta for irrigation and recreational use (North Dakota State Water Commission 2014). Note that these rates are maximum appropriations and the actual amount used is less and annually variable, depending on precipitation during the growing season.

The Sheyenne delta aquifer also has been the focus of a search for a new extensive source of municipal water due to its proximity to the large population and industry in the Fargo area (U.S. Bureau of Reclamation 2005) but has yet to be developed for that purpose. More recently, efforts to extend drainage across the SNG have come forward to manage the periodically high water table in the community of McLeod in the heart of the SNG (Kadrmas Lee & Jackson 2010). If implemented, this major new drain would affect hundreds of hectares of wetlands along its channel.

Figure 5. Palmer Hydrological Drought Index (PHDI) for the southeastern North Dakota climate division (NOAA, 2014b). This index is generated monthly and indicates the severity of a wet or dry spell. It is based on the principles of a balance between moisture supply and demand. Human-made changes such as increased irrigation, new reservoirs, and added industrial water use were not included in the computation of this index. The index generally ranges from -6 to +6, with negative values denoting dry spells and positive values indicating wet spells. A few exceptional values exceed +7 or -7. PHDI values 0 to -0.5 = normal; -0.5 to -1.0 = incipient drought; -1.0 to -2.0 = mild drought; -2.0 to -3.0 = moderate drought; -3.0 to -4.0 = severe drought; and greater than -4.0 = extreme drought. Similar adjectives are attached to positive values of wet spells. This is a hydrological drought index used to assess long-term moisture supply. Accessed from ftp://ftp.ncdc.noaa.gov/pub/data/climdiv/drought-readme.txt

Study Area and Management Context
The Sheyenne delta area experiences a cyclical pattern of drought and deluge extending back centuries and millennia (Winter and Rosenberry 1998), with the last major drought in the Sheyenne grassland region occurring in 1988-1992 (Riebsame et al. 1991; Trenberth et al. 1988). Since 1993, inter-annual rainfall has been well above average with concomitant moist conditions (Figure 5), leading to a very rapid expansion of tile drainage in the region (e.g. Pates 2011) with a resulting increase in surface drainage and conveyance. North Dakota regulations require that a state permit be issued for tile drainage of a single contiguous area of 32 ha (80 ac) or more (Saxowsky 2015), but only local permits are required for smaller areas. Because of a lack of consistency in the manner that drainage is managed by counties and local soil and water conservation districts, there is no means available to determine the overall extent and recent expansion of drainage tile installation in the region (Finocchiaro 2014). This is a serious issue in the SNG because of the past, present, and future impacts to wetlands from rapid incision of existing drainage ditches.

The effects of agricultural drainage from tiles and ditches on wetlands are problematic because of the potential for channel disequilibrium and rapid incision as has been observed for Iron Springs Creek (Gerla 2012). Incision exacerbates lateral drainage, causes water table decline, and results in loss of wetlands by lowering the local base level. Tiling can introduce large volumes of low-sediment water to drainages with potential erosive capability, thereby aggravating erosion (Kondolf 1997). Although more than two decades have passed since the last major drought (Figure 5), there remains a strong likelihood for the expansion of irrigation and increased demand for water appropriation for municipal and industrial use. According to North Dakota Century Code Section 61-04-06.1, conservation and ecosystem water (listed as “fish, wildlife, and other outdoor recreational uses”) is last on the priority list for appropriation, and falls behind domestic, municipal, livestock, irrigation, and industry use, in that order. Finally, although unlikely, construction of large on-channel dams in the Sheyenne valley would also affect the hydrology of the Sheyenne National Grassland.

Clearly, diversions, ditching, pumping, and other manipulations of groundwater and surface water on non-federal lands adjacent to the SNG are likely to affect the hydrologic budget on federal lands. For example, Ditch 10 (Figure 2), which is perhaps the most prominent drain in the SNG, was excavated in 1907 according to a newspaper record ( Wahpeton Globe-Gazette 1906) and has become increasingly incised in recent years, with a current depth of 2 m (6.6 ft) at the study quadrants, based on LiDAR data (International Water Institute 2014) and field observation.

Issues associated with ditching and tile drains are critical to the SNG because of its position in the midcontinent where even small changes can quickly shift the regional water budget from surplus to deficit and from deficit to surplus. Furthermore, hydrologic effects associated with ditching will be exacerbated by climate change. Synthesis of multiple global-climate models (ClimateWizard 2014) predict that by the mid-21st century this region will experience warmer and slightly drier summers (average 2.8° C (5° F) increase), coupled with greater precipitation during the fall and spring (15-20% increase above current average), suggesting increasing periods of drought and surplus. These changes will exacerbate potential impacts from water diversion and drainage.

iii. Goals and Objectives

The work described here provides the protocol and tools necessary to protect groundwater-dependent
ecosystems that occur on the Sheyenne National Grassland that are critical to the natural ecological structure and function of the regional ecosystems. Core to the process is determining to what degree alteration of the overall water budget can occur before the ecosystems are impaired to the point where they no longer provide ecosystem services. This report provides the framework for analyzing and assessing these critical threshold conditions.

The report is organized as follows: 1) methods overview where the selection of study quadrants, instrumentation, monitoring, and modeling approaches are described; 2) results section that provides a summary of observations and modeling of water fluctuations and distribution of species according to relative elevation in the dune-swale landscape; and 3) a section where we couple the hydrological dynamics to groundwater-dependent ecosystems and provide recommendations for management. This last part is intended to provide the Forest Service with the information and tools necessary to optimize protection of the SNG’s wetland resources.

iv. Methods overview

Following the method for investigating groundwater-dependent ecosystems (USDA Forest Service, Groundwater Inventory, Monitoring and Assessment Technical Guide, in press; Figure 3), we focused on the extensive areas of small groundwater-dependent wetlands that occur in the swale portion of the swale-dune landscape. The first step was to establish three 40-75 ha (100 - 180 ac) blocks or quadrants that host groundwater-dependent wetlands and are sufficiently large to represent the trends observed on the landscape (Figure 2). These consisted of two quadrants that are minimally altered (reference quadrants) and one obviously affected by deep drainage based on visual observation. One reference quadrant was selected west of the disturbed quadrant outside the zone of influence of the ditch, and another at The Nature Conservancy’s Brown Ranch. For these blocks, the topographic index was calculated and mapped to characterize the landscape position along the continuum from dune crests to swale bottoms. A random sample of short (<50 m, <150 foot) paired transects was selected for vegetation and hydrological analysis. Vegetation communities were assessed along the paired transects, but only a subset of these was fully instrumented for hydrological monitoring. The results of the hydrological monitoring were then interpolated to approximate the depth to the water table for the entire quadrant, which included the non-instrumented transects. All these data were integrated with precipitation records and estimated evapotranspiration to formulate a water budget for the quadrant. In the context of the regional hydrological setting, several analytical methods and the numerical code MODFLOW-2005 (Harbaugh 2005) were used to simulate the influence of the ditch on water level fluctuation and to more thoroughly characterize the local water budget.

Crucial to this project was our ability to establish a set of potential water-table ranges for the topographic positions along transects from dune crest to swale bottom. With that information, we were able to identify species that qualify as good indicators of hydrology. The overall objective of our work was to determine the thresholds in water level drawdown at which indicator species are lost, and to use that information to set conditions to the extent, proximity, and depth of ditch excavation. These results were used to formulate a management prescription that the SNG can use to evaluate wetland impact from SNG tiling and ditching.
i. Regional Hydrology

The Sheyenne National Grassland lies within the southern end of the Red River of the North, which drains northward to Manitoba’s Lake Winnipeg and ultimately into Hudson Bay. The Sheyenne River, a major tributary of the Red River, is perhaps the most prominent hydrological feature in the SNG area. The river flows through the northern one-third of the Sheyenne grassland and has eroded into glacial till that underlies the deltaic sediments. As a result, erosion along the margin of the river by discharging groundwater since the beginning of the Holocene Epoch (roughly 12,000 years before present) has led to short, small, and deeply incised perennial streams that are entirely groundwater-fed.

Generally, in areas more distant from the Sheyenne River, the shallow groundwater system in the deltaic sediments and the dune-swale topography results in ecosystems that depend on groundwater processes. This dune and swale landscape has a contrasting hydrological function at different scales. On a broader scale that covers the expanse of the delta, infiltration of precipitation slowly recharges the unconfined aquifer within the aeolian fine sand and silt. This century- to millennia-long process has resulted in a broad and very gently sloping groundwater “dome” with its highest elevation in the center of the delta most distant from the Sheyenne River. Superimposed on this regional system are much smaller local flow systems driven by recharge and discharge within individual sets of dunes and swales. These are seasonally and ephemerally active, with rapid changes in water-table elevation triggered by precipitation and evapotranspiration.

Our work focuses on characterizing the superposition of these hydrological systems at both the local and Sheyenne grassland scale. Drainage and irrigation have perturbed the hydrology, thereby affecting the intricate relationships among recharge, lateral groundwater flow, discharge, and wetland ecosystems. We assumed a typically level and smooth water table across the landscape, which is perturbed ephemerally following snowmelt and infiltration of heavy rainfall.

ii. Climate

Large seasonal temperature and precipitation differences characterize the climate of the Sheyenne grasslands region, with warm to hot and often humid summers and cold winters. According to the Köppen Climate Classification system, the region is classed as having a humid continental climate. For the long-term weather station at Fargo, about 64 km (40 mi) northeast of the SNG, the average annual precipitation is 51 cm (20 in), with roughly 40% falling during June, July, and August and 25% during the fall (September, October, and November) and 25% in the spring (March, April, and May). The balance, 10%, falls almost entirely as snow during the winter (December, January, and February). Seasonal snowfall averages about 58 cm (23 in), but has ranged from as little as 25 cm (10 in) (1957-1958) to as much as 305 cm (120 in) (1996-1997). Temperatures vary greatly, with January average temperature near -14°C (7°F) and July’s at 22°C (71°F) with extremes of 46°C (114°F) in July 1936 to -44°C (-48°F) in January 1887 (Godon and Godon 2002).
The climate of the region is punctuated with drought and, in more recent times, surplus. The Palmer hydrological drought index takes into account both antecedent precipitation and evapotranspiration to provide a measure of drought and moisture stress. Since 1895, southeastern North Dakota has experienced episodes of relatively moist conditions (prior to 1930), drought (1930-1940 and 1988-1992) and an unusually wet period since 1993 (Figure 5). Regionally, the length and intensity of this recent and on-going episode of moist conditions is unprecedented during at least the last 2,000 years (Winter and Rosenberry 1998).

### iii. Soils

Three main soil associations have been delineated within the deltaic sediments of SNG (Thompson and Joos 1975; Schwarz and Alexander 1995) (Figure 6). Nearly level, moderately well-drained soils of the Tiffany - Hecla - Glyndon - Embden association developed on silt-rich to loam lacustrine sediments, with calcareous accumulation at shallow depth in the Glyndon Series. The Ulen - Hecla - Hamar association occurs on sandy lake plain and deltaic sediments where the landscape is nearly level to gently undulating. The coarse to

![Figure 6](https://example.com/figure6.png)  
*Figure 6. Map of the Sheyenne National Grassland (outlined) and main soil associations based on NRCS STATSGO (Schwarz and Alexander 1995).*
medium textured soils of this association tend to range from moderately well to very poorly drained. Finally, the Serden - Maddock - Hecla - Hamar association comprises coarse, excessively drained soils that occur on gently undulating to hilly dunes formed on lacustrine and deltaic sediments (Figure 6). This association hosts the swale wetlands that depend on shallow groundwater flow for their occurrence and function. Soil data for the monitoring / characterization quadrants were obtained from both on-site soil logging completed during the installation of monitoring instruments and published sources.

Soil profiles were observed to be generally consistent across the three quadrants (Appendix), with a paleosol noted near the base of the dunes (Figure 7) that were intersected along the north edge of Ditch 10 quadrant. This paleosol, which is likely correlative to the Maddock Dune paleosol described by Hopkins and Running (2000), has been dated at 2,370 +/- 60 years BP. It was intersected in all the later dune borings used for characterization and monitoring.

**Figure 7.** Hydrogeological cross-section of LiDAR-derived topography (green), water-table elevation measured on 5 July 2011 (blue), and prominent stratigraphic features: paleosol (gray) and isolated clay layer (brown). This cross-section was derived from shallow borings taken perpendicular to Ditch 10 along the north edge of the quadrant. All of the section shown in this figure lies within the disturbed quadrant, with the far west end (right side) ending near profile 28.

### iv. Aquifer Properties

Hydraulic conductivity, specific yield, and transmissivity for the Sheyenne delta aquifer were based initially on existing published data, including information available from the North Dakota State Water Commission (2014), various state agency publications, the U.S. Geological Survey, and SSURGO (Natural Resources Conservation Service 2014). Calibrations of analytical and numerical models of groundwater flow are...
described later and were used to improve a best estimate range of aquifer properties.

Published data indicate transmissivity ranges from about 65 - 93 m²/day (700-1001 ft²/day) and a long-term aquifer test that accommodated delayed yield resulted in an estimated specific yield of 0.17 (Downey and Paulson 1974). With an average saturated thickness of roughly 10 m (32.8 ft) (Baker and Paulson 1967), the hydraulic conductivity likely ranges between 5-10 m/day (16.4-32.8 ft/day). This is consistent with estimates provided by Baker and Paulson (1967) and Armstrong (1982), who found transmissivity ranging from 372 m²/day (4004 ft²/day) in the coarsest deltaic sediments deposited on the west side of the delta to 62 m²/day (667 ft²/day) in the more distal deltaic sediments on the east side. A recharge rate of 0.15 - 0.18 m/yr (0.5-0.6

Figure 8. Generalized hydraulic conductivity of the shallow unconfined aquifer (m/day) estimated from the saturated thickness (dots show borehole control points), average grain size, and transmissivity from several aquifer tests. Red stars show the locations of the study quadrants. Numerous borings in the southwest part of this map are related to development of the partially confined Milnor Aquifer.
ft/year) is reported to occur in the delta (Baker and Paulson 1974; Armstrong 1982), based on infiltration rates and increases in flow in the Sheyenne River through the delta during periods of base flow. Subsequent to these studies, two other reports (Strobel and Radig 1997; North Dakota State Department of Health 2006) use similar values, but neither of these reports provided new data.

In exploratory work on the delta sediments north of the Sheyenne River, Parkin (2010) estimated transmissivity using specific capacity tests and found a range of 37-92 m²/day (398-990 ft²/day). Using saturated thickness reported on the drilling reports, hydraulic conductivity was estimated to range from about 3-5 m/day (9.8-16.4 ft/day). This range of hydraulic conductivity is consistent with very-fine to fine sand containing some silt.

To be of greatest value to future modeling and drainage analysis, a map of the Sheyenne grassland showing the general trend of hydraulic conductivity of sediments was constructed using existing information, which included grain size and aquifer thickness distributed by area from North Dakota State Water Commission drilling records. These were combined with estimates of sediment transmissivity to create a map of shallow hydraulic conductivity (Figure 8). Because of the large degree of uncertainty in mapping aquifer properties, reasonable ranges of hydraulic conductivity, transmissivity, storativity, and aquifer thickness values were used in models described later to help provide a reasonable calibration to observed hydrological conditions.

v. Establishing Dune-Swale Transects

Visual appearance, such as droughty swales lacking a typical diversity of wet meadow species, suggested strongly that groundwater-dependent ecosystems across the Sheyenne delta had been perturbed by nearby ditches. Our monitoring approach involved collecting data to characterize the small scale changes in hydrology and vegetation related to individual dune-swale systems, including areas affected by ditch drawdown, in the context of the broader hydrology of the landscape. To do this, we used a GIS approach to identify dune crests and swale bottoms within the swale-dune landscape that would depend only on topographic characteristics.

The first step in the GIS process (Appendix) was to calculate the topographic position index (TPI) (Gallant and Wilson 2000, De Reu et al. 2013) throughout the study quadrants. A digital elevation model (DEM) with one-meter raster cell dimensions was obtained from the International Water Institute (2014) with aerial LiDAR data collected in 2008. The TPI is unitless and measures how the mean elevation of a specified neighborhood varies around a given raster cell. The largest TPI scores correspond to cells with the majority of neighbors lying at a lower elevation. Similarly, the smallest scores indicate a low area on the landscape with most neighbors lying at a higher elevation. We applied a circular neighborhood with a 50 m (150 ft) radius in our application. Sensitivity of the result to the size of the radius and the geometry of the search window was tested to assure that the scale and geometry were appropriate for the dune-swale landscape within the quadrants.

TPI values were divided into ten quantile classes that were used to discriminate between dune crests (cells scoring within highest quantile - 90% of all the scores were smaller) and swale bottoms (cells scoring within the lowest two quantiles - 80% of all the scores were larger). Raster cells representing the dune crests tended to be more isolated than the interconnected and irregular swales. Therefore, dune crests were more easily captured statistically when compared to the swales. Only the one upper quantile was needed to categorize
dune crests whereas the two lowest quantiles were necessary to delineate swales. Centroids for groups of adjacent swale cells and groups of adjacent dune crest cells were used to define a specific point that represented the discrete swale and dune crest locations.

Potential monitoring transects throughout the quadrants were then established by connecting a line from each dune crest centroid to the nearest swale centroid. The actual transects used in our analysis were selected randomly from the full set of several hundred dune crests identified within each quadrant. Forty transects were selected within the three study quadrants (Figure 9). For the hydrological monitoring, a subset of

Figure 9. Dune crest (red circles) and swale bottoms (blue dots) based on a statistical analysis of topographic position index (TPI), at (a) Ditch 10 disturbed and reference quadrants and (b) Brown Ranch reference quadrant. Green stars show randomly selected sample dune-to-swale profiles for plant community inventory. Profiles 15, 20, 21, 25, 28, 35, and 39 at Ditch 10 and 5, 7, and 13 at Brown Ranch were instrumented for hydrological monitoring.
three transects each was selected for the two quadrants unaffected by drainage (Ditch 10 Undisturbed and Brown Ranch). Four transects were selected from the disturbed quadrant adjacent to Ditch 10. Monitoring points and corresponding vegetation characterization plots along the transects were established in the field by locating the swale bottom (S), dune crest (H), the midpoint (M), and two other points along that continuum: low transition (L) and upper transition (T). Identification of the transition points was based on a visual assessment of the topographic position and the distribution of upland versus wetland vegetation communities.

vi. Water-Level Elevations

Methods. To better understand vertical and temporal patterns in hydrology, depths to the water table from the ground surface were measured using discrete hand measurements at the hydrology monitoring points. In addition, water levels were monitored automatically every six hours at selected points in the disturbed quadrant (profiles 35 and 39 and 28), although the equipment malfunctioned at profile 28 (Figure 10). In the groundwater modeling sections that follow, water-level elevations relative to mean sea level were used in computations. Sensitivity and calibration were analyzed using depth measurements, which were converted to water-level elevations, and then integrated with model output. “Maximum depth” means that the water level is at its lowest position, measured from ground surface, corresponding to the driest times. Depending on the context, this level may also be referred to as the “minimum elevation”.

![Graph](https://via.placeholder.com/150)

**Figure 10.** One-hour interval logging of the water table at profiles 35 (left), 39 (middle), and 5 (right) during summer and fall 2013. MIDPT lies roughly halfway between profile 39 and Ditch 10. Dashed lines show approximate ground elevation. Profiles 35 and 39 are in the Ditch 10 disturbed quadrant and profile 5 lies south of The Nature Conservancy’s Brown Ranch headquarters. Profiles followed by the letter L are swale; MH are upper transition; and H are dune crest.

Equipment included two fully sealed Solinst Model 3001 Level Loggers with a complementary installation of a Solinst Barologger to provide atmospheric pressure data, which allows for barometric compensation. Five Global Water series 16L loggers were also installed. The Global Water water-level loggers have transducers that are vented to the atmosphere and therefore do not need barometric compensation.

The depth to the water table was estimated across the area within the study quadrants by interpolating and
extrapolating from discrete point measurements. This was done by tabulating measured maximum (driest) and minimum (wettest) water depths on a particular date and converting these into a smooth regular grid across the study quadrants, projected in UTM Zone 14, NAD83 coordinates. Gridding using the radial basis function (Franke 1982; Carlson and Foley 1991) provided results that most closely matched depth-to-water table data that were collected. Using the same cell size and position, LiDAR data (International Water Institute 2014) were used to define a topographic grid discretized identically as the water table grid. ArcGIS was used to subtract the water table grid from the topographic grid, thereby providing a depth-to-water table grid for both the wettest and driest conditions encountered during the monitoring period.

Using GIS, the maximum (driest) and minimum (wettest) water-table depth was estimated for each vegetation characterization plot. These depths were then plotted relative to the five plot types along the swale to dune continuum to obtain a range of water table levels relative to the topographic surface. To evaluate the uncertainty, 43 non-instrumented sites were bored to the water table, allowed to recover, and the depth of the water table measured from the ground surface. This was done within three days following collection of water level data at the instrumented sites. A linear, non-parametric regression of the paired measured and estimated data was performed to estimate uncertainty at the 90% quantile.

Another more sophisticated protocol to estimate the depth to water table uses the method of Demissie et al. (2009), which combines deterministic modeling with artificial neural networks (ANNs). In this method, the groundwater flow system is simulated deterministically and interpolated output enhanced using ANNs. Results give improved estimates of water table depth, based on topographic elevation and output from the coupled model. Demissie et al.’s (2009) approach was applied to the Sheyenne delta groundwater system by Gusyev et al. (2013), who found that depths to the water table could be predicted to within 0.15 m (0.5 ft). The area tested by Gusyev et al. (2013) lies north and west of the study sites described in this report. By using 30 m (100 ft) MODFLOW grid cells and a 10 m (30 ft) DEM grid, however, the results do not provide the resolution necessary to predict how plant communities vary within dune-swale transects. Applying this modeling protocol to finer grids and LiDAR topographic data would likely provide very good results, but beyond the scope of our work.

**Results: Intra-profile Water Levels.** Automated monitoring of water levels within individual profiles showed generally that there is little difference in the elevation of water levels below dune crests when compared to swales (Figure 10). For example, at profile 35, roughly 660 m (0.41 mi) east of the ditch, the maximum difference in water level was about 0.1 m (0.33 ft), with the largest difference occurring for extended periods after rainfall (Figure 10, left hydrograph).

Profile 39 showed similar features, except for a peculiar irregularity in the water levels in 39L after mid-August (Figure 10, middle hydrograph). This was approximately the time that cattle began to graze and frequent the area immediately around the profile well, which may have affected the conditions in the vicinity, perhaps by reducing the storage properties of the organic-rich soils at the well.

Profiles for both 35 and 39 (Figure 10) show the typical growing-season pattern of the water table in the region (Gerla and Matheney 1996), with a shallow water table in the spring affected by a strong diurnal pattern indicating groundwater loss to evapotranspiration. Even large pulses of rainfall and infiltration during the summer are lost quickly. As vegetation begins to senesce in mid-September, the diurnal pattern is lost and an increasing volume of infiltrating rainfall is stored for a longer period (blocky steps show increasing recharge and groundwater storage).
Although the landscape relief at profile 5, southwest of Brown Ranch headquarters was the greatest of the three profiles monitored, there was little difference observed in the level of the water table between the dune and swale (Figure 10, right hydrograph). In this case the transducer-data logger used at 5H did not have sufficient pressure range to measure head differences greater than 3.28 feet (1 m), so parts of the record are missing. For 5L, this was a shallow well with a bottom at 325.89 m (1069.2 ft); records ceased when the water

---

**Figure 11.** Estimated elevations of the water table (in meters, blue labels), along with contours (blue lines) and LiDAR topographic contours (gray, background), in (upper panel) the Ditch 10 disturbed and reference quadrants where Ditch 10 lies on the east, and (lower panel) the Brown Ranch reference quadrant with estimated elevations of the water table at profile 5 (west), 7 (south), and 13 (northeast). The Nature Conservancy’s headquarters lies just off the center north edge of the map. Axis labels show UTM zone 14 NAD83 coordinates in meters.
These results demonstrate that the silty sands of the dunes tend to equilibrate their water levels quickly, thus larger scale water table maps based on average water level data from the profiles will represent adequately the overall smooth water table pattern within quadrants. Furthermore, maps based on average water levels for a few profiles within a study quadrant are useful for defining the pattern of the water table within the quadrant as a whole.

**Results: Inter-profile Water Levels.** Tabulation and mapping of the minimum (driest) and maximum (wettest) elevation of the water table at each of the profiles was used to provide control points to contour the elevation of the water table across the quadrants (Figure 11). Although small irregularities are likely to exist, the relatively large hydraulic conductivity of the aeolian delta sediments indicate that the water table will be generally smooth across the landscape. The validity of this assumption is corroborated by the consistency of the intra-profile records. Both observations point toward a rapid adjustment of water levels after infiltration and recharge perturbations. Results show a pattern that is not influenced strongly by the distribution of dunes and swales (Figure 11), which is in contrast to the pattern of depth to the water table (Figure 12). Note the strong influence of Ditch 10, where the pattern is characterized by a deeper water table during both wet and dry times (right side, Figure 12 left-hand panels).

![Figure 11](image1.png)

**Figure 11.** Tabulation of minimum (driest) and maximum (wettest) water table elevations at each profile. The “profile” is used in a general sense because it may refer to a transect, a monitoring stage, or a traverse. The maps show a pattern that is not influenced strongly by the distribution of dunes and swales.

![Figure 12](image2.png)

**Figure 12.** Map of depth to the water table in meters for the wettest (top) and driest (bottom) times during 2012-2013 monitoring for (left-hand panels) Ditch 10 disturbed and reference quadrants and (right-hand panels) Brown Ranch monitoring quadrant. Yellow circles show locations where vegetation was characterized and water levels monitored.

Similar features were observed at the monitoring quadrant at The Nature Conservancy’s Brown Ranch. With three instrumented profiles, only a simple linear plane representation of the water table could be obtained (Figure 11 lower panel). Using this result, a map of the depth to the water table was constructed for the Brown Ranch quadrant in the same manner (Figure 12 right-hand panels). Note that ditches along
the roadside do not have much effect on the depth to the water table, perhaps because the ditches are poorly graded, not incised or eroded, and do not drain water effectively.

**Predicting the Depth to the Water Table within the Study Quadrants.** By collecting numerous actual measurements of the depth to the water table during a single day, validity of the predicted depths described in the previous section can be tested for non-monitored sites. This was done late in the 2013 field season during relatively dry conditions. Statistical analysis showed that 80% of the predicted - measured data pairs were within 36.6 cm (1.2 ft). A plot of the data ([Figure 13](#)) shows the pair-wise relationship for the three monitoring quadrants: the disturbed area near Ditch 10, the reference quadrant west of Ditch 10, and the reference area at Brown Ranch.

The greatest amount of variance is due to data from the Brown Ranch study quadrant ([Figure 13](#)). By excluding these data from the analysis, the predicted depth to the water table at any randomly selected location within the Ditch 10 quadrants is reduced to 30.5 cm (1.0 ft) or less of the actual depth for the 10 - 90

![Figure 13](#). Correlation plot between the measured and predicted depths to the water table at the three monitoring quadrants. Dashed lines show the mean and the 90% quantile.
percentile range. Additional monitoring would likely improve the estimate, especially at Brown Ranch where there were only three profiles. Regardless, these results provide assurance that measurement of a small set of points in the quadrants provides a method to predict the depth to the water table across the study area.

**Application of the Predictive Results to Profile Positions.** Using GIS, the maximum and minimum water table depth were estimated at each vegetation characterization site. These depths are plotted relative to landscape position (**Figure 14**) to show the mean and range for each of the dune-swale profile positions used in characterizing the vegetation. Results show the following range of the water table depths at different dune profile positions:

Swale: -0.2 (wet conditions) to 1.1 m (-0.7 - 3.5 ft) (dry conditions)

Midpoint: 0.6 - 1.7 m (2 - 5.5 ft)

Dune crest: 1.4 - 2.74 m (4.5 - 9 ft)

**Figure 14.** Plot of the predicted depths to the water table for the all profile positions at each of the vegetation monitoring sites. Plots include swale bottoms (S), low transition (L), midpoint (M), transition (T), and dune crest (H). For a description of each point see text 2(y) and 3(i). The linear best-fit trend is shown for wet conditions (green) and dry conditions (blue). Note that the range is roughly 1.2 meters.
vii. Water budget

In other EFL case studies, a rough water budget is used to evaluate the importance of groundwater to the ecosystems’ water supply (e.g. Aldous et al. 2014). That step was not done here because there was already a general understanding of both shallow and deeper groundwater processes, and the swale wetlands were known to be GDEs. In this case, a more refined water budget was used to better understand seasonal variation in groundwater processes, and how the ditch affects those processes. The main components of the water budget can be related by

\[
\text{input} - \text{output} = \Delta S
\]

where \(\Delta S\) is change in water stored and the inputs are precipitation and groundwater inflow. In areas that are affected by drainage, some surface water may become stored along banks, so surface water in some instances constitutes one of the inputs. Outputs include evapotranspiration, surface water runoff (in areas of drainage ditches), and groundwater outflow:

\[
(\text{rainfall} + \text{snowmelt} + \text{groundwater inflow} + \text{bank storage from surface water}) - (\text{evapotranspiration} + \text{surface water runoff} + \text{groundwater outflow}) = \Delta S
\]

Some of the water budget parameters were relatively straightforward to derive (e.g., precipitation and evapotranspiration) whereas others required field instrumentation and hydrologic models (e.g., change in storage, groundwater flow).

a. Precipitation and Evapotranspiration

Methods. Several fully equipped weather stations in and near the Sheyenne National Grassland provide weather records for the monitoring period. The closest station is the ROMAN (Real-time Observation Monitor and Analysis Network) RAWS (Remote Automated Weather Station) Mesonet SNGN8 station that lies about two km (1.3 miles) west of the Ditch 10 quadrants (46.467°, -97.317°). Current and historical data were accessed from the National Oceanic and Atmospheric Administration web site (NOAA 2014a). Other near-continuously monitoring weather stations are operated by the North Dakota Agricultural Weather Network (NDAWN 2014) at Ekre, Lisbon, Leonard, and Wyndmere. Data from these stations, which includes both hourly precipitation and daily Penman-Monteith evapotranspiration, can be downloaded directly from the NDAWN web site. None of these stations record snowfall and snowmelt; for these data the closest weather observer is east of McLeod (NOAA - GHCND:USC00325754 - MC LEOD 3 E, ND US). The closest fully instrumented station for snow precipitation is at Hector International Airport in Fargo, about 65 km (40 miles) north of the study area (NOAA 2014b).

To supplement data from nearby weather stations, recording rain gages (Spectrum Technologies WatchDog 1120 model) were installed during the 2013 field season at The Nature Conservancy’s Brown Ranch headquarters on the north edge of the Brown Ranch quadrant (46.356°, -97.364°), and at a site where the two Ditch 10 quadrants adjoin (46.468°, -97.281°). The measurement interval was set at 15 minutes. In addition to the rain gage, a Spectrum Technologies ET Gauge (Colorado State University Cooperative Extension 1999) fitted with a grass-reference cover was installed at Brown Ranch and maintained by The Nature Conservancy staff. The ET gage is a device that is designed to replicate closely the water loss from leaf
surfaces, in this case calibrated to evapotranspiration from a grass-reference cover crop.

**Results.** Monitoring during 2012 showed generally less precipitation and greater rates of Penman-Monteith evapotranspiration than average (Figure 15). In April and May 2012, precipitation was either at or above normal, with above average evapotranspiration. These conditions created a strong net deficit of precipitation going into the summer months, which were unusually dry. In contrast, 2013 experienced wetter than normal conditions, especially in April, May, and June of 2013, along with lower than average potential evapotranspiration, which created conditions for a relatively moist summer (Figure 15). Thus using information from both seasons was useful to capture the full variation in weather patterns.

Measured grass-reference evapotranspiration at the Brown Ranch weather station from May 28 through October 15 was 49.4 cm (19.5 in), which is slightly lower than estimated Penman-Monteith evapotranspiration at the NDAWN weather station at West Fargo during the same period (73.56 cm, 28.96 in).

![Figure 15](image)

**Figure 15.** Precipitation (bottom) and Penman-Monteith estimated evapotranspiration (top) for 2012 and 2013 (bold shade) and the long-term average (light shade). Average precipitation is based on 1970 - 2000 records at Fargo and average Penman-Monteith evapotranspiration is based on 1990 - 2013 records at Fargo. 2012-2013 precipitation is that recorded for the Sheyenne Remote Automated Weather Station (RAWS) site and Penman-Monteith estimated evapotranspiration is for the West Fargo, North Dakota NDAWN weather station.

b. **Surface Water Flow and Groundwater Flow**

Except for the continuously variable flow of water within Ditch 10, no surface-water channel flow was observed in the three quadrants. A groundwater seepage face was observed to occur along the full length of
Ditch 10, and the channel flow was restricted to a level consistently below the top of the face, however, the
discharge of surface water was not measured or monitored. Having these data would have been useful in our
analysis, but no attempt was made to quantify the rate because the flow appeared to be small and largely lost
evaporation from the exposed coarse textured soil. Despite the small magnitude of surface water flow in
the annual water budget, over the course of just a few years this drainage results in extensive drawdown that
affects the other components of the water budget, as demonstrated in the sections that follow.

c. Changes in Storage

Weather conditions and climate vary both inter- and intra-annually for the Sheyenne grassland region.
As a result, seasonal and annual changes in water storage form an important component of the region's
overall water budget, which is often neglected under more static conditions (Fetter 2000). Changes in
storage depend on the specific yield of the unconfined aquifer. The rate of change of groundwater storage
is determined by multiplying the change of the water table by the specific yield, and dividing by the
the corresponding time interval. In some instances, when the water table rises above the ground surface, the
change in storage is simply the water level rise or fall divided by the time. Changes in storage related to the
compressibility of water or the aquifer matrix is assumed negligible relative to changes in pore saturation.

To determine change in storage for the water balance, we modeled the effects of drainage drawdown as
described below. Results for changes in storage that follow are based on observed changes in the depth to
the water table, and in a few cases the depth of surface water within swales. Although it is important to note
that these changes in storage may be large, amounting to several tenths of meters per year, only a small
fraction of the input (precipitation) is transferred to groundwater discharge to surface drainages; most is lost
evapotranspiration. Because the change of storage is generally consistent across the landscape, a gentle
hydraulic gradient persists through both wet and dry times, which precludes much lateral flow of water.

d. Modeling the effects of drainage drawdown

In the water budget formulation given above, $\Delta S$ is mostly due to seasonal and ephemeral rise and fall in
the water table. Only a very small fraction of the water stored generates recharge to deeper flow within the
unconfined Sheyenne delta aquifer. For this water budget equation to be meaningful, rates of the components
need to be approximated over a specific three-dimensional space with well-defined boundary conditions.
In many studies, the water budget relationship is used to determine one of the unknown components, but
the large uncertainty involved makes this approach risky (e.g. Winter 1981). By defining the rates of all the
water budget components, however, the potential effect of changing one or more of the components can be
assessed by evaluating the sensitivity of the model to such changes. In the case of ditch drainage, the effect
on groundwater conditions can be predicted roughly, which in turn will provide insight into the potential
change to the overall ecological system supported by groundwater. After characterizing the inputs, outputs,
and change in storage, two analytical models and a numerical model were used separately to integrate and
calibrate the water budget components for the Ditch 10 quadrants and associated hydrological boundaries. A
final summary of the water budget is presented at the end of this section after discussion of the model results.

The goal of the modeling portion of the work was two-fold. First, we wanted to create a model of drainage and
drawdown related to the deeply incised Ditch 10, which lies adjacent to swale wetlands in the ditch quadrants.
The models were designed to estimate the permanent and seasonal effects of drainage related to the ditch. The second goal focused on developing a modeling protocol sufficiently simple and robust for land managers to use when faced with future drainage plans in and near the SNG.

The Sheyenne grassland lies in a mid-continental zone where inter-annual evapotranspiration generally exceeds long term precipitation. This does not preclude groundwater recharge, however, because the timing of infiltration is important and recharge can occur readily if precipitation infiltrates when there is minimal evapotranspiration (early spring, late fall, and times of strong drought and senescent vegetation).

The unconfined Sheyenne delta aquifer is dynamic, with large intra- and inter-annual water table changes. Application of an analytical or numerical model requires an algorithm and code that can accommodate transient conditions, including variable recharge and bank storage. The observed water level variability suggests at least 1.2 m (4 ft) of annual fluctuation during a dry-wet cycle similar to the one observed for our 2012 - 2013 monitoring period. This water level fluctuation will decrease closer to points where drainage occurs, although bank storage during spring runoff may be important adjacent to open drainage channels.

A. Analytical Models.

Our approach used a graphical, water-balance method based on the Dupuit-Forchheimer assumption (Korom 2010), which can be applied to calibrate recharge and hydraulic conductivity, followed by application of a robust analytical method (STWTI) to model transient channel - unconfined aquifer interaction (Barlow and Moench 1998) for the purposes of further estimating the hydraulic conductivity. For more detailed methods and results, see Appendix.

The most important outcome of the graphical discharge method is a constraint on the recharge rate at approximately $1.8 \times 10^{-3} \text{ m/yr} (5.9 \times 10^{-3} \text{ ft/yr})$, which is only 1% of the largest recharge rate noted in the literature. Our low value only includes recharge that becomes deeper, laterally flowing groundwater and not simply a change in storage where recharge gained is quickly lost to evapotranspiration. Much of this shallow groundwater is recharged briefly during the fall and spring infiltration events and then lost to evapotranspiration during the growing season. These results are used to further constrain boundary conditions for the transient numerical model described later in this section.

The most important results of the STWTI analytical model are simply that it helps to further establish a hydraulic conductivity of about 7 m/day for the aquifer sediment in the monitored quadrants. Results also suggest that the specific yield of the sediments tend to increase with greater drainage, which likely reflects differences in saturated hydraulic properties of aeolian soils versus deeper sediments.

B. Numerical Model

Introduction and Objectives

The objective for creating the numerical model is to define the following features of the hydrological system near Ditch 10: (a) short- and long-term drawdown related to the ditch; and (b) the seasonal water-level variability that occurs within both the undisturbed areas and areas affected by drawdown.
The greatest variability within the water budget comes through the coupled interaction of infiltration, recharge, and evapotranspiration. Evapotranspiration is a function of water-table depth and its interaction with infiltration and recharge creates non-linearity in the water budget. Because of the coupled non-linearity involved, simple analytical solutions cannot adequately describe the dynamics of the situation and a more robust modeling approach was necessary (Figure 16). MODFLOW-2005 (version 1.11.00), a full-featured finite-difference groundwater modeling code (Harbaugh 2005), was used to expand on the analytical models results.

Figure 16. The effect of ditch drawdown on evapotranspiration and recharge. Greater drawdown and a concomitant lower water table generate greater recharge. This difference occurs because less infiltration is lost to evapotranspiration in areas underlain by a deeper water table. (Diagram modified from Chen et al. 2014).

**Methods -- Assumptions**

The model was constructed using simplifying assumptions that include:

1. The water level in the ditch is static and lies 2 m (6.6 ft) below the original static water level, based on the depth to Fe-oxide rich zones, mottling, and other persistent hydric features observed in the soil.

2. Topography is level at an elevation of 325 m (1066 ft), which essentially discounts the local effect of dunes.
3. Water can pond on the surface.

4. Sediments are homogeneous and isotropic (a reasonable assumption for aeolian sediments).

5. Evapotranspiration is distributed equally throughout the year, while recharge occurs in a single 0.1-year (approximately 5.5 week) pulse. This is likely a reasonable assumption in view of frost-related exfiltration that occurs during the winter months, which has a similar effect on the water table as does evapotranspiration, and the strong recharge brought on by snowmelt and rainfall during senescence (Gerla and Matheney 1996).

6. The extinction depth, defined as the water table depth below which ET ceases to occur, was set at 2.5 m (8.2 ft) (Shah et al. 2007) with the evapotranspiration surface at ground level. Evapotranspiration was set as active in the upper-most active cell of the model.

As required in MODFLOW’s standard evapotranspiration package, evapotranspiration is at a maximum rate when the water table lies at the ground surface and diminishes linearly to zero as the depth of the water table falls to the extinction depth, recognizing that patterns of evapotranspiration are considerably more complex under natural conditions. To simplify the temporal aspects of the model and assure consistency of units, fraction of years is used rather than months, weeks, days, etc.

Methods -- Model Input and Discretization

A multilayer two-dimensional profile with variably spaced columns was modeled. Finite-difference columns were narrowed toward the ditch following the general convention that cells be no more than 1.5 times the width of adjacent columns. Total distance from the ditch extended 16,000 m (10 miles), which is roughly the distance from the quadrants to the groundwater divide within the Sheyenne grassland. Variable aquifer properties, hydraulic conductivity and specific yield, along with recharge that depended on the distribution of evapotranspiration, were adjusted to calibrate the model and test sensitivity. Calibration and sensitivity within a range of model properties was based on the water levels observed in the two monitoring quadrants adjacent to Ditch 10, while maintaining the parsimonious assumptions noted previously.

Figure 17. Spatial model discretization used in MODFLOW2005 to represent the unconfined aquifer west of Ditch 10. The shaded cell in the upper left shows the constant head (18 m) representing the water level in the ditch. The elevation datum for the MODFLOW models was set at 305 m. Column spacing is enumerated in Table 3.
Figure 17 shows the spatial discretization and boundary conditions and Table 1 provides the temporal discretization and aquifer properties used in modeling the hydrological system west of Ditch 10. The model elevation datum (0 m) corresponds to an elevation of 305 m (1000.66 ft). Because of the general continuity of hydrological conditions toward both the north and south of where Forest Service Road 1211 crosses the ditch, a two-dimensional profile model was chosen to represent the groundwater conditions in the simplest way possible on the west side of Ditch 10. The left, right, and bottom edges of the model are no-flow; the upper layer is unconfined. Whenever the water level rises above 20 m (65.6 ft) in model cell, the rise is considered free water at the surface and its actual depth adjusted by converting the specific yield to one. For example, if the model water table rises to 20.2 m and the Sy is 0.1 in the upper layer of the model, then 0.02 m of free standing water ([(20.0 - 20.2) * 0.1]) is assumed.

Table 1. Temporal and spatial discretization, aquifer properties, and solution conditions used in the MODFLOW model.

<table>
<thead>
<tr>
<th>TEMPORAL DISCRETIZATION</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>total time</td>
<td>10 years</td>
</tr>
<tr>
<td>stress periods</td>
<td>20 (repeats with a 0.9 and 0.1 year step each full year)</td>
</tr>
<tr>
<td>time steps</td>
<td>10 steps for 0.9 years, 3 steps for 0.1, time-step multiplier = 1.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SPATIAL DISCRETIZATION</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>layers</td>
<td>fixed --- 20-17, 17-14, 14-7, and 7-0 meters</td>
</tr>
<tr>
<td>columns</td>
<td>fixed --- 26 (increasing width from the constant head boundary)</td>
</tr>
<tr>
<td>column width</td>
<td>2, 3, 4.5, 7, 10.5, 13, 18, 27, 35, 50, 70, 100, 150, 200, 250, 360, 500, 700 ....</td>
</tr>
<tr>
<td>constant head</td>
<td>18 m (2 m below initial water table)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AQUIFER PROPERTIES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>hydraulic conductivity</td>
<td>variable --- 2, 7, and 24.5 m/day</td>
</tr>
<tr>
<td>specific storage</td>
<td>variable --- 0.06, 0.12, and 0.24</td>
</tr>
<tr>
<td>storage coefficient</td>
<td>fixed --- 0.001</td>
</tr>
<tr>
<td>recharge rate</td>
<td>fixed --- 4.868 x 10^-3 m/day (applied during 0.1 year stress periods)</td>
</tr>
<tr>
<td>evapotranspiration rate</td>
<td>fixed --- 6.950 x 10^-4 m/day (applied during all stress periods)</td>
</tr>
<tr>
<td>surface</td>
<td>fixed --- 20 m (at the ground surface)</td>
</tr>
<tr>
<td>extinction depth</td>
<td>fixed --- 17.5 m (2.5 m below the surface)</td>
</tr>
<tr>
<td>yearly water deficity</td>
<td>fixed --- 0.7 (evapotranspiration to recharge ratio)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SOLUTION</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>initial head</td>
<td>20 m (saturated to the surface, 0 m)</td>
</tr>
<tr>
<td>matrix solver</td>
<td>conjugate-gradient method (using default MODFLOW2005 variables)</td>
</tr>
</tbody>
</table>
Results -- Sensitivity Analysis

The combination of hydraulic conductivity, recharge, and evapotranspiration rates lead to short-lived transient conditions. A near-steady state pattern of drainage and water-table change develops in as few as two or three years (Figure 18), suggesting that drain excavation and tile installation will affect the local hydrology quickly, essentially after the first year or two. To check the calibration and test the sensitivity of the model, simulations also were performed using a K three times smaller and three times larger.

Figure 18. MODFLOW output showing rapid establishment of near-equilibrium conditions within two years. Lines correspond to distances from the constant head boundary (purple = 86 m, green = 220 m, blue = 660 m, and red = 1,400 m). Aquifer properties: K = 7 m/day, Sy = 0.12, t = 10 years, with two stress periods per year, see Table 3. The model datum corresponds to an elevation of approximately 305 m.

Results from the best-fit results and sensitivity analysis suggest that the natural water-level fluctuation will be altered to a distance of 1 to 2 km (0.6 - 1.2 mi) from the ditch, using a 10% change as a minimum benchmark for what we consider as “altered” versus “natural” (Figure 19 left panel). This model
perturbation of groundwater levels marginal to the ditch corresponds approximately to the actual measurements made in 2012 - 2013 (also shown in Figure 19 left panel). In comparison, the distance to the edge of the ditch drawdown fringe (defined as a 10% departure from unaltered conditions) ranges from 1.0 km (0.6 mi) for K = 2 m/day to about 4.2 km (2.6 mi) for K = 24.5 m/day.

It is important to note that drawdown and resulting water levels are not static beyond the disturbance zone related to the ditch, but will vary with the pattern of specific yield, recharge, and evapotranspiration. For example, the right side of Figure 19 left panel shows that the normal greatest depth to the water table will be 20 m (model ground surface)-18.75 m = 1.25 m (65.6-61.5 ft = 4.1 ft) below the ground surface, which will occur during the driest periods. Its magnitude is controlled mostly by Sy. Given that evapotranspiration and recharge rates are fixed and that Sy is constant in the model, this seasonal low level for the water table is the same for any value of K at a distance sufficiently far from Ditch 10.

The greatest range of seasonal water levels occurs in a zone roughly midway between the maximum effect of the ditch and the outer fringe of drawdown (Figure 19 right panel). Using K = 7 as an example (red line, Figure 19 right panel), note that the largest range in seasonal water level occurs at x = 415 m (1,362 ft). This is almost 350 m (1150 ft) beyond the point where the ditch fully drains the soil profile, which extends only about 65 m (213 ft) outward from the ditch (red line, Figure 19 left panel).

The reason for this pattern relates to the decreasing actual evapotranspiration with depth to the water table. Near the ditch most recharge will be “out-of-reach” to evapotranspiration because the water table remains at a depth of 2 m (6.6 ft). In contrast, evapotranspiration in the more distal zones of the drawdown will be greater because saturated soils remain closer to the surface and available to the plants (Figure 19 right panel). The lowered water table due to the ditch will adversely affect species that are adapted to phreatic conditions. Furthermore, it will likely encourage and provide a niche for invasive species that thrive in an altered hydrologic setting (e.g., Webb et al. 2013) characterized by larger fluctuations in the depth to the water table.
Varying Sy does not change the width of the drawdown fringe, but instead changes the seasonal minimum level of the water table significantly away from the stress of the ditch (Figure 20 left panel). For example, a small Sy (0.06) will lead to more robust change in water level caused by seasonal recharge and subsequent evapotranspiration. At roughly 200 m (656 ft) from the ditch, the simulated water table actually drops below 18 m (59 ft), leading to water flow from the ditch during the driest periods (Figure 20 left panel, Sy = 0.06), assuming that water remains available in the ditch. In contrast, an unusually large Sy leads to a much higher minimum water level beyond the edge of the drawdown fringe, falling to only slightly less than 19 m (62 ft) annually. Note, however, that in areas close to the ditch there is little difference in the minimum water level among the full range of Sy.

Smaller values of Sy amplify the seasonal range of the water table in the simulation (Figure 20 right panel). For example, for Sy = 0.06, the range exceeds 2 m (6.6 ft). In Figure 20 right panel, the range is corrected for ponding at the surface (where Sy = 1). In areas where the ground surface exceeds 20 m (65.6 ft) above the 305 m (1,000.7 ft) model datum, as it does under the dunes, the water table would rise more than what is shown in Figure 19 right panel. Therefore, in fine grained aeolian soils with lower storage during periods of little rainfall and strong evapotranspiration, the water table beneath the dunes would be higher than in the swales driving some local flow from dunes toward swales. This condition would help maintain groundwater flow necessary to support wetland vegetation in the swales during the summer. Finally, based on field measurements and model results, the best match for the overall seasonal fluctuation is roughly 1.2 m (3.9 ft) (Figure 20 right panel), which corresponds closely to the range that is predicted for the Ditch 10 and reference monitoring quadrants from the GIS analysis (Figure 14).

The most important lessons learned from the numerical MODFLOW are:

1. Hydraulic conductivity of the fine sands of roughly 7 m/day fits the observed water levels most closely, consistent with the graphical discharge results.

Figure 20. Model results for (left panel) the annual minimum (lowest) water levels and (right panel) seasonal variability using K~7 m/day and Sy~0.06 (blue), Sy~0.12 (red), Sy~0.24 (green). Black squares show the range of water-level change measured during 2012-2014. The model datum corresponds to an elevation of approximately 305 m. The distance from the ditch at which the elevation returns to 18.7 m indicates the distance at which the ditch no longer has a significant effect.
2. The seasonal water level variability, which influences seasonal changes in storage, is strongly controlled by the specific yield Sy. Overall, a Sy = 0.12 fits the observed data the best, although Sy will vary depending on the position of the water table in the soil and sediment profile.

3. A near-steady state pattern of drainage and water-table change develops in as few as two or three years, suggesting that drain excavation and tile installation will affect the local hydrology quickly, essentially after the first year or two.

4. Evapotranspiration is strongly affected by the proximity of the water table to the ground surface. Even with the numerical code requiring a fixed extinction depth and simple linear variation of evapotranspiration with depth, model results corroborate the observations showing drawdown associated with the ditch diminishes evapotranspiration.

5. Model results improve the capability to formulate a general water balance for the drained and undisturbed areas.

e. Completing the Water Budget

Output from the MODFLOW model, using K = 7 m/yr, Sy = 0.12, and other model parameters (Table 1), provides the data necessary to formulate a water budget for the repetitive (quasi-steady-state), one-year recharge-evapotranspiration cycle. For 90% of the year, the Ditch 10 dune-swale system is influenced by evapotranspiration without recharge. During the remaining 10% of the year, a strong pulse of recharge is applied within the model (Table 1). Quantitatively, the model water budget (Figure 21) shows that most of the water entering as recharge (2,844 m³/yr) (1 x 105 ft³/yr) is lost to evapotranspiration (2,760 m³/yr) (9.75 x 104 ft³/yr), with only a small fraction draining to the ditch (84 m³/yr) (2.97 x 103 ft³/yr). These rates are based on a unit length of the ditch. Recharge for a short period during the year and then persistent evapotranspiration, especially during the summer months, imparts a vertical “push and pull” on the regional water table. Note that although the ditch has only a minor influence on the overall water budget (approximately 3%), the drainage and subsequent drawdown outward to a distance of roughly one kilometer (0.62 miles) are hypothesized to have a profound effect on plant communities and wetlands. For an evaluation of model assumptions, see Appendix.
Figure 21. MODFLOW model water budget for a one-year cycle, with 90% of the year influenced by evapotranspiration without recharge (upper part of the figure) and remaining 10% of the year characterized by strong recharge combined with the year-long evapotranspiration rate (lower part of the figure). Numbers give the water budget component volumes in m³ (per meter reach of the ditch). Storage values in red indicate a loss and blue indicate a gain, with no net change in storage over the course of the model year. As described in the text, the water budget for the reference condition (no ditch) would be similar, with roughly 1% of recharge entering the deeper groundwater flow system, and the remaining recharge lost to evapotranspiration.
The Sheyenne National Grassland covers less than 0.2% of the state of North Dakota, but hosts about 850 of the 1,200 (70%) of all the native plant species known to occur in the state, including a large diversity of grass and sedge species. On the driest sites, *Schizachyrium scoparium* (little bluestem), *Stipa spartea* (porcupine grass), and *Bouteloua gracilis* (grama grass) dominate. In slightly moister areas, *Andropogon gerardii* (big bluestem) and *Sorghastrum nutans* (Indian grass) are more common. In the still wetter meadows and swales *Calamagrostis canadensis* (bluejoint) and *Carex pellita* (wooly sedge) are predominant.

Svedarsky and Van Amburg (1996) list one threatened plant, *Platanthera praeclara* (western prairie fringed orchid), and 34 sensitive species. Other unusual and rare plants found in the heart of the SNG include *Senecio blochmaniae* (dune ragwort), *Helianthemum bicknellii* (Bicknell’s sunrose), *Crocanthemum bicknellii* (hoary frostweed), *Lechea stricta* (upright pinweed), and *Athyrium filix-femina* (northern lady-fern). Because of the geological framework of the SNG, these habitats are unusual for the upper Midwest region, placing many species at the margins of their natural range.

More than 22 species of butterfly have been identified in the SNG, including the rare *Hesperia dacotae* (Dakota skipper) and *Speyeria idalia* (regal fritillary); the latter’s larvae depending entirely on *Viola* sp. for food. In addition, *Chlorochroa belfragii*, a Heteroptera or true bug, is a species of special concern throughout its range and the SNG is the only known occurrence in North Dakota. Two bird species of concern, the greater prairie chicken (*Tympanuchus cupido*) and loggerhead shrike (*Lanius ludovicianus*), occur in the SNG.

Most of the sensitive plant species occur in the xeric locations on dune crests or in swale wetlands characterized by groundwater discharge. As described in previous sections, the hydrology of these ecosystems is naturally very dynamic, with water levels varying on average by 1.2 m (Figure 14). The distributions of plant species in seasonally inundated habitats are closely tied to several aspects of that dynamic hydrology, including the magnitude, frequency, duration, timing, and rate of change of water levels (Figure 22) (Poff et al. 1997; Rogers et al. 2012; Webb et al. 2013). Here we define these terms as follows:

1. Magnitude: how much water occurs in a certain habitat (expressed as the depth either above- or below-ground)
2. Frequency: how often a particular water level (or sequence of water levels) is achieved (e.g., monthly, annually, decadally)
3. Duration: how long a certain water level is maintained (e.g., number of days or weeks)
4. Timing: at what time of the year a certain water level is maintained (e.g., which days or weeks)
5. Rate of change: how quickly or slowly one water level gives way to another (e.g., change in water level per day, measured as the slope of the rising or falling limb of the hydrograph).

The hydrologic attributes selected for developing EFL recommendations depends on which attributes, if altered, are most likely to affect the key species and ecosystem processes, and how the hydrologic system is likely to be altered due to human activities. Key hydrologic findings relevant to the plant communities of this area are as follows:

1. The water table is generally close to level despite the undulating dune-swale topography because of relatively well-sorted sands that permit rapid equilibration of the water table. However, there is a slight slope of the water table outward from a broad regional groundwater mound in the core of the SNG.
   a. The water table experiences dramatic fluctuation over the course of the year
   b. During the wet season, most precipitation and snowmelt lead to a rise in the water table rather than running off, due to the relatively flat topography and the high infiltration capacity of the soils.
   c. During the dry season, which largely corresponds to the growing season, recharge is mostly lost to evapotranspiration; very little incoming precipitation (roughly 1%) ultimately flows laterally within the unconfined Sheyenne delta aquifer. During the dry season, the water table in the dunes is higher than in the swales, inducing flow from the dunes to the swales and supporting wetland vegetation in the swales.
   d. Annual water level fluctuation is about 1.2m

5. Ditching leads to lower water levels in the area of influence of the ditch

6. A near-steady state pattern of drainage and water-table change develops in as few as two or three years following ditching or installation of drain tiles

7. Ditching leads to a decrease in the annual wet-dry water level fluctuation within the area of influence of the ditch.

Thus the magnitude and duration of the seasonally shallow water table are affected by ditching (Figure 22). With lower minimum water levels, changes in the rate that the water table rises and falls is also likely to decrease, although its effects on the plant communities are difficult to quantify.

These hydrologic changes should have the most impact on the swale wetland plant communities because species that thrive within transitional habitats are able to shift downslope to locate favorable hydrologic conditions, and species found on the dune crests are most likely limited by factors other than proximity to the water table. Plant species found in the SNG are adapted to seasonally and interannually variable water levels, but there are thresholds in water level drawdown beyond which even the most drought-adapted wetland plants cannot survive. Thus the focus of this analysis is on identifying ecological thresholds in water level drawdown due to drainage, and using that information to provide specifications for design of ditches. To do this, we inventoried plant species growing in plots at different topographic positions, and identified indicator species that are sensitive to water level drawdown and can be used to set drawdown thresholds.
Plant species distributions - methods

As described in section “Establishing Dune-Swale Transects”, our methods involved first identifying a representative sample of the topographic dune-swale zones in the three quadrants (one disturbed and two “natural” quadrants). All plant species within small plots along the 40 randomly selected transects were cataloged and categorized. Because the position of the water table is variable both intra- and inter-annually, each transect included one plot from each topographic zone. We did not attempt to identify any indicator species a priori; instead, we used the vegetation and hydrological data to identify the most appropriate indicators. Good indicator species are those that have a strong relationship with the depth and variability of the water table. If the relationship between the presence of a given species and the water table is too broad and poorly constrained, then that species is not an appropriate indicator of hydrologic conditions.

The following protocol was used for characterizing the vegetation in the three monitoring quadrants in 2012 and 2013. Forty transects of four quadrats each were sampled, for a total of 160 quadrats. Two-thirds of the transects (27) were selected and inventoried within reference areas where the water table is not affected by ditches, and the remaining one-third of transects (13) inventoried in the area affected by Ditch 10 (Figure 9). This strategy was implemented in the field using the following steps:

![Diagram of water level changes](image)

Figure 22. Potential changes to the annual hydroperiod of swale wetlands in the Sheyenne National Grasslands. Solid lines show reference seasonal water level variation, and dotted lines show potential changes associated with ditching. The timing and frequency of water level changes are not noticeably changed by ditching.
1. In the field, GPS was used to navigate to the first dune crest point where a transect was extended from the dune top to the closest swale point previously identified in GIS.

2. Five vegetation plots were read along each transect:
   a. The randomly selected dune crest point (H)
   b. The midpoint between this point and the adjacent swale (M)
   c. The swale point (S)
   d. An additional position referred to as the dune-swale transition (T), selected jointly by the botanist and hydrologist, which was chosen to capture the vegetation continuum between the swale and dune slope.
   e. Low transition (L) was selected as a point representing vegetation characterizing the margin of the lowest and wettest point on the dune-swale continuum.

3. At each of the four or five sampling points on each transect, the following procedure was carried out
   a. A 1 X 1 m (1 m²) quadrat was positioned. All species present within the plot were recorded, including both vascular plants and bryophytes. This step was completed when the plants were alive and robust, after emergence and before senescence.
   b. The local zone category was recorded (from #2 above).
   c. The GPS coordinates of the point were checked and re-recorded to the nearest meter.
   d. After the growing season in 2013, the elevations of each sampled quadrat, relative to well levels, were determined using a laser level.

Data were analyzed by combining data for the 2012 and 2013 field seasons, and matching each plot to its expected range in water levels described in the section entitled “Water-Level Elevations” (Figure 14). Indicators of water level drawdown were identified by selecting native common wetland plants found in swale habitats, using the following approach:

1. Non-native species were identified using the USDA Plants Database (USDA NRCS 2015) and removed from the data set.

2. Common species are those with a large enough sample size for a robust analysis, here defined as found in >=10 plots.

3. Wetland plants were defined as those coded as Obligate (OBL) and Facultative Wet (FACW) by the U.S. Army Corps of Engineers Wetland Indicator Database (U.S. Army Corps of Engineers 2012).

4. Swale species were defined as those where at least 40% of occurrences were recorded in swale plots. This number may seem low; however, many of the more common wetland plants across the Sheyenne delta are perennial, thus their current occurrence to some extent reflects the wetter conditions of the last decade, and so some species may have extended their ranges into the transitional zone during wetter times.
Because this approach will miss the rarer species that may be sensitive to water level drawdown, we also repeated these steps including species found in 6-10 plots.

To identify thresholds of water level drawdown, we adapted an approach currently under development by the European Union in the implementation of the Water Framework Directive (Schutten et al. 2011; UK TAG 2012). The threshold value is defined as the 25th percentile of the maximum depths to the water table across all plots where the indicator species are found (SAS Inst. 2013), implying a management goal of maintaining water levels above those values. This method takes a precautionary approach by setting thresholds higher than the absolute maximum water levels at which the species are found. The drawdown threshold was then determined by summarizing this information across all indicator species.

The site-based data were supplemented with data from the published and grey literature of depth to water table for the indicator species in other wetlands. This was done to create a larger data set to help inform the range of tolerances in depth to water table. To identify papers and reports, we conducted web searches (both Google and Google Scholar), searched The Nature Conservancy’s literature database, used data sets we have collected in the past, and contacted individual scientists for unpublished data.

ii. Plant species distributions – results

Vegetation monitoring took place in 2012 and 2013. Fewer plots were monitored in 2012 than originally intended because grazing commenced on two of three study quadrants on the SNG in response to seasonal drought. Furthermore, some of the species were impossible to identify in 2012 because they had been grazed. Therefore, only 20 transects (80 plots) were surveyed in 2012, but all 40 transects (160 plots) were surveyed in 2013 (Table 2).

Table 2. Number of transects and plots surveyed in 2012 and 2013, and the minimum number of plots required for adequate sampling.

<table>
<thead>
<tr>
<th></th>
<th>All sites</th>
<th>Brown Ranch</th>
<th>Road reference</th>
<th>Ditch impacted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transects (plots) surveyed – 2012</td>
<td>20 (80)</td>
<td>13 (52)</td>
<td>3 (12)</td>
<td>4 (16)</td>
</tr>
<tr>
<td>Transects (plots) surveyed – 2013</td>
<td>40 (160)</td>
<td>13 (52)</td>
<td>14 (56)</td>
<td>13 (52)</td>
</tr>
<tr>
<td># plots to achieve an average Sorenson distance of 10%</td>
<td>73</td>
<td>33</td>
<td>38</td>
<td>38</td>
</tr>
</tbody>
</table>

A total of 195 species were detected over all study quadrants, including one USFS Region 1 sensitive species found in dune plots (*Gentiana affinis*). The numbers of species detected at each quadrant were very similar: 134 at Brown Ranch and Road Reference, and 123 at the Ditch Impacted site. We calculated the Sorensen (Bray-Curtis) distance measure for all observed species using the software PC-ORD (McCune and Mefford 2011). Examination of the species-area curves for all study quadrants combined and for each quadrant
individually suggests that sample plot numbers of 52 or 56 per quadrant provided adequate sampling coverage (Dietvorst et al. 1982) (Table 2; also see Appendix). From this dataset, indicators of the swale habitats were identified using the rules above:

1. Of the 195 species recorded in the complete data set, non-native or invasive species were removed (*Phalaris arundinacea*, *Cirsium arvense*, *Euphorbia esula*, *Melilotus officinalis*)

2. Of the remaining species, 78 were identified as common.

3. Of the 78 common species, 23 were either OBL or FACW.

4. Of the 23 common wetland plants, 11 were recorded from swale plots at least 40% of the time. All 11 species are perennial (Table 3).

5. Repeating these steps for rarer species (i.e., found in 6-9 plots), 6 OBL and FACW species are found in swale plots at least 40% of the time. All 6 species are perennial (Table 3).

From the published literature we identified 54 publications containing 136 water level data points for the 17 indicator species (Table 3). Many papers contained data for more than one species. Some more widespread species such as *Eleocharis palustris* were well-represented in the literature (N=38), whereas more rare species such as *Stachys palustris* were not well represented (N=2).

**Table 3.** Indicator species, their species codes and wetland indicator status, number of plots where they were recorded, percent of those plots that were swales; data for indicator species found in the scientific literature, and maximum depth thresholds of the indicator species, defined as the 25th percentile of maximum depth to water table in the plots in which these species are found.

<table>
<thead>
<tr>
<th>Species</th>
<th>4-letter symbol</th>
<th>Frequency</th>
<th>Wetland indicator status</th>
<th>Total # plots</th>
<th>% Swale plots</th>
<th># publications</th>
<th>Maximum depth threshold (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calamagrostis stricta</td>
<td>CAST36</td>
<td>Common</td>
<td>FACW</td>
<td>98</td>
<td>45</td>
<td>14</td>
<td>1.6</td>
</tr>
<tr>
<td>Carex crawei</td>
<td>CACR3</td>
<td>Common</td>
<td>FACW</td>
<td>10</td>
<td>40</td>
<td>2</td>
<td>1.8</td>
</tr>
<tr>
<td>Carex pellita</td>
<td>CAPE42</td>
<td>Common</td>
<td>OBL</td>
<td>147</td>
<td>46</td>
<td>8</td>
<td>1.8</td>
</tr>
<tr>
<td>Carex sartwellii</td>
<td>CASA8</td>
<td>Common</td>
<td>FACW</td>
<td>38</td>
<td>82</td>
<td>9</td>
<td>1.3</td>
</tr>
<tr>
<td>Eleocharis palustris</td>
<td>ELPA3</td>
<td>Common</td>
<td>OBL</td>
<td>51</td>
<td>92</td>
<td>38</td>
<td>1.3</td>
</tr>
<tr>
<td>Hordeum jubatum</td>
<td>HOJU</td>
<td>Common</td>
<td>FACW</td>
<td>31</td>
<td>81</td>
<td>9</td>
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<td>Common</td>
<td>OBL</td>
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<td>4</td>
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<td>57</td>
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<td>1.7</td>
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<td>OBL</td>
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<td>40</td>
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<td>Rare</td>
<td>FACW</td>
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<td>3</td>
<td>1.7</td>
</tr>
<tr>
<td>Hypoxis hirsuta</td>
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<td>Rare</td>
<td>FACW</td>
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<td>67</td>
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<td>1.7</td>
</tr>
<tr>
<td>Juncus alpinoarticulatus</td>
<td>JUAL4</td>
<td>Rare</td>
<td>OBL</td>
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<td>4</td>
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<tr>
<td>Juncus torreyi</td>
<td>JUTO</td>
<td>Rare</td>
<td>FACW</td>
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<td>Rare</td>
<td>FACW</td>
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<td>OBL</td>
<td>8</td>
<td>88</td>
<td>2</td>
<td>1.4</td>
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Quantify groundwater ecohydrology 48
Combining the 17 indicator species with water level data for each plot in which they were found, it is apparent that most of these species are found in swales where the water table remains within 1.5 - 2 m (5.0 - 6.6 ft) of the surface (Figure 23). One exception is Carex pellita (CAPE42) which has a much broader tolerance range, and although it was only found in one dune crest plot (of 147 plots total), that plot had a maximum water table depth of 3.3 m (10.8 ft). Similar data for the indicator species as reported in the literature are shown in Figure 24. It is evident from comparing values from the literature and values from the study plots that the indicator species generally occur in wetlands with higher water tables and/or less water level fluctuation than those occurring in the study plots.

The 25th percentile of maximum depth to the water table ranged from 1.33-1.89 m (4.36-6.20 ft) for data collected in this study and 0.03-1.8 m (0.10-5.90 ft) for data reported in the literature (Table 3). Figure 25 illustrates the progressive loss of species with increasing water level decline. This figure shows a large difference between data from the study sites and data from the scientific literature. The study sites indicate a drastic loss in species at a threshold of 1.25 m (4.10 ft), with complete loss at 1.9m. In contrast, data from the literature indicate a gradual loss of indicator species, starting with as little as 0.2 m (0.66 ft) of drawdown, with a median of 0.91m, and progressing to complete loss at the same drawdown as the study.

The marked difference between the study data and data from the scientific literature is different from the first EFL study (Aldous et al. 2014), where published data closely mirrored the site data. This difference could be due to various causes. One hypothesis is that wetlands on the SNG might be much more hydrologically variable than most other wetlands where these species occur, supporting species that are able to tolerate water table extremes. This hypothesis is supported by the following: (i) all indicator species are perennials which are more able to tolerate year-to-year environmental variation in comparison to annuals; and (ii) the indicator species were not confined to the swale plots (none were found exclusively in swale plots and 8 of 17 were found in non-swale plots at least 50% of the time). A second hypothesis is the conditions during the study were unusually dry and the species were stressed during the dry year but had not disappeared because that dry year followed a decade of wetter years. A third hypothesis is the study plots have undergone stress from ditching not accounted for in our study design. Indeed some of the reference plots were within 1 km (3,280 ft) of the ditch, which is the zone of impact identified by the modeling work. A fourth hypothesis is some rhizomatous wetland species may be able to spread into upland areas when the rhizomes provide the upslope ramets with sufficient water to grow under drier conditions. Whatever the cause, relying solely on data published in the scientific literature would produce a far more conservative result compared to using the study site data to estimate a drawdown threshold.

Because the difference between the drawdown thresholds indicated by data from the literature compared to the study data, we lowered the threshold from the obvious 1.25m cut-off suggested by the study data to 0.91 m, the median threshold value indicated by data from the literature.
Figure 23. Boxplots of maximum water table depths for the 17 indicator species. For species codes see Table 5. The length of the box represents the interquartile range (the distance between the 25th and 75th percentiles). The blue ‘◊’ symbol in the box interior represents the group mean. The horizontal line in the box interior represents the group median. The vertical lines (called whiskers) beyond the box extend to the group minimum and maximum values. Outliers are identified with an ‘o’.

Figure 24. Boxplots of maximum water table depths for the 17 indicator species, using data reported in the literature. For species codes see Table 3. For explanation of box plots see Figure 23.
Figure 25. Cumulative percent of indicator species lost with water level drawdown. Data are from this study (blue line) and data reported in the scientific literature (red line). A species is considered to be lost when the water level passes its maximum water table depth threshold.
The final step is to evaluate the general relevance of the ecological threshold to ditching and drainage in the SNG. Any ditch excavated deeper than 0.91 m below the water table (3 ft) will exceed the tolerance threshold of the indicator plants. Ditches excavated to this depth will affect the water table up to 400 m away (1312 ft) in either direction. Areas within these distances will be adversely affected by persistent drawdown and reduction of seasonal rise and fall of the water table, with areas closest to the ditch most affected. The expected zone of impact is approximately 1 km (3,300 ft) for ditches 2 m (6 ft) deep, and about 2.5 km (8,200 ft) for ditches and channels of the greatest depth feasible (eg., 3 m (9.8 ft)) (Figure 26). For shallow ditches and field scrapes (i.e., less than 1 m (3.3 ft)), correspondingly smaller zones are affected.

**Figure 26.** Effect of ditches of 1, 2, and 3 m (roughly 3, 6, and 9 ft) on the seasonally average water table as a function of distance from the ditch. “Wet” indicates early spring / moist weather (dots) when the water table is shallow; “Dry” corresponds to the driest conditions annually when the water table is at maximum depth (solid lines). These results are based on MODFLOW models using K = 7 m/day and S_y = 0.12.

To illustrate the scale of effect on swale wetlands across the Sheyenne grasslands, we estimated the area of wetlands mapped by the National Wetlands Inventory (U. S. Fish and Wildlife Service 2014) within the zone...
of impact of the main ditch system (Figure 27). The east reach of Ditch 10 is generally >2m deep (>6 ft), and this was buffered by a distance of 1km (3,300 ft) on either side of the ditch. The ditches to the west of Ditch 10 (Highway 27 reach, western tributary, and McLeod reach) are all approximately 1 m (3,300 ft) deep, and so were buffered with a distance of 400 m (1,312 ft) (Table 4). The area within the combined zones of impact of the ditches is approximately 2,877 ha (7,109 acres), and this area contains 350 ha (865 acres) of wetlands. Thus 36% of the total wetland area within the watershed is affected by this ditch system.

This goal of this project was to provide the Forest Service with the hydrological information and tools to

Figure 27. Wetlands found within the zone of impact of the major ditch systems on the SNG. Wetlands were identified using the National Wetlands Inventory (USFWS 2014). Wetlands within 1km of the N-S Ditch 10, and within 400 m of the ditch system to the west of Ditch 10, were considered within the zone of impact.
help guide protection of the Sheyenne National Grassland’s wetland natural resources from degradation by drainage ditches. For the typical fine sand sediments of the Sheyenne Delta, these findings indicate a lateral zone of impact extending outward from drainage ditches. This zone of impact ranges from 400m for a 1m-deep ditch to 1km for a 3m-deep ditch. These distances are greater for coarser sediments that occur toward the west and less for silts and clay sediments that flank the delta. Changes in ecosystem structure and function, including loss of biodiversity and degradation of soil and forage conditions, will occur along a continuum that decreases from the ditch outward (Figure 28). Thus zones of impact should be evaluated around new or planned ditches to ensure that they are not routed through areas with sensitive wetlands or important groundwater-dependent species.

Here we show that the Environmental Flows and Levels method can be used to determine how agricultural drainage ditches in the Sheyenne National Grassland can be constructed and managed in a manner that minimizes their effects on groundwater-dependent wetlands. This method is scientifically sound and considers to many uses and benefits of groundwater, in supporting both society and nature.

Table 4. Summary of analysis of wetlands affected by ditch drawdown.

<table>
<thead>
<tr>
<th>Affected Area</th>
<th>Size or distance</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ditch 10 watershed above Iron Springs Creek</td>
<td>10,567 ha</td>
<td></td>
</tr>
<tr>
<td>Total length of the main ditch system</td>
<td>20,866 m</td>
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</tr>
<tr>
<td>Ditch 10 east reach (~2 m deep)</td>
<td>9,308 m</td>
<td>45%</td>
</tr>
<tr>
<td>Highway 27 reach (~1 m deep)</td>
<td>2,014 m</td>
<td>10%</td>
</tr>
<tr>
<td>Western tributary (~1 m deep)</td>
<td>1,912 m</td>
<td>9%</td>
</tr>
<tr>
<td>McLeod reach (~1 m deep)</td>
<td>7,632 m</td>
<td>36%</td>
</tr>
<tr>
<td>Total area affected by ditch drawdown</td>
<td>2,877 ha</td>
<td>27% of watershed</td>
</tr>
<tr>
<td>NWI wetlands in entire watershed</td>
<td>1,835 ha</td>
<td></td>
</tr>
<tr>
<td>NWI wetland area within the entire watershed</td>
<td>968 ha</td>
<td>9% of watershed</td>
</tr>
<tr>
<td>NWI wetlands affected by ditch drawdown</td>
<td>483 ha</td>
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</tr>
<tr>
<td>NWI wetland area in the drawdown affected area</td>
<td>350 ha</td>
<td>36% of the total wetland area</td>
</tr>
</tbody>
</table>
Figure 28. Hypothetical ecosystem changes associated with groundwater drawdown from ditching.


North Dakota State Water Commission. 2014. The “Map Services” page (http://mapservice.swc.nd.gov/) on the NDSWC web site provides a geographical search interface to provisional groundwater and surface water data, including water appropriation permits.


References 59


Wahpeton Globe-Gazette. 1906. Iron Springs Drain No. 10. November 8 issue (need to check on this one ... there were three papers in Wahpeton, all published on Thursday, the Globe, the Gazette, and the Times .... see http://history.nd.gov/archives/cities/wahpeton.html for information on the what's available at the state archives)

