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Ogochukwu Ozotta

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USING THERMAL IMAGING TO CHARACTERIZE GROUNDWATER SEEPAGE IN A
NORTH DAKOTA FEN

by

Ogochukwu Ozotta

Bachelor of Technology, Federal University of Technology Owerri, 2011

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

In partial fulfillment of the requirements

For the degree of

Master of Science Geological Engineering

Grand Fork, North Dakota

December

2018

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This thesis submitted by Ogochukwu Ozotta in partial fulfillment of the requirement for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Ogochukwu Ozotta
September 26, 2018

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ABSTRACT

Groundwater flow and its dissolved mineral transport plays a fundamental role in the ecology of many wetlands. Installation of equipment to map groundwater seepage, however, is invasive and may damage vegetation and potentially affect biodiversity. By mapping surface temperature remotely in the late summer, when the differential between warm soil and cold groundwater is the greatest, the temperature patterns may reveal areas of greatest upward gradient and flow.

To test the hypothesis, the effect that hydraulic gradient has on surface temperature in a fen located at the north end of the Cherry Lake Aquifer, Eddy County, ND (47.73, -98.66) was monitored and measured. Thermal imaging was used to characterize groundwater seepage, the results were compared to conventional method of installing shallow ceramic cup tensiometers to measure hydraulic gradient, and estimate flux using Darcy's law. Shallow temperature loggers were installed to characterize soil temperature at the same sites. The approach was applied at contrasting two locations: a sedge-cattail covered site (Sedge) and a nearby site with cordgrass and closed-canopy shrubs and trees (Willow).

Both sites showed variable hydraulic gradients between the shallow and deep tensiometer, perhaps related to variation in transpiration. The temperature trend determined from the thermal imaging showed a closer relationship to hydraulic gradients measured at the Sedge site more than at the Willow site. The hydraulic conductivity, K ranged from 6×10^{-6} to 2×10^{-4}

m/s for both sites, which falls within values typical for fen sediments. The flux calculated for the Willow site ranged from 1.4×10^{-5} to 1.1×10^{-4} m/s and that of the Sedge site ranged from 4.5×10^{-6} to 1.1×10^{-5} m/s. Willow site thermal imaging did not show similar trend with the hydraulic gradient, suggesting tree cover can affect thermal signature at the surface. Temperature profile observations from the thermal aerial imagery and the FLIR C2 camera showed a similar trend.

Both forward and inverse modeling of temperature profiles, which is based on a one-dimensional solution to the advection-conduction equation (Kurylyk et al. 2017), were used to more thoroughly characterize the shallow variation of flux compared to thermal imaging, coupled with additional field data on temperature distribution, thermal conductivity, depth, and layer thickness. Accounting for soil layer properties plays a role in characterizing groundwater seepage direction and rate.

The gradients are affected at some depth because of the varying soil stratigraphy, which explains the reason why the seepage faces cannot be mapped completely using thermal imaging at these sites.

CHAPTER I

INTRODUCTION

Understanding the basic principles and dynamics of surface water - groundwater interaction will aid in proper management and conservation of global water resources. Brunner et al. (2017) outlined the importance of understanding the interaction between groundwater and surface water because it is a channel for provision of water, contamination, and management of environmental flow regimes. Understanding the flow pattern and direction will guide in managing the water resources. Surface water- groundwater interaction is complex. To understand the dynamics of surface water-groundwater interaction, it requires contribution and knowledge from wide range of disciplines including hydrogeology, hydrology, sedimentology, biology, ecology, and chemistry (Brunner et al. 2017). Groundwater seepage is the process in which groundwater flows from an aquifer and reaches the surface. The groundwater seepage zone or face is a place where the groundwater discharges at the surface. Mapping groundwater seepage zones in a wetland can provide information about the groundwater flow system and about the potential transport of groundwater contaminants (Banks et al. 1996). With the basic understanding of the surface water – groundwater interaction and its flow regime, water resource managers can determine the overall health of the wetland, its watershed, the connected aquifer and extent, and its water budget. Characterizing groundwater flow at seepage faces is essential because seepage faces are a potential source of groundwater discharge and contamination, and seepage influences the water budgets of watersheds, lakes, and streams. Groundwater flow or

flux is the rate at which water seeps from groundwater (aquifer) to the surface (Fetter 2001); seepage is difficult to measure directly.

Installation of field equipment to measure hydraulic gradient, hydraulic conductivity, and calculate groundwater flux (referred to herein as the *conventional method*), however, is time consuming, expensive, equipment intensive, and intrusive. It can damage vegetation, disrupt soil profiles, and potentially diminish biodiversity. Therefore, it is very important to define a better means of mapping and characterizing groundwater seepage to conserve the wetland, nutrient source, and ecology. Thermal imagery may provide a less invasive and cost-effective technique to characterize groundwater seepage in wetlands because it simply requires the use of a thermal imaging camera to capture on-the-ground image. These data can be analyzed by identifying cold and hot spots and then mapping areas showing groundwater seepage. The thermal imaging cameras in recent years have become relatively inexpensive, and the image acquisition does not involve any subsurface equipment installation.

Heat has been identified and used as a groundwater tracer (Anderson 2005). Heat carried by groundwater has been used as a tracer to identify surface water infiltration (Anderson 2005; Hare et al., 2015), indicate seepage dynamics, and zones of groundwater seepage (Hare et al. 2015). Since groundwater temperature is relatively constant while surface water temperature varies on diurnal and seasonal cycles (Deitchman & Loheide 2009), the differences can be used as a tracer to map seepage.

The study area is part of North Dakota National Guard's Camp Grafton South (CGS). This research focuses on two sites about 800 meters apart within a single, large seepage zone

(Figure 1), one is willow, shrub and tree covered referred to in this research as the *Willow site* and the other sedge and herbaceous plant covered referred to as the *Sedge site*. These sites were selected because of their diverse plant community, perhaps more diverse than any wetland in North Dakota (Altrichter 2017). Plant communities common at this location are the cattail marsh, herbaceous meadow, and forested wet meadow. Certain species present at this wetland are among those proposed for conservation priority in North Dakota. Species are ranked in levels; Level I, Level II, or Level III to prioritize conservation efforts. Six species found at the study site are on the proposed list for conservation. *Cypripedium candidum* (White Lady's-slipper) is a Level I species, *Cypripedium parviflorum* (Small Yellow Lady's-slipper Orchid) and *Carex sterilis* (Sterile Sedge) are Level II species, and *Parnassia palustris* (Small-flowered Grass-of-Parnassus), *Rhynchospora capillacea* (Hair Beakrush) and *Utricularia intermedia* (Flat-leaved Bladderwort) are Level III species (North Dakota Natural Heritage Program 2013). The presence of these species within the study area makes this site a priority for conservation in North Dakota. Hydrological alteration of the wetland would cause degradation of the vegetative communities within these ecosystems (Altrichter 2017).

The location is currently used by the National Guard for training and needs to be protected against any contamination, environmental degradation and extinction of the diverse plant community. The primary land use contaminant in Camp Grafton South is munitions and explosives, and cattle grazing. The location is leased for grazing during spring and fall, which raises the possibility of contamination from livestock waste (Schuh 1994).

Figure 1. Outline of the study area in Camp Grafton South, Eddy County, North Dakota (Sources: ArcGIS online; State of North Dakota; NRCS 2013).

Research Goals

The goals of this research are to map groundwater seepage using thermal imaging and demonstrate thermal imaging as an effective tool to locate and characterize groundwater seepage, which can be accomplished without disturbing the soil profile and by eliminating the cost of installing monitoring equipment. If this research is successful, then thermal imaging would be used to map the groundwater seepage, characterize the flow direction, and quantify the vertical flux, therefore providing a thorough understanding of the groundwater system without disturbing the soil profile.

To achieve the goals, three methods are applied in this research. The first method uses the conventional method of measuring groundwater flow direction and rate of flow. This will determine the groundwater flux and the flow direction (upward or downward). The second method employs thermal imagery captured on the surface of the wetland using thermal camera, coupled with thermal imagery acquired using an unmanned aerial vehicle (drone), to characterize groundwater seepage. These methods will be compared in relationship to their efficiency and accuracy. The third method applies a one-dimensional analytical model to characterize groundwater seepage in the wetland, accounting for the subsurface layers properties.

Hypothesis

By mapping surface temperature in the late summer, when the differential between warm surface and cold groundwater is the greatest, the hypothesis is that thermal imagery at the surface would reveal areas of greatest upward hydraulic gradient and groundwater seepage.

Identification of the anomalously warm and cool areas will show the upwelling of groundwater across the surface. Cold spots in summer will indicate upwelling of relatively colder groundwater to the surface to stabilize the warmer surface water temperature, warm spots will indicate upwelling of relatively warmer water from the groundwater to the surface to stabilize the cold and frozen surface water temperature in winter.

To test the hypothesis, the effect that groundwater seepage has on surface temperature in the wetland was monitored; on-the-ground thermal imagery using FLIR C2 coupled with thermal imagery gathered using a drone was captured, the surface temperature was logged and analyzed using HOBO pendant thermistors, and the subsurface was analytically modeled using the soil layers properties. Data were acquired with a combination of all the methods at both the Willow and Sedge sites.

Background

To provide a basis for the research, an overview of the basic concepts, literature review, and principles governing this research is discussed in this section.

Surface water -groundwater interactions

Surface water and groundwater are connected in most landscapes (Winter et al. 1998). Due to the exchange of water between surface water and groundwater, alteration in one will affect the other due to the connectivity (Winter et al. 1998; Hare et al. 2015). The area groundwater discharges to the surface water is referred to as the seepage zone in areas where upward gradient of groundwater flow occurs. Generally, in these areas of significant upward gradient, groundwater discharge creates wetlands and stream flow. Seepage zones create complex interaction between surface water and groundwater (Hare et al. 2015; Brunner et al. 2017). Groundwater discharge occurs along the stream banks (Hare et al. 2015; Brunner et al. 2017), well walls (Deitchman & Loheide 2009), hill slopes, shorelines (Danielescu et al. 2009), and in drainage canals where a sharp pressure gradient exists between the internal saturated zone and external seepage area (Deitchman & Loheide 2009). Wetlands are present in climates and landscapes that cause groundwater to discharge to land surface or that prevent rapid drainage of water from the land surface (Winter et al. 1998). Wetlands are not only found in low points and depressions on the landscape but also on slopes (Figure 2). Fens are wetlands that are commonly formed and maintained by discharge of groundwater seepage. A fen is a wetland that receive nutrients from sources other than precipitation, usually from upslope sources through drainage from surrounding mineral soils and from groundwater seepage (USEPA 2016). The wetland of the study area is classified as a fen based on the nature of the hydrology system, and the geomorphology of the area. Fens with high species diversity usually have moderate pH; the pH of this fen ranges from 7.23 to 7.67 (Altrichter 2017; California Soil Resources Lab 2018).

Seepage zones are now recognized as an important path for water and nutrients from the groundwater to the surface (Taniguchi et al. 2007) and are crucial to maintaining ecologically healthy streams (Loheide & Gorelick 2006) and wetlands, more generally.

Figure 2. The source of water to wetland from groundwater discharge at seepage faces and at breaks in slope of the water table (Winter et al. 1998)

Measuring groundwater seepage and direction using conventional method

Darcy's Flow

Measuring groundwater seepage and direction using Darcy's flow is the conventional method, which may be accomplished by installing tensiometers to measure pressure head (usually negative), elevation head and total head. A tensiometer is a small (2 cm) diameter closed tube with a porous tip (ceramic cup) (Fetter 2001). The tensiometer is filled with water, sealed with the septum stopper, and the end with the ceramic cup pushed into the soil. The water level

in the tube is above the water table. As water seeps from the tube to the soil through the porous ceramic cup, the tension inside the tube reaches equilibrium with the soil water. The tensiometer is then used to measure the tension (negative pressure) created inside the tensiometer. The measured hydraulic gradient is used to determine the groundwater flow direction.

Hydraulic variables

Hydraulic gradient

The hydraulic gradient is the difference in total head over a specified distance along a flow path (Fetter 2001). Hydraulic gradient will determine the flow direction with the use of installed pair of tensiometer seated at different depths to hydraulic heads based on an assumed datum, which is often mean sea level.

Hydraulic Conductivity

Hydraulic conductivity, K describes the rate at which water can move through a permeable medium. Hydraulic conductivity is important to understand water flow rate through soils. The characteristics that affect K are the particle size distribution, roughness, tortuosity, porosity, bulk density, shape, and degree of interconnection of water-conducting pores. Measured hydraulic conductivity will give information about the groundwater flow rate to the surface.

Temperature as a groundwater flow indicator

Temperature has been used to trace groundwater movement (Banks et al. 1996; Bravo et al. 2002; Anderson 2005; Loheide & Gorelick 2006; Lowry et al. 2007; Deitchman & Loheide 2009; Pfister et al. 2010; Schuetz & Weiler 2011). Many studies (Anderson 2005; Deitchman & Loheide 2009; Hare et al. 2015; Mundy et al. 2016) have used heat as a groundwater tracer to study the flow system, flow direction, and recharge and discharge, and therefore potentially understand groundwater dynamics. Temperature information offers the possibility to detect the movement of groundwater, and location of discharge, and therefore the spread of groundwater reaching the surface water (Schuetz & Weiler 2011; Hare et al. 2015).

Groundwater seepage zones are often significantly cooler in summer and warmer in winter than the water at the surface (Schuetz & Weiler 2011; Hare et al. 2015). The outflow temperature difference can directly be detected using thermal imaging (Schuetz & Weiler 2011). Therefore, since groundwater seepage has a thermal signature on the surface, it may be used to characterize the seepage at this fen and show how it correlates with using conventional method to characterize seepage.

Thermal Imaging

Thermal imaging detects infrared energy (heat) remotely and converts it into an electronic signal, which is then processed to produce a thermal image, on which you can perform temperature calculations (FLIR 2018). Thermal imaging is the conversion of electromagnetic waves emitted by a body into images (Liang et al. 2012). All matter with a temperature above

absolute zero emits heat. Infrared radiation has a 700 nanometer – 1 millimeter wavelength, 430 terahertz - 300 gigahertz frequency, and 1.24 millielectronvolts - 1.7 electronvolts energy (Liew 2001).

Thermal-infrared imagery has been proven to delineate groundwater seepage (Banks et al. 2006; Loheide & Gorelick 2006; Danielescu et al. 2009; Hare et al. 2015). It has also been identified that groundwater has a thermal signature on the surface water (Banks et al. 2006; Loheide & Gorelick 2006; Danielescu et al. 2009; Hare et al. 2015). All temperature-based models take advantage of the fact that in seasonal climates groundwater has a smaller intra-annual temperature amplitude than surface water (Schuetz & Weiler 2011). Ground-based thermal imagery is a simple, practical tool to discriminate between areas with snow cover, snow melt, water seepage, and stream water (Pfister et al 2010). Distributed temperature sensors (DTS) has been used to detect concurrent spatial variability in discharge and make continuous measurements in time at the groundwater – surface water interface (Lowry et al. 2007). The advantages of DTS compared to point measurement such as forward looking infrared thermal imaging (FLIR), which takes snapshots of temperature in time, is that the DTS takes continuous temperature measurements concurrently in many locations along the length of the cable. This is in contrast to single point measurements made at different times; DTS also can detect concurrent spatial variability in discharge, which may be missed in the point measurements (Lowry et al. 2007).

Thermal imaging has been used to map groundwater discharge, characterize seepage faces, and distinguish between areas of low, moderate, and high groundwater discharge at the

seepage boundary. Thermal image is best captured when there is minimal sun radiation to reduce heat absorption, which minimizes emissivity (Deitchman & Loheide 2009).

Clausing (2007) defined emissivity as the measure of how much less than perfectly a material radiates when compared to a black body. Black body denotes a body which has the property of allowing all incident rays to enter without surface reflection (Planck & Masius 1914). Emissivity can vary with material, surface roughness, wavelength, temperature, camera viewing angle, and surface geometry. Water has an emissivity of around 0.98, indicating a thermal radiation behavior like a black body, which has emissivity of 1.0, and 100% emission (Liang et al. 2012). Incorrect emissivity influences the accuracy of temperature measurement. Emissivity of water, soil, and leaf surfaces differs, which are the major surfaces in the fen-wetland. Reflection of this surfaces from solar radiation will affect the thermal image, hence it is best to collect data when there is less reflection, and no environmental interference (Banks et al. 1996). This explains the reason why thermal imaging is better captured at night, with the earth materials acting more as an ideal black body at that time (zero reflection).

Early and late summer are considered best season for collection of thermal infrared imaging, when the temperature gradient between the surface water and groundwater are the greatest. Field observation are focused on times when solar radiation is minimal or not present (Mundy et al. 2016), but when there is a significant thermal differential between the atmosphere and subsurface (Deitchman & Loheide 2009). Thermal infrared imaging has successfully been the most effective at locating and analyzing seeps when the temperature differential between groundwater and the ambient air temperature is large (Mundy et al. 2016).

Analytical model

Using an analytical solution, Kurylyk et al. (2017) described heat as a groundwater tracer in shallow and deep heterogeneous media and developed a spreadsheet tool for modeling and field applications. This model was used to estimate vertical water fluxes and account for sediment layers and the soil properties. Kurylyk et al. (2017) expands on a previous analytical solution by Shan and Bodvarsson (2004) that was originally used for studying water and heat fluxes in the vadose zone and then applies that solution to investigate using heat as a hydrologic tracer in layered, saturated environments.

Research contribution of this study

This research will contribute to the existing study of using thermal imaging by using thermal imaging in a groundwater-dependent ecosystem. Thermal imaging will be compared with conventional method to determine the effectiveness of thermal imaging in characterizing groundwater seepage. Previous studies have used thermal imaging to map groundwater seepage zones along stream banks (Hare et al. 2015; Brunner et al. 2017), lakes (Deitchman & Loheide 2009), shorelines (Danielescu et al. 2009), and in drainage canals (Deitchman & Loheide 2009). This research will utilize thermal imaging in a groundwater-dependent fen to characterize the seepage. This research will also provide insights on how soil heterogeneity will influence groundwater seepage in a fen.

CHAPTER II

METHOD

Study Site

The fen is located at 47.728, -98.655 coordinates, within the North Dakota National Guard Camp Grafton South (CGS) facility, Eddy County, North Dakota. Camp Grafton South covers 31 km² (Comeskey 1989), but the portion of interest covers about 2.5 km². Comeskey (1989) described the hydrogeology of Camp Grafton South and performed a detailed study of its geomorphology, stratigraphy, and water quality. Camp Grafton South is underlain by glacial drift, which overlies the Cretaceous Pierre Formation (Comeskey 1989).

Hydrological study

The study site overlies the northern portion of the Cherry Lake Aquifer, which discharges groundwater into a 2-3 km zone that forms the fen (Comeskey 1989) (Figure 1). The aquifer has an area of about 60 km² (NDSWC 2016) and is 800 to 1200 meters wide, extending northward from Cherry Lake through the south end of North Washington Lake and through Lake Coe (Trapp 1966; Comeskey 1989) (Figure 3). Comeskey (1989) classified three major aquifer units within the Cherry Lake Aquifer system: a surficial unit, a shallow confined unit, and a deep confined unit. The sediments within the Cherry Lake Aquifer consist of poorly sorted and interbedded clay, sand, shale, till and gravel (Figure 4).

Figure 3. Extent of the Cherry Lake Aquifer showing the study area location. The base map is from the North Dakota State Water Commission Map Service (NDSWC 2018)

The recharge of Cherry Lake Aquifer occurs through closed depressional areas on the McHenry Moraine and discharges into Cherry Lake (Comeskey 1989). The local flow system from the moraine extends toward the dividing lowlands; hydrologic information indicates that most groundwater and surface water flow to the Sheyenne River through the Cherry/Washington chain of lakes (and subunits), and through the Colvin Creek basin (Schuh 1994).

Figure 4. Unconsolidated sediments information obtained from observation and test wells (Appendix A) drilled in Cherry Lake Aquifer (Appendix A.1) (NDSWC 2016). Well 1, the closest boring, lies 600m from Willow site and 800m from the Sedge site (see Figure 1).

Soil classifications

The seep soils at the study site is a complex of several soil series: Vallery - 35%, Hamerly - 25%, Wyndmere - 20%, Arveson - 14%, Balaton - 3% and Seelyeville - 3%, with 2-6 % slopes. The seep soil is poorly drained and has a clay range of 14-26 %, sand range of 38-70%, organic matter of 5-8 % at the depth < 20cm, and saturated hydraulic conductivity, K range of 2×10^{-5} - 8×10^{-6} (NRCS 2013).

Climate of Eddy County

The climate of Eddy County North Dakota is continental, with winters that begin in early November or in October and summers that occur between May and August. Frost usually leaves the soil in mid-April (Schuh 1994). Eddy County has an average temperature of about -15°C in winter, 25°C in summer, and an annual average temperature of 10°C (NOAA 2018). The moisture regime is borderline between semi-arid and sub-humid, with a long-term average precipitation of about 48 cm (Schuh 1994). Groundwater temperature at this site is expected to be approximately 4°C (about 40°F) (USEPA 2018) with the average surface temperature ranging from -18°C to 27°C (U.S. Climate Data 2018).

Field approach

An on-the-ground approach was used to capture thermal images. The coldest temperature reading for each of the images was plotted against the results determined from the conventional method of using field instrumentation and Darcy's law to measure hydraulic gradient and flux.

Onset HOBO pendant temperature data loggers were installed to measure surface water temperatures at all the points in the study area. Eight points in the Willow site and seven points in the Sedge site were distributed across the study area to provide an overview of the subsurface (Figures 5 and 6).

Figure 5. Distribution of the monitoring points at the Willow site. The aerial image is from Flores (2017).

Figure 6. Distribution of the monitoring points at the Sedge monitoring site. The aerial image is from Flores (2017).

Geospatial Analysis

Background. This section describes the application of a geographical information system to characterize the topography and determine the flow direction, based on information for water levels in the Cherry Lake Aquifer and nearby areas. Data used for this included a digital elevation model (DEM), water level elevation, lake and stream data, and soil map. Surface watershed and groundwatershed delineation provide information on the area extent of water contribution and interaction. Geospatial analysis will guide in defining the extent of groundwater seepage from Cherry Lake Aquifer into the wetland.

The data used in this section were sourced from different government agencies (Appendix B). A base map of Cherry Lake Aquifer was obtained from the North Dakota State Water Commission Map Services (NDSWC 2016). Water level data were obtained from the North Dakota State Water Commission groundwater observation and test wells in and around the aquifer location (NDSWC 2018). Lake and stream data were obtained from United States Geological Survey National Hydrography Database (USGS 2018). The soil map was downloaded from National Resources Conservation Service (NRCS 2013) and the 3 m DEM was obtained from the United States Geological Survey via National Map Viewer (USGS 2018). All geospatial data were projected into the UTM Zone 14N NAD 1983 coordinate system for analysis.

Surficial Geology

Information on the soils in the study area was obtained from the Natural Resources Conservation Service's (NRCS) Soil Survey Geographic Database (SSURGO) (NRCS 2013). The spatial soil data were used to define the surficial geology, hydrologic soil groups, and soil classifications. The spatial soil map of the hydrological unit code eight (HUC 8) for the watershed boundary dataset (WBD), which maps the subbasin level, was used to help infer the geology.

Water table/water level estimation

The water level grid and contour lines were mapped using Surfer 12 (Surfer® 2014) (Appendix C). Estimated water table/water level contours were achieved by digitizing the points of water level elevation obtained from observation and test wells (NDSWC 2018). The flow direction of the water was estimated based on the water table readings from observation and test wells. The water level elevations of the waterbodies shown in the National Hydrography Database (USGS 2018) were measured from the digital elevation model (DEM). The direction of groundwater flow was deduced visually based on the assumption that water flows directly down the hydraulic gradient. The 3 m DEM and contour map of the study area and adjacent areas was used to estimate surface elevation and predict areas of possible recharge and discharge.

Watershed delineation

Watersheds and stream channels were delineated using the digital elevation model. The delineations will show the area extent affected by the surface water and the possible source and

flow pattern of groundwater. The watershed was delineated using generalized steps used in GIS, using the seep soils as the outlet polygon (Appendix D), which is the group of raster cells (the seep area) that lie below the watershed from which all water flows into the polygon (ESRI 2017). Similar to using topographic contour lines to define the watershed, the groundwatershed was mapped by drawing lines perpendicular to the contour lines of the water levels that lie above the seep soils.

Conventional Method

Hydraulic gradient

Darcy's law was used to estimate the groundwater flow direction and seepage rate, based on measured hydraulic gradients and hydraulic conductivity.

Instrument setup

Tensiometer pairs were installed at points in the fen (Figures 5 and 6) to solve for the vertical gradient; three hydraulic gradients between points A-B, B-C, and A-C were measured (Figure 7).

Figure 7. Set-up of paired tensiometers to measure hydraulic gradient in-situ, A is the shallow tensiometer, B is the deep tensiometer, and C is the water table.

The hydraulic gradient was determined relative to a local datum elevation at the monitoring site. For convenience to avoid negative hydraulic head values the assumed datum is 30.5 meters (100 feet) below midpoint of the deep tensiometer ceramic cup (A) (Figure 8a).

Figure 8a. Tensiometer used for measuring hydraulic head, (b) Tensimeter measures negative pressure in the tensiometer by passing a hypodermic needle (connected to the transducer in the instrument) through the rubber septum stopper on the tensiometer (Soil Measurement System 2017).

With the tensiometers, the pressure of the water was determined using a tensimeter (Figure 8b) that senses and measures the negative pressure. Tensiometer is a grey plastic pipe connected to a 2 cm diameter ceramic porous cup at the lower end, with a 5 cm section of clear plastic tube at the uppers end (Figure 8a). The tensiometer pipe is pushed gently into the subsurface in the field

so a few centimeters remain above the ground, filled with water to the top, closed with a silicone filled rubber septum stopper, and left for some hours to stabilize. Once the tensiometer is in contact with saturated soil, the pressure inside the tensiometer equilibrates with the pressure in the surrounding saturated soil. The pressure inside the tensiometer pipe, which is in equilibrium with the pressure in the saturated soil was then measured with the tensiometer (Figure 8b). The tensiometer measured pressure in millibar (mb) as water slowly flows into the surrounding from the ceramic cup. The negative pressure reading from the tensiometer was used to estimate the hydraulic heads and hydraulic gradient in the subsurface. The total hydraulic head was solved (that is, elevation head + negative pressure head) at the water table (C), at the deep cup (B), and the shallow cup (A). By definition (Fetter 2001), the pressure head at the water table is 0 and the elevation head is the elevation above the datum. Therefore, the total head at the water table (C) is simply the elevation above the assumed datum (30.5m). The total head at the ceramic cup of the deep tensiometer (B) was solved, knowing that the elevation head equals the assumed datum (30.5 m). The tension head is the tensiometer reading (in meters H₂O) plus height of water within the tube (total length of tube minus length of air space at the top). The result was added to the elevation head, which gave the total head at B. Same calculation was done for tensiometer A, using the tensiometer reading and the height of the column of water within the shallow tensiometer. This gives the total head at A. At this point, three total heads were achieved: at point A, B, and the water table C (Fig. 6). Because groundwater flows from higher head to lower head, then for upwelling groundwater, $h_B > h_A > h_C$.

The hydraulic gradient was then found by taking the difference in head and dividing by the difference in elevation above the datum between A, B, and C, in this case, three hydraulic gradients were estimated using:

$$\frac{(h_C - h_B)}{(Elevation_C - Elevation_B)}, \frac{(h_C - h_A)}{(Elevation_C - Elevation_A)}, \frac{(h_A - h_B)}{(Elevation_A - Elevation_B)} \quad (1)$$

Where the hydraulic gradient is positive (+), the flow is downward; where the gradient is negative (-) then the flow is upward. The calculations and solutions for the gradients are all in Appendix E.

Hydraulic Conductivity

The hydraulic conductivity, K, of the soil was estimated in the field using Bouwer and Rice slug test method (Bouwer & Rice 1976). This in-situ field test method is based on the principle that the rate at which the soil transmits water from a well screen and casing is related to the saturated soil K:

$$K = \frac{r_c^2 \ln(R_e/R)}{2 L_e} \frac{1}{t} \ln \left[\frac{H_0}{H_t} \right] \quad (2)$$

where K is hydraulic conductivity (L/t);

r_c is the radius of the well casing (L);

R is the radius of the well (including gravel envelope) (L);

R_e is the radial distance over which head is dissipated (L);

L_e is the length of the screen (L);

t is the time since $H=H_0$ (t);

H_0 is the drawdown at time $t=0$ (L);

H is the drawdown at time $t=t$ (L), with L representing length and t representing time for units (Bouwer & Rice 1976).

This test estimate application was achieved in the field by installing a partially penetrating hydrometer in the subsurface. The hydrometer was filled with water and the water level measured and timed as it recovered to the static level.

Darcy's flux

The vertical Darcy flux at the monitoring points within the two sites was calculated using the result from the hydraulic gradient and the conductivity analyses. Darcy's flux is the discharge per unit cross sectional area of a porous medium (Fetter 2001). For vertical flux, q is expressed in terms of the hydraulic head applied through a porous medium.

$$q = -K \frac{dh}{dL} \quad (3)$$

where q is the vertical flux in meters per seconds ($L^3/L^2 - t$); K is the hydraulic conductivity in meters per seconds (L/t); dh is change in head between each pair of tensiometer in meters (L); L is the length in meters (L) (Fetter 2001).

The hydraulic gradient and the hydraulic conductivity were substituted into Darcy's law to get the vertical flux at each monitoring point in the field. Vertical flux, q , was then used to correlate with the lowest temperature reading obtained from the thermal image.

Thermal Imaging

Thermal images were captured using a FLIR Systems C2 camera (Figure 9). The FLIR C2 measured surface temperature using a 320×240 focal plane arrays with a spectral range of $7.5 - 14 \mu m$. The camera sensor pixels are heated by the incoming infrared radiation, thereby

changing the pixel resistance. The pixel resistance is measured and calibrated to a temperature value, and the temperature raster is presented as an image. Infrared cameras have several thousand measurement sensors, analogous to a thermometer measuring temperature at every spot. A temperature measurement was made from any of those spots in the infrared image. In a 320×240 focal plane arrays, a 76,800-infrared pixel image with a temperature value at each pixel was achieved. It is a full-featured, pocket-sized thermal camera. The captured thermal images with visible light features was used to identify the hot and cold spots.

Figure 9. Image of the pocket-sized Forward Looking InfraRed FLIR C2 used for on-the-ground thermal imaging (FLIR 2015)

The FLIR C2 was used to capture thermal images at every monitoring point on both sites and the temperature value was plotted against the hydraulic gradient for each of the points. An emissivity value of 0.98 was assumed based on the emissivity value of water (0.98-0.99) vegetation (0.96-0.99), wet soil (0.95-0.98), and dry soil (0.92-0.94) reported in the literature (Deitchman & Loheide 2009).

Thermal Aerial Imagery

The thermal aerial imagery of Sedge site was captured using an Unmanned Aerial Vehicle (UAV) on October 13, 2017 by Dr. Joao Paulo Flores of North Dakota State University's Carrington Research Station. A hexacopter (DJI S900) fitted with a thermal camera (ICI 8640P Series) was flown to collect thermal imagery from the research site. Thermal imagery was collected over only the Sedge site and not the Willow site because of the tree cover and thick vegetation, which prevented the aerial view of the site's ground surface. In addition to the DJI S900 hexacopter, missions were flown with a DJI Phantom 4 Pro quadcopter, which was equipped with a 20.1 mega pixel resolution RGB camera. Prior to each flight, three targets placed in a broad triangle were set out at both research sites in order to validate georeferencing data gathered by the instruments. The thermal aerial imagery was used to visualize the temperature trend on the site and, map cooler areas, which may indicate groundwater seepage. Thermal imagery was also used to map distinct boundaries of vegetation, water boundaries, and the local break-in-slope.

Analytical Model

Computational method

The subsurface was modeled using a one-dimensional analytical method to understand the processes driving the output response of the groundwater seepage from the thermal imagery. The spreadsheet tool (Flux-LM) was developed by Kurylyk et al. (2017) using Microsoft Excel™. The Flux-LM calculates flux through one or more layers. This method analyzed the deviation of subsurface temperature from expected conduction-dominated regime to estimate vertical water fluxes. Temperature data were analyzed to estimate the upwelling Darcy's flux in the fen.

Figure 10. Diagram of an n-layered medium (Kurylyk et al. 2017), parameters are defined in the text.

In a multilayer subsurface (Figure 10) with the layer numbering 1, 2, 3, ..., n starting from the top (layer 1) to the bottom (layer n). Each layer with its own thickness b (m) and bulk thermal conductivity λ ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$) represented in the model. The distance from the top boundary to the bottom of the layer i is denoted as d_i . The governing equation for steady state heat transfer in layer i is written as (Bredehoeft & Papadopoulos 1965);

$$\lambda_i \frac{d^2 T_i}{dz^2} - q C_w \rho_w \frac{dT_i}{dz} = 0 \quad (i = 1, 2, \dots, n) \quad (4)$$

where T_i is the temperature distribution in layer i ($^\circ\text{C}$); z is the vertical distance downwards from the upper boundary of the top layer (m); q is the Darcy flux (m/s, positive downwards) assumed to be constant and uniform through all layers; C_w is the specific heat of water ($4.18 \times 10^3 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$); and ρ_w is the density of water (kg m^{-3}).

The thermal Peclet number (P_e) is a dimensionless number equivalent to the ratio of the advective heat flux to the conductive flux defined as the bulk P_e of the n -layered system;

$$P_e = \frac{q C_w \rho_w (T_o - T_B)}{-\lambda_b (T_B - T_o) / d_n} = q C_w \rho_w \sum_{i=1}^n (b_i / \lambda_i), \quad (5)$$

where the boundary conditions at the top ($z = 0$) and bottom of the domain ($z = d_n$) are specified temperatures equal to T_o and T_B ($^\circ\text{C}$) respectively (Figure 10), λ_b is the bulk thermal conductivity of the n -layered system ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$), which is then calculated as the thickness-weighted harmonic mean of the layer conductivities because the heat flow is perpendicular to the layering. The numerator in the middle expression $q C_w \rho_w (T_o - T_B)$ (Equation 5) is the net advective heat flux into the domain as well as out of the domain. With this automated spreadsheet tool (Flux-

LM), the temperature and layer parameters were inputted to solve the inverse problem, which provided an estimate of the groundwater flux rate. Temperature is solved as a function of:

1. Depth (m)
2. Layer thickness
3. Thermal conductivity of each layer
4. Flux

Flux-LM determined the upper and lower boundary conditions based on the field T-z profile and then calculated the theoretical T-z profile for a given flux. The root mean square error (RMSE, °C) was found between the measured and calculated T-z profiles, which measures how much error is between values calculated by the model and the values measured. The optimal Darcy flux represents the lowest root mean square error (RMSE). The solution includes the thermal Peclet number, found by calculating the absolute value of Equation 5 that quantifies the relative influences of advection and conduction.

The data used in this method were collected in situ using thermistors fixed on a wooden rod 1.2 meters long driven vertically into the wetland sediments. Wooden rod, which insulates heat, was used to avoid heat transport along the rod. The thermistors were tied to the wooden rod using nylon cable ties at 0.4 m intervals. The top thermistor measured the air temperature at 40 cm above the ground surface, the second measured the surface water contact temperature, while the third and the fourth thermistors measured the subsurface temperature. The installation was done on December 3, 2017 with the thermistors set to measure temperature at every 30 minutes until April 11, 2017, when the wooden rods were removed. The temperature profiles were all

installed along a north-to-south transect, two wooden rods at the Willow site and three at the Sedge site. Thermal conductivity of soils varies depending on the method used for calculation and the soil variability. The thermal conductivities information used in this model is uncertain. For the layer parameters, thermal conductivities were assumed to be 3.12, 1.7 and 0.55 W m⁻¹ K⁻¹ for saturated sand, clay and peat, respectively (e.g. Lawrence & Slater 2008). The layer thicknesses for all the model points were kept constant for the whole analytical model; 0.35, 0.4, and 0.45 m for layer 1, layer 2, and layer 3 respectively. Temperature data were downloaded from the thermistors dataloggers and depths measured from intervals marked on the wooden rod. Flux was varied in the model, ranging between -40 m/year (discharge) and 40 m/year (recharge).

Limitations

The governing equation in using analytical model for steady state heat transfer is based on four assumptions (Kurylyk et al. 2017):

- a. The heat transfer is restricted to one dimension;
- b. The Darcy flux is constant and uniform throughout the layers;
- c. The temperature profiles are at steady-state; and
- d. The properties are homogenous within each layer.

CHAPTER III

RESULTS

Geospatial Analysis

Water level elevation estimation

Figure 11. Contour map of the water table/water level within the Cherry Lake Aquifer showing the groundwater capture zone. The units of the contours are in meters. The lake and well water levels shown on the map are from NDSWC (2018).

The water level elevation map of the Cherry Lake Aquifer reveals that the water level or water table elevation decreases westward (Figure 11, note blue arrow), which indicates westward flow of groundwater. The southeastern portion of the aquifer has a higher water level when compared to the northwestern portion of the aquifer. Recharge of the aquifer occurs in the central east part of the aquifer and discharges northward into the fen of interest. Groundwater flow direction confirms Comeskey's (1989) observation that the aquifer recharge occurs through the terminal part of the McHenry Moraine. The water level/water table analyses suggest that the fen receives groundwater seepage from Cherry Lake Aquifer.

Soil Classification of the fen

The seep soils at the study site are mapped as hydrologic group B (Figure 12) (NRCS 2007). Group B has moderate low runoff potential when wet, high porosity and permeability, and unimpeded water transmission with 10-20% clay, 50-90% silty-sand (NRCS 2007). The Willow site has all of its monitoring points on the seep soil, the Sedge site has all of its points on the seep soil except for monitoring points S2, S4, and S6. This information confirms that the soil stratigraphy likely permits the groundwater to seep to the surface. The Willow and Sedge sites form a groundwater discharge zone (seepage area) for the Cherry Lake Aquifer.

Watershed delineation

The topographic watershed of the study area (outlined in Figure 12) covers about 2 square kilometers. The Willow site has about 1.4 square kilometers and the Sedge site has about 0.6 square kilometers. The surface watershed extends southward beyond the distribution of the

seep soils. The groundwatershed is about 3.5 km², and extends southeast from the surface watershed (Figure 11), from the edges of the outlet polygon southeastward.

Figure 12. Hydrologic soil group (NRCS 2007) of the Cherry Lake Aquifer area based on the NRCS classification. The map is sourced from the NRCS (2013).

Conventional method

Hydraulic gradient

Monitoring points at both the Willow and Sedge sites revealed variable gradients (Tables 1 and 2). The plot of the gradient at the shallow tensiometer for all the points in the Willow fen showed upward gradient except for W2 and W3 on July 23, 2017; W4 and W8 on October 28, 2017; and W7 on September 2, 2017 (Figure 13). For the deep tensiometer, W7 and W6 showed upward gradient on September 2 and October 28, 2017 respectively. Gradients at the water table (Figure 13c), for all the monitoring points are upward flow except for W1 on all dates and W6 on October 28, 2017.

The plot of the shallow tensiometer gradients for all the monitoring points at the Sedge fen showed strong upward gradient except for S1 on October 28, 2017 and S2 on July 23, 2017 (Figure 14a). Deep tensiometer gradients for all the monitoring wells are upwards except for S1 on October 28, 2017 (Figure 14b). The water table gradient for all the monitoring points at the Sedge site are all upward flow (Figure 14c). The water table hydraulic gradient defines the seepage interaction at the near surface between the water table and the shallow tensiometer. The shallow hydraulic gradient defines the hydraulic gradient between the shallow and deep tensiometer, whereas the deep hydraulic gradient is between the water table and the deep tensiometer.

A (Shallow cup)	7/23/2017	9/2/2017	9/21/2017	10/28/2017
W1	-0.19	-0.19	-0.34	-2.59
W2	0.20	-0.01	0.03	-0.16
W3	0.37	-0.12	-0.22	-0.61
W4	0.01	0.00	-0.17	0.27
W5	-0.18	-0.05	-0.09	-0.14
W6	-0.06	-0.09	-0.09	-1.26
W7		0.12	-0.01	-0.50
W8		-0.02	-0.19	1.00
B (Deep cup)	7/23/2017	9/2/2017	9/21/2017	10/28/2017
W1	-0.01	-0.01	-0.06	-0.95
W2	-0.01	0.01	-0.01	-0.30
W3	-0.08	-0.14	-0.21	-0.54
W4	-0.06	-0.10	-0.17	-0.49
W5	-0.15	-0.10	-0.22	-0.59
W6	-0.13	-0.15	-0.21	0.33
W7		0.03	-0.08	-0.64
W8		-0.04	-0.16	-0.38
C (Water table)	7/23/2017	9/2/2017	9/21/2017	10/28/2017
W1	0.23	0.23	0.31	1.46
W2	-0.05	0.02	-0.06	-0.49
W3	-0.61	-0.15	-0.20	-0.46
W4	-0.15	-0.23	-0.17	-1.39
W5	-0.12	-0.19	-0.42	-1.19
W6	-0.25	-0.26	-0.46	3.14
W7		-0.01	-0.11	-0.69
W8		-0.06	-0.15	-1.04

Table 1. Gradients at the Willow site for the shallow tensiometer (A), deep tensiometer (B), and the water table (C). The spreadsheet for calculation of hydraulic gradient is attached in Appendix E

Figure 13. Plot of the gradients at the Willow site for the shallow tensiometer (A), deep tensiometer (B), and the water table (C).

A (Shallow cup)	7/23/2017	9/2/2017	9/21/2017	10/28/2017
S1	-0.48	-0.02	-0.54	1.29
S2	0.26	-0.02	-0.07	-0.15
S3	-0.51	-0.46	-0.41	-0.60
S4	-0.43	-0.41	-0.32	-0.55
S5	-0.82	-0.69	-0.50	-0.57
S6		-0.06	-0.17	-0.12
S7		-0.39	-0.39	-0.40
B (Deep cup)	7/23/2017	9/2/2017	9/21/2017	10/28/2017
S1	-0.28	-0.19	-0.44	0.22
S2	-0.11	-0.21	-0.25	-0.33
S3	-0.45	-0.45	-0.55	-0.47
S4	-0.56	-0.54	-0.59	-0.54
S5	-0.51	-0.48	-0.43	-0.56
S6		-0.36	-0.41	-0.35
S7		-0.30	-0.39	-0.46
C (Water table)	7/23/2017	9/2/2017	9/21/2017	10/28/2017
S1	-0.15	-0.32	-0.38	-0.54
S2	-0.36	-0.34	-0.39	-0.45
S3	-0.39	-0.45	-0.72	-0.34
S4	-0.72	-0.70	-0.92	-0.53
S5	-0.20	-0.27	-0.36	-0.55
S6		-0.78	-0.76	-0.70
S7		-0.21	-0.38	-0.52

Table 2. Gradients at the Sedge site for the shallow tensiometer (A), deep tensiometer (B), and the water table (C). The spreadsheet for calculation of hydraulic gradient is attached in Appendix E

Figure 14. Plot of the gradients at the Sedge site for the shallow tensiometer (A), deep tensiometer (B), and the water table (C).

Hydraulic conductivity

The estimated average hydraulic conductivity for the Willow site is somewhat larger than the Sedge site. The hydraulic conductivity, K , ranged from 6×10^{-6} to 2×10^{-4} m/s for both sites (Tables 3 and 4), which falls within values typical for fen sediments (NRCS 2007; Lawrence & Slater 2008).

Willow site	Hydraulic Conductivity (m/s)
W1	1×10^{-4}
W2	9×10^{-5}
W3	2×10^{-4}
W4	2×10^{-4}
W5	1×10^{-4}
W6	9×10^{-5}
W7	8×10^{-5}
W8	6×10^{-5}

Table 3. Hydraulic conductivity at the Willow site monitoring points.

Sedge site	Hydraulic Conductivity (m/s)
S1	2×10^{-5}
S2	7×10^{-5}
S3	9×10^{-5}
S4	1×10^{-4}
S5	3×10^{-5}
S6	4×10^{-5}
S7	6×10^{-6}

Table 4. Hydraulic conductivity at the Sedge site monitoring points.

Darcy's Flux

The hydraulic gradient measured on October 28, 2017 and hydraulic conductivity were substituted into Darcy's law to calculate the groundwater flux for each monitoring point. The positive and negative ($\pm$) sign before the flux shows the direction of flow; downward flow if positive (+) sign, and upward flow if negative (-) sign. The flux calculated for the Willow site ranged from 1.4×10^{-5} to 1.1×10^{-4} meter per second (Table 5) and that of the Sedge site ranged from 4.5×10^{-6} to 1.1×10^{-5} meter per second (Table 6).

Points	Gradient	K (m/s)	Flux (m/s)
W1	-2.59	1×10^{-4}	-2.7×10^{-4}
W2	-0.16	9×10^{-5}	-1.4×10^{-5}
W3	-0.61	2×10^{-4}	-1.2×10^{-4}
W4	0.27	2×10^{-4}	4.9×10^{-5}
W5	-0.14	1×10^{-4}	-2.0×10^{-5}
W6	-1.26	9×10^{-5}	-1.1×10^{-4}
W7	-0.50	8×10^{-5}	-4.0×10^{-5}
W8	1.00	6×10^{-5}	6.2×10^{-5}

Table 5. Groundwater flux at the Willow site calculated from the hydraulic gradient and hydraulic conductivity measured on October 28, 2017. The negative values indicate upward flow and positive values indicate downward flow.

Points	Gradient	K (m/s)	Flux (m/s)
S1	1.29	2×10^{-5}	2.5×10^{-5}
S2	-0.15	7×10^{-5}	-1.1×10^{-5}
S3	-0.60	9×10^{-5}	-5.2×10^{-5}
S4	-0.55	1×10^{-4}	-6.3×10^{-5}
S5	-0.57	3×10^{-5}	-1.8×10^{-5}
S6	-0.12	4×10^{-5}	-4.5×10^{-6}
S7	-0.40	6×10^{-6}	-2.2×10^{-6}

Table 6. Groundwater flux at the Sedge site calculated from the hydraulic gradient and hydraulic conductivity measured on October 28, 2017. The negative values indicate upward flow and positive values indicate downward flow.

Thermal Imaging

Thermal images were captured at the same monitoring points where hydraulic gradient and conductivity were measured. Thermal images show the temperature differences across the ground surface (Figure 15 and Appendix F). The temperature values for the both sites were extracted from the thermal image for each date of data capture (Tables 7 and 8). One of the thermal images captured using the FLIR C2 camera, with temperatures ranging from 17.2 °C to 11.0°C (Figure 15) and a digital visible light image of the surface, is used to illustrate the temperature display on a thermal image. The coldest temperature was used because groundwater temperature is expected to be cooler than the surface temperature at the time when the thermal images were captured (July 1, July 23, September 2, September 21). The warmest temperature was used for December 2, 2017 because groundwater temperature is expected to be warmer than the surface water at that date.

Figure 15. Example of thermal image used to illustrate the use of the camera and the temperature (°C) reading. A one-half square meter constructed ~ 2 cm-diameter of pvc pipe was used to record the scale of the thermal image (Appendix F).

Thermistor data

The temperature reading from the thermistor for 9 am at the Willow site and 10 am at the Sedge site on October 28, 2017 were plotted, which corresponds to approximately the time the hydraulic gradient was measured on-site. With the data collected on October 28, 2017, graphs of temperature versus hydraulic gradient (Figure 16) and temperature versus flux (Figure 17) were plotted for both sites.

Point A	1-Jul-17	23-Jul-17	2-Sep-17	21-Sep-17	2-Dec-17
W1	9.1	13.1	8.1	11.9	6
W2	8.2	9.7	5.1	14.4	-0.3
W3	9.4	11.2	8.2	13.2	-0.3
W4	7.4	15.1	8.9	12.2	10.1
W5	8.2	14.0	8.6	11.5	3.8
W6	9.8	13.2	8.2	12.8	2.9
W7		10.9	9.6	11.7	1.0
W8		12.7	9.2	11.1	1.9

Table 7. Coldest observed temperature (°C) obtained from the thermal images captured at the Willow site. 2-Dec-2017 column shows a record of warmest temperature. (see Appendix F).

Point B	1-Jul-17	23-Jul-17	2-Sep-17	21-Sep-17	2-Dec-17
S1	8.7	20.5	11.0	17.1	1.5
S2	8.1	18.3	9.8	14.9	1.5
S3	10.3	16.2	11.8	19.3	2.3
S4	9.5	20.4	11.6	18.3	5.2
S5	11.2	19.1	13.1	16.9	5.8
S6		17.3	13.3	17.8	6.5
S7		20.3	14.8	15.3	5.8

Table 8. Coldest observed temperature (°C) obtained from the thermal images captured at the Sedge site. 2-Dec-2017 column shows a record of warmest temperature. (see Appendix F).

Figure 16. Plot of the gradient and thermistor temperature value for monitoring locations (Figures 5 and 6).

Figure 17. Plot of the groundwater flux and thermistor temperature value for monitoring locations (Figures 5 and 6).

Drone thermal imagery

The northern portion of the aerial thermal imagery at the Sedge site (Figure 18) shows a distinctive boundary of the mounds that occur at the site, the green areas show seepage, shrubs, and trees, and the break-in-slope is evident just to the south of the monitoring points. The green areas are also possibly cold spots indicating upwelling of colder groundwater to the surface. The groundwater seepage areas seen on the thermal imagery supports seep soil structure, which permits seepage of groundwater to the surface. For every temperature values on the drone thermal imagery within and below the average groundwater temperature of 4°C (USEPA 2018) on this site, indicates groundwater seepage.

Figure 18. Drone thermal imagery of the Sedge site taken on October 13, 2017 (imagery recorded and processed by Flores 2017).

Temperature Profile

On September 21, 2017, a temperature image profile was captured for the Willow site (Figure 20a) and Sedge sites (Figure 20b) using FLIR C2. The interpolated temperature profile line on the aerial thermal imagery at the Sedge site in a South - North direction (Figure 19) was compared with a temperature profile from the FLIR C2 (Figure 20b).

Figure 19. Zoomed in drone thermal imagery of the Sedge site taken on October 13, 2017 (imagery recorded and processed by Flores 2017), with the temperature profile line in South – North direction.

The interpolated temperature profile of the thermal imagery (Figure 20c) showed a similar temperature trend with the temperature profile at the Sedge site, although the images were captured at different dates. The result of both profiles shows that temperature increased down the slope.

Figure 20. Temperature profile from the FLIR C2 for the Willow and Sedge sites, and aerial thermal imagery (the red trendline is a moving average of period 10) temperature profile for the Sedge site.

Flux-LM (Layered Media) Model

Temperature data from the vertically distributed thermistor loggers for December 10, 2017 and April 10, 2018 were analyzed to estimate the Darcy flux in the fen (Willow and Sedge site). Temperature-depth profiles were generated using the collected field temperature readings from the thermistor, and compared to profiles generated from model thermal conductivity (Lawrence & Slater 2008), layer thickness, and Darcy fluxes ranging from 40 m/yr (recharge) to -40 m/yr (discharge). This was done for both the Willow (Figure 21) and Sedge sites (Figure 22).

The best-fit root-mean-square error (RMSE) for Willow site is 0.05 °C and was achieved for Darcy flux of 18.53 m/yr in April 2018, which indicates a Peclet number 2.49 (Table 9). The best fit RMSE for Sedge site is 0.04 °C and was achieved for Darcy flux of 13.14 m/year in December 2017, which indicates a Peclet number of 1.76 (Table 10). The highest RMSE for Willow site is 2.16 °C in December 2017 and 0.85 °C in April 2018 and for the Sedge site is 2.20 °C in December 2017 and 1.35 °C in April 2018.

Spatial and material properties	Value	Unit(s)
Thickness of layer 1 (b_1)	0.35	m
Thickness of layer 2 (b_2)	0.4	m
Thickness of layer 3 (b_3)	0.45	m
Total thickness (d_3)	1.2	m
Thermal conduct. of layer 1 (λ_1)	0.55	$\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$
Thermal conduct. of layer 2 (λ_2)	1.7	$\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$
Thermal conduct. of layer 3 (λ_3)	3.2	$\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$
Heat capacity of water (cwpw)	4182000	$\text{J m}^{-3} \text{ }^\circ\text{C}^{-1}$
Boundary condition		
Top thermal boundary (T_0)	-4.031	$^\circ\text{C}$
Bottom thermal boundary (T_B)	1.221	$^\circ\text{C}$

Table 9. Spatial and material properties and the boundary conditions used for the analytical model, the values are defined in the table and kept constant for both sites.

Figure 21. Comparison of the measured temperature-depth profile from the Willow site (black dashed line) and those calculated with the analytical solution (colored solid lines) q is the optimal Darcy flux. (a) for December 2017, and (b) for April 2018.

Figure 22. Comparison of the measured temperature-depth profile from the Sedge site (black dashed line) and those calculated with the analytical solution (colored solid lines) q is the optimal Darcy flux. (a) for December 2017, and (b) for April 2018.

12/10/2017										
Optimal Darcy flux (m/yr)	-40.00	-30.00	-20.00	-10.00	1.00	8.38	20.00	30.00	40.00	
RMSE (°C)	2.16	2.03	1.77	1.32	0.61	0.19	0.93	1.58	2.11	
Peclet Number	5.37	4.03	2.68	1.34	0.13	1.12	2.68	4.03	5.37	
4/10/2018										
Optimal Darcy flux (m/yr)	-40.00	-30.00	-20.00	-10.00	1.00	10.00	18.53	30.00	40.00	50.00
RMSE (°C)	0.85	0.81	0.73	0.61	0.40	0.20	0.05	0.23	0.38	0.50
Peclet Number	5.37	4.03	2.68	1.34	0.13	1.34	2.49	4.03	5.37	6.71

Table 10. The result of estimating optimal Darcy flux on Flux-LM spreadsheet using the temperature data from the Willow site. The green represents the lowest root mean square error and the red represents the highest root mean square error.

12/10/2017											
Optimal Darcy flux (m/yr)	-40.00	-30.00	-20.00	-10.00	1.00	10.00	13.14	20.00	30.00	40.00	
RMSE (°C)	2.20	2.09	1.86	1.47	0.84	0.22	0.04	0.46	1.04	1.50	
Peclet Number	5.37	4.03	2.68	1.34	0.13	1.34	1.76	2.68	4.03	5.37	
4/10/2018											
Optimal Darcy flux (m/yr)	-40.00	-30.00	-20.00	-10.00	-5.00	1.00	5.84	10.00	20.00	30.00	40.00
RMSE (°C)	1.15	1.07	0.92	0.66	0.48	0.23	0.06	0.20	0.66	1.05	1.36
Peclet Number	5.37	4.03	2.68	1.34	0.67	0.13	0.78	1.34	2.68	4.03	5.37

Table 11. The result of estimating optimal Darcy flux on Flux-LM spreadsheet using the temperature data from the Sedge site. The green represents the lowest root mean square error and the red represents the highest root mean square error.

CHAPTER IV

DISCUSSION

Darcy's flow

Monitoring points at the Willow site revealed variable gradients (Table 1) perhaps related to greater transpiration from surrounding vegetation (Figure 5). Kozlowski (1983) describes the effects of vegetation on transpiration and evaporation. Herbaceous plants have direct responses to saturation (Kozlowski (1983). This information can aid in management of vegetation to maximize the yield of water and water balance study. W1 is installed within a *Salix* thicket, which can be drawing water from the surface to its roots. The willow tree beside W1 behavior suggest that the roots lie below the water table but above the shallow and deep tensiometers. All the gradients measure at the Sedge site (Table 2; Figure 14) have an upward flow except for the shallow (Table 2A; Figure 14A) and deep (Table 2B; Figure 14B) tensiometer gradient for monitoring point S1 in October. The reason for this behavior can be defined more if the stratigraphy is investigated in detail or might be attributed to disturbance to the soil profile. The monitoring points S4 and S6, located about 2 m from the break-in-slope at the Sedge site (Figure 6), show more groundwater seepage, based on the result of the hydraulic gradient (Table 2) than point S3 and S5, which are about 10 m farther from the break-in-slope. A monitoring point in between S2 and S1 would have confirmed the hydraulic gradient trend as shown between S3 and S5. At monitoring point S7, the seepage rate is between -0.39 to -0.40, is greater than the seepage in point S5 ranging between -0.69 to -0.50 by about 60 percent. Groundwater seepage occurs more at the break-in-slope than it occurs northward within the wetland. The conventional method

of characterizing groundwater seepage stands to quantify the rate of flux, and the vertical direction of flow, but it is equipment intensive and disturbs the soil profile, which results from installation of equipment in the field.

Hydraulic conductivity measured at the sites is similar to organic rich sediment (Lawrence & Slater 2008; NRCS 2007). The conventional method measures vertical flux of the location because it is calculated based on depth of the soil distribution than on the spatial payout.

Thermal imaging

Mapping cold spots in summer and warm spots in winter suggested points where groundwater seepage is occurring at this location. Based on the coldest observed temperature from the FLIR C2 at the Sedge site (Table 8), monitoring point S2 showed lower temperature reading than point S1, suggesting more groundwater seepage happening at point S2 than at point S1. Points S3 and S4 showed similar behavior as point S1 and S2 except in July 23, 2017. In general, groundwater temperature is expected to be higher than surface water temperature during winter (USEPA 2018). Point S4 has greater temperature reading than point S3 suggesting groundwater seepage occurring at point S4 during winter (December 2, 2017). The thermal images acquired in this research confirm that temperature can be used to trace groundwater seepage (e.g., Banks et al. 1996; Bravo et al. 2002; Anderson 2005; Loheide & Gorelick 2006; Lowry et al. 2007; Deitchman & Loheide 2009; Pfister et al. 2010; and Schuetz & Weiler 2011). Willow site thermal imaging did not show a similar trend with the hydraulic gradient, suggesting

that shade from vegetation can affect temperature readings. Identifying groundwater seepage depends strongly on the temperature difference between surface water and groundwater. Cold spots in summer indicated upwelling of relatively colder groundwater to the surface to disrupt the surface water temperature, warm spots indicated upwelling of relatively warmer groundwater from the subsurface to the surface to heat-up the cold and frozen surface water temperature in winter.

Aerial thermal imagery (Figure 18) showed wetland surface features: a distinct vegetation boundary, break-in-slope above the fen, and the wetland boundary. Due to poor resolution, however, aerial imagery lacks the details of the temperature change of the environment as would the on-the-ground thermal images (Figure 20). Aerial thermal imagery is helpful in certain conditions, by providing less surface noise, easier calibration, and more convenient image processing (aerial thermal imagery processed by Dr. Joao Paulo of NDSU). Aerial thermal imagery may not be used to characterize or quantify the groundwater seepage in areas with thick and dense vegetation like the Willow site because of shadowing from surrounding vegetation.

The temperature profile from the thermal imagery (Figure 20C) of the Sedge site showed a similar temperature trend with the temperature profile acquired using the FLIR C2 (Figure 20B). The temperature profile acquired on-the-ground eliminates possible environmental noise (topographic feature like the mounds and physical obstructions), which the thermal aerial imagery captured. Applying a moving average with a period 10 (Figure 20C) dampened the noise during processing of the temperature profile trend.

Snapshot in time and surface-skin nature of thermal imaging data limited groundwater seepage detection at the research location. But under the right set of conditions on-the-ground thermal imaging and aerial thermal imagery will detail similar groundwater seepage dynamics (Hare et al. 2015) to data collected in situ from field equipment (conventional method) for the fraction of the effort. Due to the large temperature differential between the groundwater and the surface water based at certain times during seasonal cycles, Deitchman & Loheide (2009) were able to identify seepage of groundwater. Based on result analysis, identification of groundwater seepage using thermal imaging trend does not completely correlate with conventional method. On-the-ground thermal imagery data collection is therefore;

1. Quick
2. Less labor intensive
3. Point-in-time evaluation
4. Influenced by environmental and physical factors
5. Measurements are limited to the surface (skin) temperature of water features

Thus, the application of thermal imaging to map groundwater seepage requires both remote and direct temperature measurement and additional data on soil stratigraphy to fully capture the seepage zone at this site.

Analytical model

The homogenous analytical model yielded a Darcy flux that is incorrect in terms of magnitude and direction (Figures 21 and 22; Tables 10 and 11). Not accounting for layers of distinct thermal conductivity can cause issues when differentiating recharge and discharge zones (Kurylyk et al. 2017). Applying an analytical solution when using heat as a hydrologic tracer is limited if it assumes a homogeneous subsurface. Details of the thermal properties of subsurface layers should be accounted for. Kurylyk et al. 2017's model was used to estimate vertical Darcy flux in the Quashnet River, Massachusetts, USA and in South Australia. The resultant temperature profile model was found to be in general agreement with significant water movement at both locations (Kurylyk et al. 2017). By applying appropriate boundary conditions and layer properties, the analytical model characterized adequately the groundwater seepage at the Willow and Sedge sites. Thus, thermal imaging is a valuable tool but not reliable and of limited use in areas where the soils are heterogeneous. Nevertheless, application of the simple one-dimensional model helps to define the significance of sediment layer properties in characterizing groundwater seepage when using temperature as a groundwater seepage tracer.

CHAPTER V

CONCLUSION AND RECOMMENDATION

Using heat as a groundwater tracer is a valuable and easily applied tool when the temperatures of the surface water contrasts strongly with the temperature of the groundwater. For example, localized groundwater discharge can be detected and quantified in wetland ecology studies. This study aimed at using temperature differential between the surface water and the groundwater in mid-summer and mid-winter to characterize seepage. The information obtained from this research would be used to map out areas in the wetland that are connected with the groundwater.

Thermal imaging is quick, less-labor intensive, and point-in-time evaluation. Thermal imaging is therefore qualitative; indicating zones of groundwater seepage but cannot be used to quantify groundwater seepage at this fen. Conventional method is quantitative and can be used to characterize groundwater seepage at this fen. Thermal imaging can be utilized if the aim of the study is to indicate areas of groundwater seepage at the surface. In the case of using thermal imaging to indicate groundwater seepage, thermal imaging should be captured at night to eliminate all interference from reflection and absorption of heat by materials on the ground surface of the fen.

The seepage zone is an outcome of a recharge zone that occurs over a wide area. The groundwatershed is larger than the surface watershed for the seepage zone by about 1.5 square kilometers. It is therefore important to apply multiple groundwater seepage characterization techniques to increase confidence in the result.

Soil heterogeneity is also a big factor influencing groundwater seepage. Fined-grained layer of soil near surface can prevent seepage from reaching the surface, which can only be measures and quantified using the conventional method. Defining the soil layer properties accurately are significant in characterizing groundwater seepage, especially when using temperature as a groundwater seepage tracer because soil permeability can alter the flow rate of groundwater to the surface. Further research on the layer properties can be obtained by studying the soil stratigraphy within the fen.

Thermal imaging can be of great importance to water resource and environmental managers in mapping and characterizing zones of groundwater seepage to identify areas susceptible to groundwater – surface water quality influence. After this research, further investigation of the water quality is recommended; constant water quality check of all wells directly or indirectly connected to the Cherry Lake Aquifer. Water quality should be monitored at least yearly and water samples taken for quality test. More observation wells should be drilled to have a better representation of the water quality across, and monitored annually. It is also important to investigate if livestock grazing influences groundwater seepage at this location.

APPENDICES

Appendix A (Well 1)

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149-063-13 BAAB1

Data Source	ND State Water Commission	Well Index	5317
County	Eddy	Date Drilled	1987-08-12
Aquifer	Cherry Lake	Purpose	Observation Well
Basin	Devils Lake-Sheyenne River	Casing Type	PVC
MP Elevation (ft)	1500.18	Diameter (in.)	1.25
Surface Elev. (ft)	1498.58	Screened Interval (ft)	96 - 101
Elevation Source (Datum)	Survey 0.01 ft (NAVD88)	Coord (Long,Lat)	-98.66522, 47.730164
Total Depth (ft)	160.00	USGS ID	
Bedrock Depth (ft)	124.00		

Lithologic Log

Interval (ft)	Unit	Description
0 - 3	TOPSOIL	
3 - 7	CLAY	Very silty, soft, plastic
7 - 12	SAND	Fine to coarse, predominantly medium to coarse, subrounded to rounded, predominantly quartz
12 - 13	CLAY	
13 - 14	GRAVEL	Sandy, medium sand to pebbles, predominantly subangular to rounded, limestone and shale granules
14 - 21	CLAY	Silty
21 - 23	SAND	
23 - 25	CLAY	Silty
25 - 26	SAND	
26 - 43	CLAY	Very silty, very sandy, pebbly, soft, slightly crumbly, olive gray (till)
43 - 45	GRAVEL	Rounded, shale pebbles
45 - 96	CLAY	Slightly silty, slightly sandy, very pebbly, firm, waxy (till), rock at 84 ft.
96 - 101	GRAVEL	Very sandy, coarse sand and fine pebbles, predominantly very coarse sand and fine and medium granules; 30% coarse sand to very coarse sand, subangular to rounded, 1/2 quartz, 1/2 shale and limestone, 50% granules, subangular and rounded, limestone and shale, 20% rounded shale pebbles
101 - 124	TILL	As above
124 - 160	SHALE	Nonsilty, poorly to moderately indurated, waxy, dark gray to black, some is very fissile

Well 2

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149-063-25 DBBC1

Data Source	ND State Water Commission	Well Index	5327
County	Eddy	Date Drilled	1987-08-05
Aquifer	Cherry Lake	Purpose	Observation Well
Basin	Devils Lake-Sheyenne River	Casing Type	PVC
MP Elevation (ft)	1537.82	Diameter (in.)	1.25
Surface Elev. (ft)	1535.92	Screened Interval (ft)	263 - 268
Elevation Source (Datum)	Survey 0.1 ft (NAVD88)	Coord (Long,Lat)	-98.66233, 47.692202
Total Depth (ft)	280.00	USGS ID	
Bedrock Depth (ft)	272.00		

Lithologic Log

Interval (ft)	Unit	Description
0 - 3	TOPSOIL	
3 - 8	CLAY	Very silty, very soft, plastic, oxidized, dark yellow-orange (fluvial or lacustrine)
8 - 12	SAND	Very fine to fine
12 - 22	CLAY	Very silty to clayey silt, soft, medium gray mottled with light gray to greenish gray, slightly carbonaceous (fluvial or lacustrine)
22 - 24	SAND	Fine to very coarse, predominantly coarse to very coarse, predominantly quartz
24 - 40	CLAY	Silty, sandy, pebbly, soft, cohesive, plastic (till)
40 - 48	SAND	
48 - 58	GRAVEL	Fine granules to pebbles (1 in. diameter), predominantly rounded shale and limestone, some igneous, fine granules subangular to rounded with pebbles rounded
58 - 81	CLAY	Silty, sandy, pebbly, slightly firm, slightly brittle and crumbly, cohesive, olive gray (till)
81 - 85	GRAVEL	Sandy, very coarse sand to pebbles, 606 subangular to rounded, limestone 30% rounded shale, 10% others; rock at 84 ft.
85 - 97	TILL	As above
97 - 102	CLAY	Silty, sandy, pebbly, dark gray, macerated shale with shale pebbles
102 - 127	SHALE	Medium dark gray, nonsilty, waxy (Pierre Formation); 127 ft, slightly silty
127 - 182	CLAY	Very silty to slightly silty to very fine sand interbedded, shale and lignite gravel; below 140 ft., predominantly very sandy clay; below 180 ft., more interbedded shale gravels
182 - 272	GRAVEL	Very coarse sand to granules-predominantly fine granules, angular to rounded, equal quartz, shale, and limestone interbedded with clay; below 197 ft., more clay and shale pebbles; with equal proportions of igneous, shale, and limestone pebbles; more clay below 229 ft.
272 - 280	SHALE	Dark gray, nonsilty, waxy (Pierre Formation)

[\[Hydrograph\]](#) [\[Water Levels\]](#) [\[Water Chemistry\]](#)

Well 3

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148-063-02 BABC1

Data Source	ND State Water Commission	Well Index	16122
County	Eddy	Date Drilled	1992-09-21
Aquifer	Cherry Lake	Purpose	Observation Well
Basin	Devils Lake-Sheyenne River	Casing Type	PVC
MP Elevation (ft)	1523.22	Diameter (in.)	2.00
Surface Elev. (ft)	1521.22	Screened Interval (ft)	69 - 74
Elevation Source (Datum)	Topographic Map (NAVD88)	Coord (Long,Lat)	-98.665107, 47.671102
Total Depth (ft)	89.00	USGS ID	
Bedrock Depth (ft)	80.00		

Lithologic Log

Interval (ft)	Unit	Description
0 - 4	SAND	very fine to very coarse, topsoil
4 - 11	SAND	very fine to very coarse, predominantly fine and medium, yellow
11 - 12	CLAY	soft, gray
12 - 40	SAND	very fine to very coarse, predominantly fine and medium, predominantly quartz, some carbonates and detrital shale, shield silicates
40 - 74	SAND	as above, interbedded with thin clay layers, one layer at 40 ft
74 - 76	ROCK	pink and white granite
76 - 78	SAND	(bit slipped fast)
78 - 80	SHALE	cobbles
80 - 89	SHALE	(PIERRE), hard, black, angular chips, some sticky clay

[\[Hydrograph\]](#) [\[Water Levels\]](#) [\[Water Chemistry\]](#)

Well 4

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148-063-11 CCB

Data Source	ND State Water Commission	Well Index	5278
County	Eddy	Date Drilled	1964-07-16
Aquifer	Unknown	Purpose	Observation Well
Basin	Devils Lake-Sheyenne River	Casing Type	ABS
MP Elevation (ft)	1514.02	Diameter (in.)	1.25
Surface Elev. (ft)	1512.22	Screened Interval (ft)	30 - 40
Elevation Source (Datum)	Topographic Map (NAVD88)	Coord (Long,Lat)	-98.669756, 47.648007
Total Depth (ft)	84.00	USGS ID	
Bedrock Depth (ft)	70.00		

Lithologic Log

Interval (ft)	Unit	Description
0 - 1	TOPSOIL	Sandy, silt loam, black
1 - 3	SAND	Clayey, light gray, soft, loose, marly
3 - 7	GRAVEL	Fine to medium, sandy, moderately sorted, subangular to subrounded, moderately rusty
7 - 10	CLAY	Silty to sandy with pebbles, olive gray, soft, cohesive, tight, sticky (till)
10 - 20	TILL	As above
20 - 30	SAND	Coarse and very coarse (1/2 to 2 mm), well-sorted, subangular to subrounded, clean, predominantly quartz with shale, limestone, feldspar and other granitic derivatives, and also a few pyrite or marcasite crystals, very good looking sand
30 - 40	SAND	As above
40 - 50	SAND	As above-to-clay, silty to sandy with pebbles, olive gray, moderately soft, cohesive, slightly plastic, quite tight (till)
50 - 60	TILL	As above, occasional rocks and possible small gravel layers
60 - 70	TILL	As above
70 - 84	SHALE	Olive black, hard, fissile, brittle, tight, noncalcareous

[\[Hydrograph\]](#) [\[Water Levels\]](#) [\[Water Chemistry\]](#)

Appendix A.1

Appendix B

Data collection

3-meter Digital Elevation Model

- USGS National Map Viewer: <https://viewer.nationalmap.gov/basic/>

Lakes, Waterbodies, and Streams

- USGS National Map Viewer: <https://viewer.nationalmap.gov/basic/>

North Dakota state and county boundaries

Cherry Lake Aquifer boundary

- North Dakota State Water Commission Mapservice: <http://mapservice.swc.nd.gov/>.

Water level estimation

- North Dakota State Water Commission: Ground/Surface Water Data:
www.swc.nd.gov/info_edu/map_data_resources/groundsurfacewater/

Surficial Geology and soil data

- Natural Resources Conservation Service: Soil Survey Geographic Database (SSURGO):
<http://resources.arcgis.com/en/communities/soils/02ms0000000n000000.htm>.

Appendix C

Water level estimation

The water level contour generalized method by Dr. Phil Gerla, University of North Dakota:

1. Save a map view of the feature you intend to contour.
2. Digitize the waterbody (lakes) elevation gotten from the DEM and water level elevation gotten from observation well to be plotted in Surfer. Download the map view image file into Surfer.
3. Digitize the elevations by selecting on the map image and click on a feature (waterbody or observation well) to insert elevation (Z value). Repeat same step for all the known water level and waterbody elevations. For elevation of lakes, digitize a good number of points along the shore and on the lake to avoid the contour crossing over lakes.
4. Copy all the digitized x-coordinates, y-coordinates and elevation into a spreadsheet and save.
5. Go back to Surfer to grid the data saved in the previous step. Make sure that X and Y coordinates and Z elevation corresponds to the columns A, B, and C in your sheet, leave all the other options as default.
6. Then add the contour layer using the grid file created in step 5 and furnish.

Appendix D

Watershed Delineation method by Dr. Phil Gerla, University of North Dakota

1. Download the 3 m DEM and NHD lakes and streams of the location of interest and its surroundings in a project folder for easy access.
2. Open ArcMap and set your layer projection to UTM Zone 15 N projection, connect to the folder containing all the download data from ArcCatalog.
3. There are often small depressions in the DEM that create little sinks along the drainage channels that need to be filled so that water will be allowed to flow continuously across the DEM. Run the Fill tool from the Spatial Analyst toolbox.
4. Use the output from the previous step for the Flow Direction tool. The output of flow direction gives unique number based on the eight directions (N, S, E, W, NW, NE, SW, SE).
5. Next, run the Flow Accumulation tool using the output file of the flow direction. The output sums the number of cells that flow into a cell. Classify the output numbers by selecting a threshold value to make the high values standout on the map view.
6. Create a pour point within the flow accumulation high values, using a create new point feature from the ArcCatalog. Zoom into the high values and be sure the pour point is sitting on it. Or use the feature of interest at the feature pour point.
7. Run the Watershed tool using the flow direction output and the pour point. If the output of the watershed is not satisfying (absent of channels), you can readjust the pour point and burn channels across the bridges to rerun the watershed tool.

8. Create a buffer around the watershed output with surrounding distance of 300 meters.

You can then determine the area of the surface watershed and the feature contributing and affecting it.

Appendix E

Hydraulic gradient solution spreadsheet

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
July 23, 2017	Tensiometer	Water level -		Top of		measuremen	difference in	Tensiometry			Elevation	Tension head	Total head	Hydraulic
Willow site	(ft)	surface	in feet	tensiometer	in feet	t below	G (ft)	reading (mb)	in ft H2O	in (ft)	head (ft)	(ft)	(ft)	gradient
W1	2.00	4.75	0.40	6.00	0.50	1.50		-22.00	-0.74	A	101.99	1.16	103.15	-0.19
	4.00	5.38	0.45	6.13	0.51	3.49	1.99	-12.00	-0.40	B	100.00	3.54	103.54	-0.01
W2	2.00	7.25	0.60	8.75	0.73	1.27		-16.00	-0.54	A	101.94	1.34	103.28	0.02
	4.00	8.50	0.71	9.44	0.79	3.21	1.94	-20.00	-0.67	B	100.00	3.25	103.25	-0.01
W3	2.00	7.88	0.66	8.50	0.71	1.29		4.00	0.13	A	101.55	2.08	103.63	0.37
	4.00	13.13	1.09	13.94	1.16	2.84	1.55	-26.00	-0.87	B	100.00	3.06	103.06	-0.08
W4	2.00	7.88	0.66	8.50	0.71	1.29		-14.00	-0.47	A	101.66	1.48	103.14	0.01
	4.00	11.75	0.98	12.63	1.05	2.95	1.66	-24.00	-0.80	B	100.00	3.12	103.12	-0.06
W5	2.00	11.75	0.98	12.75	1.06	0.94		-26.00	-0.87	A	101.47	1.05	102.51	-0.18
	4.00	18.13	1.51	19.13	1.59	2.41	1.47	-34.00	-1.14	B	100.00	2.78	102.78	-0.15
W6	2.00	10.38	0.86	11.50	0.96	1.04		-18.00	-0.60	A	101.96	1.30	103.26	-0.06
	4.00	11.00	0.92	12.00	1.00	3.00	1.96	-16.00	-0.54	B	100.00	3.38	103.38	-0.13
W7	3.00	9.75	0.81	10.63	0.89	2.11				C				
	5.00	21.50	1.79	22.44	1.87	3.13	1.02			B				
W8	3.00	8.38	0.70	9.19	0.77	2.23				A				
	5.00	18.63	1.55	19.75	1.65	3.35	1.12			B				
S1	2.00	5.00	0.42	6.50	0.54	1.46		-6.00000	-0.20100	A	100.96	1.67	102.63	-0.48
	4.00	17.00	1.42	19.00	1.58	2.42	0.96	-22.00000	-0.73700	B	100.00	3.10	103.10	-0.28
S2	2.00	7.75	0.65	9.25	0.77	1.23		-6.00000	-0.20100	A	100.85	1.67	102.52	0.26
	4.00	22.00	1.83	23.06	1.92	2.08	0.85	-48.00000	-1.60800	B	100.00	2.30	102.30	-0.11
S3	2.00	7.63	0.64	8.63	0.72	1.28		-4.00000	-0.13400	A	101.24	1.78	103.02	-0.51
	4.00	16.06	1.34	17.81	1.48	2.52	1.24	-6.00000	-0.20100	B	100.00	3.65	103.65	-0.45
S4	2.00	10.00	0.83	11.19	0.93	1.07		-2.00000	-0.06700	A	101.34	1.83	103.18	-0.43
	4.00	17.75	1.48	19.06	1.59	2.41	1.34	-4.00000	-0.13400	B	100.00	3.76	103.76	-0.56
S5	2.00	8.50	0.71	9.63	0.80	1.20		-14.00000	-0.46900	A	101.20	1.44	102.64	-0.82
	4.00	17.88	1.49	19.19	1.60	2.40	1.20	-8.00000	-0.26800	B	100.00	3.62	103.62	-0.51
S6	2.00	11.69	0.97	12.38	1.03	0.97				A				
	5.00	29.88	2.49	30.50	2.54	2.46	1.49			B				
S7	2.00	6.00	0.50	7.00	0.58	1.42				C				
	5.00	26.63	2.22	27.50	2.29	2.71	1.29			B				

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Sept 2, 2017 Willow site	Tensiometer (ft)	Water level - surface water	in feet	Top of tensiometer -	in feet	measurement below surface	difference in G (ft)	Tensiometry reading (mb)	in ft H2O	(ft)	Elevation head (ft)	Tension head (ft)	Total head	Hydraulic gradient
W1	2.00 4.00	4.75 5.25	0.40 0.44	6.00 6.00	0.50 0.50	1.50 3.50		-22.00 -12.00	-0.74 -0.40	A B	103.50 100.00	0.00 3.54	103.50 103.54	0.23 -0.01
W2	2.00 4.00	6.88 8.63	0.57 0.72	8.50 9.50	0.71 0.79	1.29 3.21	1.92	-18.00 -22.00	-0.60 -0.74	A B	101.92 100.00	1.26 3.19	103.18 103.19	-0.01 0.01
W3	2.00 4.00	7.25 12.75	0.60 1.06	8.00 13.38	0.67 1.11	1.33 2.89	1.55	-12.00 -20.00	-0.40 -0.67	A B	101.55 100.00	1.54 3.28	103.09 103.28	-0.12 -0.14
W4	2.00 4.00	8.25 12.25	0.69 1.02	9.00 13.00	0.75 1.08	1.25 2.92	1.67	-12.00 -22.00	-0.40 -0.74	A B	101.67 100.00	1.54 3.20	103.20 103.20	0.00 -0.10
W5	2.00 4.00	11.75 17.50	0.98 1.46	12.75 18.50	1.06 1.54	0.94 2.46	1.52	-24.00 -36.00	-0.80 -1.21	A B	101.52 100.00	1.11 2.71	102.63 102.71	-0.05 -0.10
W6	2.00 4.00	10.50 11.75	0.87 0.98	11.50 12.75	0.96 1.06	1.04 2.94	1.90	-18.00 -16.00	-0.60 -0.54	A B	101.90 100.00	1.31 3.38	103.21 103.38	-0.09 -0.15
W7	3.00 5.00	9.88 22.25	0.82 1.85	10.88 23.63	0.91 1.97	2.09 3.03	0.94	-24.00 -58.00	-0.80 -1.94	A B	100.94 100.00	2.11 2.94	103.05 102.94	0.12 0.03
W8	3.00 5.00	8.75 18.63	0.73 1.55	9.56 20.00	0.80 1.67	2.20 3.33	1.13	-18.00 -42.00	-0.60 -1.41	A B	101.13 100.00	2.33 3.48	103.46 103.48	-0.02 -0.04
Sedge site	Tensiometer (ft)	Water level - surface water	in feet	Top of tensiometer -	in feet	measurement below surface	difference in G (ft)	Tensiometry reading (mb)	in ft H2O		Elevation head (ft)	Tension head (ft)	Total head	Hydraulic gradient
S1	2.00 4.00	6.13 18.38	0.51 1.53	7.50 19.50	0.62 1.62	1.38 2.38	1.00	-2.00 -32.00	-0.07 -1.07	A B	101.00 100.00	1.82 2.83	102.82 102.83	-0.02 -0.19
S2	2.00 4.00	8.19 22.06	0.68 1.84	9.38 23.25	0.78 1.94	1.22 2.06	0.84	-8.00 -42.00	-0.27 -1.41	A B	100.84 100.00	1.63 2.49	102.48 102.49	-0.02 -0.21
S3	2.00 4.00	7.75 15.69	0.65 1.31	8.63 17.00	0.72 1.42	1.28 2.58	1.30	-2.00 -4.00	-0.07 -0.13	A B	101.30 100.00	1.86 3.76	103.16 103.76	-0.46 -0.45
S4	2.00 4.00	10.00 17.50	0.83 1.46	10.88 18.50	0.91 1.54	1.09 2.46	1.37	-2.00 -4.00	-0.07 -0.13	A B	101.37 100.00	1.86 3.78	103.22 103.78	-0.41 -0.54
S5	2.00 4.00	8.75 18.00	0.73 1.50	9.50 19.00	0.79 1.58	1.21 2.42	1.21	-12.00 -10.00	-0.40 -0.34	A B	101.21 100.00	1.54 3.58	102.74 103.58	-0.69 -0.48
S6	2.00 5.00	11.50 30.25	0.96 2.52	12.38 31.50	1.03 2.62	0.97 2.38	1.41	-6.00 -50.00	-0.20 -1.68	A B	101.41 100.00	1.73 3.22	103.13 103.22	-0.06 -0.36
S7	2.00 5.00	6.63 25.25	0.55 2.10	7.50 26.50	0.62 2.21	1.38 2.79	1.42	-8.00 -38.00	-0.27 -1.27	A B	101.42 100.00	1.66 3.61	103.08 103.62	-0.39 -0.30

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Sept 21, 2017 Willow site	Tensiometer (ft)	Water level - surface	in feet	Top of tensiometer	in feet	measuremen t below	difference in G (ft)	Tensiometry reading (mb)	in ft H2O	in (ft)	Elevation head (ft)	Tension head (ft)	Total head (ft)	Hydraulic gradient	Hydraulic conductivity	Flux (cm/s)	flux (m/year)
W1	2.00	4.88	0.41	6.00	0.50	1.50		-26.00	-0.87	A	103.52	0.00	103.52	0.31	0.08	-0.03	-8605.80
	4.00	5.13	0.43	5.75	0.48	3.52	2.02	-6.00	-0.20	B	100.00	3.75	103.75	-0.06			
W2	2.00	7.38	0.61	8.75	0.73	1.27		-16.00	-0.54	A	101.96	1.35	103.31	0.03	0.08	0.00	790.60
	4.00	8.25	0.69	9.25	0.77	3.23	1.96	-20.00	-0.67	B	100.00	3.25	103.25	-0.01			
W3	2.00	9.25	0.77	10.00	0.83	1.17		-16.00	-0.54	A	101.48	1.40	102.88	-0.22	0.08	-0.02	-5627.15
	4.00	15.63	1.30	16.25	1.35	2.65	1.48	-22.00	-0.74	B	100.00	3.21	103.21	-0.21			
W4	2.00	7.50	0.62	8.38	0.70	1.30		-12.00	-0.40	A	101.55	1.52	103.08	-0.17	0.08	-0.01	-4172.32
	4.00	13.00	1.08	13.75	1.15	2.85	1.55	-18.00	-0.60	B	100.00	3.33	103.33	-0.17			
W5	2.00	11.38	0.95	12.25	1.02	0.98		-16.00	-0.54	A	101.52	1.39	102.91	-0.09	0.08	-0.01	-2385.99
	4.00	17.13	1.43	18.00	1.50	2.50	1.52	-26.00	-0.87	B	100.00	3.06	103.06	-0.22			
W6	2.00	11.63	0.97	12.63	1.05	0.95		-16.00	-0.54	A	101.01	1.38	103.39	-0.09	0.08	-0.01	-2380.72
	4.00	11.50	0.96	12.50	1.04	2.96	2.01	-10.00	-0.34	B	100.00	3.58	103.58	-0.21			
W7	3.00	8.50	0.71	9.25	0.77	2.23		-14.00	-0.47	A	100.88	2.47	103.34	-0.01	0.08	0.00	-324.80
	5.00	21.50	1.79	22.75	1.90	3.10	0.88	-46.00	-1.54	B	100.00	3.35	103.35	-0.08			
W8	3.00	8.13	0.68	8.88	0.74	2.26		-10.00	-0.34	A	101.02	2.60	103.62	-0.19	0.08	-0.01	-4676.10
	5.00	19.25	1.60	20.63	1.72	3.28	1.02	-32.00	-1.07	B	100.00	3.81	103.81	-0.16			
Sedge site	Tensiometer (ft)	Water level - surface	in feet	Top of tensiometer	in feet	measuremen t below	difference in G (ft)	Tensiometry reading (mb)	in ft H2O		Elevation head (ft)	Tension head (ft)	Total head (ft)	Hydraulic gradient	Hydraulic conductivity	Flux (cm/s)	
S1	2.00	5.63	0.47	7.00	0.58	1.42		2.00	0.07	A	100.95	1.95	102.90	-0.54	0.03	-0.02	-5530.88
	4.00	18.25	1.52	19.63	1.64	2.36	0.95	-14.00	-0.47	B	100.00	3.42	103.42	-0.44			
S2	2.00	8.13	0.68	9.25	0.77	1.23		-6.00	-0.20	A	100.91	1.71	102.61	-0.07	0.03	0.00	-756.86
	4.00	21.00	1.75	22.38	1.86	2.14	0.91	-36.00	-1.21	B	100.00	2.68	102.68	-0.25			
S3	2.00	10.13	0.84	11.00	0.92	1.08		-2.00	-0.07	A	102.44	0.00	102.44	-0.72			
	4.00	17.63	1.47	18.75	1.56	2.44	1.35	-4.00	-0.13	B	100.00	3.77	103.77	-0.55	0.03	-0.01	-4187.88
S4	2.00	10.13	0.84	11.25	0.94	1.06		4.00	0.13	A	101.30	2.04	103.34	-0.32	0.03	-0.01	-3275.32
	4.00	18.38	1.53	19.63	1.64	2.36	1.30	-4.00	-0.13	B	100.00	3.76	103.76	-0.59			
S5	2.00	10.25	0.85	11.13	0.93	1.07		-14.00	-0.47	A	101.29	1.46	102.75	-0.50	0.03	-0.02	-5046.20
	4.00	18.75	1.56	19.63	1.64	2.36	1.29	-16.00	-0.54	B	100.00	3.39	103.39	-0.43			
S6	2.00	11.75	0.98	12.75	1.06	0.94		-8.00	-0.27	A	101.35	1.65	103.00	-0.17	0.03	-0.01	-1716.96
	5.00	31.38	2.61	32.50	2.71	2.29	1.35	-50.00	-1.68	B	100.00	3.23	103.23	-0.41			
S7	2.00	8.13	0.68	9.00	0.75	1.25		-6.00	-0.20	A	101.42	1.73	103.14	-0.39	0.03	-0.01	-3999.16
	5.00	26.88	2.24	28.00	2.33	2.67	1.42	-36.00	-1.21	B	100.00	3.70	103.70	-0.39			

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Oct 28, 2017 Willow site	Tensionmeter (ft)	surface water (in)	in feet	tensionmeter – surface water	in feet	below surface (ft)	difference in G (ft)	Tensiometry reading (mb)	in ft H2O	in (ft)	Elevation head (ft)	Tension head (ft)	Total head (ft)	Hydraulic gradient
W1	2.00	5.75	0.48	7.00	0.58	1.42		-76.00	-2.55	C	103.50	0.00	103.50	1.46
	4.00	5.31	0.44	6.00	0.50	3.50	2.08	86.00	2.88	A	102.08	-0.65	101.43	-2.59
										B	100.00	6.82	106.82	-0.95
W2	2.00	6.50	0.54	7.50	0.62	1.38		4.00	0.13	C	103.23	0.00	103.23	-0.49
	4.00	8.44	0.70	9.25	0.77	3.23	1.85	8.00	0.27	A	101.85	2.05	103.90	-0.16
										B	100.00	4.20	104.20	-0.30
W3	2.00	5.88	0.49	7.75	0.65	1.35		4.00	0.13	C	102.92	0.00	102.92	-0.46
	4.00	12.50	1.04	13.00	1.08	2.92	1.56	16.00	0.54	A	101.56	1.98	103.54	-0.61
										B	100.00	4.49	104.49	-0.54
W4	2.00	6.75	0.56	7.50	0.62	1.38		40.20	1.35	C	103.02	0.00	103.02	-1.39
	4.00	11.19	0.93	11.75	0.98	3.02	1.65	16.00	0.54	A	101.65	3.28	104.93	0.27
										B	100.00	4.49	104.49	-0.49
W5	2.00	9.75	0.81	10.38	0.86	1.14		16.00	0.54	C	102.66	0.00	102.66	-1.19
	4.00	15.50	1.29	16.13	1.34	2.66	1.52	8.00	0.27	A	101.52	2.48	104.00	-0.14
										B	100.00	4.22	104.22	-0.59
W6	2.00	9.88	0.82	10.75	0.90	1.10		-128.00	-4.29	C	103.05	0.00	103.05	3.14
	4.00	10.50	0.87	11.38	0.95	3.05	1.95	-56.00	-1.88	A	101.95	-2.36	99.59	-1.26
										B	100.00	2.05	102.05	0.33
W7	3.00	7.00	0.58	8.88	0.74	2.26		29.20	0.98	C	103.13	0.00	103.13	-0.69
	5.00	21.50	1.79	22.50	1.87	3.13	0.86	6.00	0.20	A	100.86	3.82	104.69	-0.50
										B	100.00	5.12	105.12	-0.64
W8	3.00	5.38	0.45	6.00	0.50	2.50		64.00	2.14	C	103.69	0.00	103.69	-1.04
	5.00	14.50	1.21	15.75	1.31	3.69	1.19	6.00	0.20	A	101.19	5.09	106.28	1.00
										B	100.00	5.10	105.10	-0.38
Sedge site	Tensionmeter (ft)	Water level - surface water	in feet	Top of tensionmeter –	in feet	measurement below surface	difference in G (ft)	Tensiometry reading (mb)	in ft H2O		Elevation head (ft)	Tension head (ft)	Total head (ft)	Hydraulic gradient
S1	2.00	6.00	0.50	7.00	0.58	1.42		8.00	0.27	C	102.42	0.00	102.42	-0.54
	4.00	17.00	1.42	19.00	1.58	2.42	1.00	-58.00	-1.94	A	101.00	2.18	103.18	1.29
										B	100.00	1.89	101.89	0.22
S2	2.00	8.25	0.69	9.25	0.77	1.23		-4.00	-0.13	C	102.08	0.00	102.08	-0.45
	4.00	21.88	1.82	23.00	1.92	2.08	0.85	-34.00	-1.14	A	100.85	1.78	102.64	-0.15
										B	100.00	2.77	102.77	-0.33
S3	2.00	7.13	0.59	8.00	0.67	1.33		-4.00	-0.13	C	102.61	0.00	102.61	-0.34
	4.00	15.50	1.29	16.63	1.39	2.61	1.28	-2.00	-0.07	A	101.28	1.79	103.07	-0.60
										B	100.00	3.84	103.84	-0.47
S4	2.00	9.00	0.75	10.00	0.83	1.17		-4.00	-0.13	C	102.42	0.00	102.42	-0.53
	4.00	18.00	1.50	19.00	1.58	2.42	1.25	-6.00	-0.20	A	101.25	1.78	103.03	-0.55
										B	100.00	3.72	103.72	-0.54
S5	2.00	9.25	0.77	10.00	0.83	1.17		-4.00	-0.13	C	102.41	0.00	102.41	-0.55
	4.00	18.50	1.54	19.13	1.59	2.41	1.24	-6.00	-0.20	A	101.24	1.80	103.04	-0.57
										B	100.00	3.75	103.75	-0.56
S6	2.00	11.50	0.96	12.13	1.01	0.99		-8.00	-0.27	C	102.42	0.00	102.42	-0.70
	5.00	30.38	2.53	31.00	2.58	2.42	1.43	-50.00	-1.68	A	101.43	1.68	103.11	-0.12
										B	100.00	3.27	103.27	-0.35
S7	2.00	8.50	0.71	9.25	0.77	1.23		-2.00	-0.07	C	102.69	0.00	102.69	-0.52
	5.00	26.75	2.23	27.75	2.31	2.69	1.46	-30.00	-1.01	A	101.46	1.87	103.33	-0.40
										B	100.00	3.91	103.91	-0.46

Appendix F

Thermal images report

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/1/2017 6:57:11 AM

7/1/2017 6:57:11 AM

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/1/2017 6:59:19 AM

7/1/2017 6:59:19 AM

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/1/2017 7:24:25 AM

7/1/2017 7:24:25 AM

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/1/2017 7:35:45 AM

7/1/2017 7:35:45 AM

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/1/2017 7:51:14 AM

7/1/2017 7:51:14 AM

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/1/2017 8:01:02 AM

7/1/2017 8:01:02 AM

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/1/2017 9:15:25 AM

7/1/2017 9:15:25 AM

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/1/2017 9:19:46 AM

7/1/2017 9:19:46 AM

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/1/2017 9:15:25 AM

7/1/2017 9:15:25 AM

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Ref. temp.	20 °C

7/1/2017 9:28:18 AM

7/1/2017 9:28:18 AM

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/1/2017 9:32:43 AM

S4.jpg

FLIR C2

720076538

7/1/2017 9:32:43 AM

S4.jpg

FLIR C2

720076538

Thermal imaging captured July 1, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/1/2017 9:39:58 AM

7/1/2017 9:39:58 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 8:14:00 AM

7/23/2017 8:14:00 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 8:27:02 AM

7/23/2017 8:27:02 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 7:26:53 AM

7/23/2017 7:26:53 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 8:27:02 AM

7/23/2017 8:27:02 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 8:39:01 AM

7/23/2017 8:39:01 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 8:49:33 AM

7/23/2017 8:49:33 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 7:53:44 AM

7/23/2017 7:53:44 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 8:06:22 AM

7/23/2017 8:06:22 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 9:47:32 AM

7/23/2017 9:47:32 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 9:55:29 AM

7/23/2017 9:55:29 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 10:10:45 AM

7/23/2017 10:10:45 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 10:18:19 AM

7/23/2017 10:18:19 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 10:33:40 AM

7/23/2017 10:33:40 AM

Thermal Imaging captured July 23, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

7/23/2017 10:42:39 AM

7/23/2017 10:42:39 AM

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

9/2/2017 7:34:05 AM

9/2/2017 7:34:05 AM

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

9/2/2017 8:02:49 AM

9/2/2017 8:02:49 AM

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

9/2/2017 8:08:20 AM

9/2/2017 8:08:20 AM

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

9/2/2017 7:49:06 AM

9/2/2017 7:49:06 AM

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

9/2/2017 8:50:09 AM

9/2/2017 8:50:09 AM

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

9/2/2017 9:02:09 AM

9/2/2017 9:02:09 AM

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

9/2/2017 9:06:28 AM

9/2/2017 9:06:28 AM

Thermal Imaging captured September 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

12/2/2017 12:21:14 PM

12/2/2017 12:21:14 PM

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

12/2/2017 12:23:58 PM

12/2/2017 12:23:58 PM

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Ref. temp.	20 °C

12/2/2017 12:25:59 PM

12/2/2017 12:25:59 PM

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

12/2/2017 12:27:47 PM

12/2/2017 12:27:47 PM

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

12/2/2017 12:30:40 PM

12/2/2017 12:30:40 PM

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

12/2/2017 1:57:34 PM

12/2/2017 1:57:34 PM

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

12/2/2017 1:59:16 PM

12/2/2017 1:59:16 PM

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

12/2/2017 2:04:14 PM

12/2/2017 2:04:14 PM

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

Thermal Imaging captured December 2, 2017

Parameters

Emissivity	0.95
Refl. temp.	20 °C

12/2/2017 2:05:36 PM

12/2/2017 2:05:36 PM

REFERENCES

- Altrichter, M. K. (2017). North Dakota wetlands: Changes over five years in prairie pothole wetlands and a description of vegetative and soil properties in a North Dakota fen. North Dakota State University of Agriculture and Applied Sciences, 114 p.
- Anderson, M. P. (2005). Heat as a ground water tracer. *Groundwater*, 43(6), 951-968.
doi:10.1111/j.1745-6584.2005.00052.x
- Banks, W. S., Paylor, R. L., & Hughes, W. B. (1996). Using thermal-infrared imagery to delineate ground-water discharge. *Groundwater*, 34(3), 434-443.
- Bouwer, H., & Rice, R. C. (1976). A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. *Water Resources Research*, 12(3), 423-428.
- Bravo, H. R., Jiang, F., & Hunt, R. J. (2002). Using groundwater temperature data to constrain parameter estimation in a groundwater flow model of a wetland system. *Water Resources Research*, 38(8).
- Bredehoeft, J. D., & Papaopulos, I. S. (1965). Rates of vertical groundwater movement estimated from the earth's thermal profile. *Water Resources Research*, 1(2), 325-328.

Brunner, P., Therrien, R., Renard, P., Simmons, C. T., & Hendricks Franssen, H. J. (2017).

Advances in understanding river-groundwater interactions. *Reviews of Geophysics*.

DOI:10.1002/2017RG000556.

California Soil Resources Lab (2018). California Soil Resource Lab, University of California

Davis. Map Unit Composition. Available at:

https://casoilresource.lawr.ucdavis.edu/soil_web/ssurgo.php?action=explain_mapunit&mukey=2576347&ogc_fid=20600545. Accessed 1 July 2018.

Clausing, L. T., (2007). Emissivity: Understanding the difference between apparent and actual

infrared temperatures. Fluke Corporation–Application Note, On line at:

http://support.fluke.com/findsales/Download/Asset/2563251_6251_ENG_B_W. PD F.

Comeskey, A. E. (1989). Hydrogeology of Camp Grafton South Eddy County North Dakota,

North Dakota Ground-Water Studies Number 88, North Dakota State Water Commission,

Bismarck, North Dakota.

Danielescu, S., MacQuarrie, K. T., & Faux, R. N. (2009). The integration of thermal infrared

imaging, discharge measurements and numerical simulation to quantify the relative

contributions of freshwater inflows to small estuaries in Atlantic Canada. *Hydrological Processes*, 23(20), 2847-2859. DOI:10.1002/hyp.7383.

Deitchman, R. S., & Loheide, S. P. (2009). Ground-based thermal imaging of groundwater flow processes at the seepage face. *Geophysical Research Letters*, 36, L14404, doi:10.1029/2009GL038103

ESRI (2017). Environmental Systems Research Institute: ArcGIS for Desktop. Version 10.5.1, <http://www.esri.com/products>. Accessed 8 May 2018

Fetter, C. W. (2001). *Applied Hydrogeology*. Fourth Edition. Prentice Hall Inc. Upper Saddle River, New Jersey, 612 p.

FLIR (2015). FLIR Instruments. Available at: <http://www.flir.com/instruments/c2/>
Accessed 11 March 2017.

FLIR (2018). What is infrared. Available at: www.flir.eu/about/display/?id=41536. Accessed 1 May 2018.

Flores, P.J. (2017). Thermal aerial imagery of a fen in North Dakota using unmanned aerial vehicle (UAV). North Dakota State University Carrington Research Station.

Hare, D. K., Briggs, M. A., Rosenberry, D. O., Boutt, D. F., & Lane, J. W. (2015). A comparison of thermal infrared to fiber-optic distributed temperature sensing for evaluation of groundwater discharge to surface water. *Journal of Hydrology*, 530, 153-166. DOI: <http://dx.DOI.org/10.1016/j.jhydrol.2015.09.059>

Kozlowski, T. T. (1983). Water deficits and plant growth. Department of Forestry University of Wisconsin Madison, Wisconsin. Academic Press, Inc New York Vol. 7, 251 p

Kurylyk, B. L., Irvine, D. J., Carey, S. K., Briggs, M. A., Werkema, D. D., & Bonham, M. (2017). Heat as a groundwater tracer in shallow and deep heterogeneous media: Analytical solution, spreadsheet tool, and field applications. *Hydrological Processes*, 31(14), 2648-2661.

Lawrence, D. M., & Slater, A. G. (2008). Incorporating organic soil into a global climate model. *Climate Dynamics*, 30(2-3), 145-160.

Liang, D., Chen, J. M., Chong, K. J., & McCorkell, C. (2012). Thermal imaging study of temperature fields in shallow flows. *Measurement*, 45(5), 1015-1022.

Liew, S. C. (2001). Electromagnetic waves. Centre for Remote Imaging, Sensing and Processing. Available at: <https://crisp.nus.edu.sg/~research/tutorial/em.htm>. Accessed 1 May 2018.

Loheide, S. P., & Gorelick, S. M. (2006). Quantifying stream– aquifer interactions through the analysis of remotely sensed thermographic profiles and in situ temperature histories. *Environmental Science & Technology*, 40(10), 3336-3341. DOI:10.1021/es0522074.

Lowry, C. S., Walker, J. F., Hunt, R. J., & Anderson, M. P. (2007). Identifying spatial variability of groundwater discharge in a wetland stream using a distributed temperature sensor. *Water Resources Research*, 43, W10408. DOI:1029/2007WR006145.

Mundy, E., Gleeson, T., Roberts, M., Baraer, M., & McKenzie, J. M. (2017). Thermal imagery of groundwater seeps: possibilities and limitations. *Groundwater*, 55(2), 160-170. DOI:10.1111/gwat.12451.

NDSWC, (2016). North Dakota State Water Commission Map Service. [Online] Available at: <http://mapservice.swc.nd.gov/>. Accessed 13 Nov 2016.

NDSWC, (2018). North Dakota State Water Commission: ground/surface water data for Cherry Lake Aquifer in Eddy County. Available at:

www.swc.nd.gov/info_edu/map_data_resources/groundsurfacewater/ Accessed 15 Jan 2018.

NRCS (2007). Natural Resources Conservation Service: Chapter 7 Part 630 Hydrology National Engineering Handbook: Hydrologic Soil Groups. Available at:

<https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17757.wba>. Accessed 28 April 2018

NRCS (2013). Natural Resources Conservation Service: Soil Survey Geographic Database (SSURGO). Available at:

<http://resources.arcgis.com/en/communities/soils/02ms0000000n000000.htm>. Accessed 1 May 2017.

North Dakota Natural Heritage Program (2013). North Dakota comprehensive wildlife strategy: proposed plant species of conservation addendum. North Dakota Natural Heritage Program, North Dakota Parks and Recreation Department, Bismarck, ND, 169 p.

Planck, M., & Masius, M. (1914). The theory of heat radiation. Philadelphia, P. Blakiston's Son & Co. 256 p.

Pfister, L., McDonnell, J. J., Hissler, C., & Hoffmann, L. (2010). Ground-based thermal imagery as a simple, practical tool for mapping saturated area connectivity and dynamics. *Hydrological Processes*, 24(21), 3123-3132. DOI:10.1002/hyp.7840.

Schuetz, T., & Weiler, M. (2011). Quantification of localized groundwater inflow into streams using ground-based infrared thermography. *Geophysical Research Letters*, 38(3). DOI:10.1029/2010GL046198

Schuh, W. M. (1994). Planning, construction, and initial sampling results for a water quality monitoring program: Camp Grafton South military reservation, Eddy County, North Dakota. Water Resource Investigation No. 27, North Dakota State Water Commission, 84 p.

Shan, C., & Bodvarsson, G. (2004). An analytical solution for estimating percolation rate by fitting temperature profiles in the vadose zone. *Journal of Contaminant Hydrology*, 68 (1-2), 83-95.

Soil Measurement System (2017). Soil Measurement System. Available at: <http://www.soilmeasurement.com/tensiometer.html>. Accessed 1 June 2018

Surfer® 12 (2014). From Golden Software, LLC. version 12. Available at:
www.goldensoftware.com. Accessed 8 May 2018

Taniguchi, M., Ishitobi, T., & Kasahara, S. (2007). Infrared measurements to evaluate groundwater discharge in the coastal zone. Remote Sensing for Environmental Monitoring and Change Detection (Proceedings of Symposium HS3007 at IUSS2007, Perugia). IAHS Publ. 316, 2007.

Trapp Jr, H. (1966). Geology and ground water resources of Eddy and Foster Counties, North Dakota; Part II. Ground Water Basic Data: North Dakota Geol. Survey Bull, 44.

USEPA (2016). United States Environmental Protection Agency: Wetland classification and types. Available at: <https://www.epa.gov/wetlands/wetlands-classification-and-types#fens>. Accessed 1 Dec 2016.

USEPA (2018). United States Environmental Protection Agency: Average Shallow Groundwater temperature. Available at:
https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/ex/jne_henrys_map.html.
Accessed 1 Feb 2018.

U.S. Climate data (2018). United States Climate Data; Your Weather Services. Available on:
<https://www.usclimatedata.com/climate/grand-forks/north-dakota/united-states/usnd0476>.
Accessed 1 May 2018

USGS (2018). United States Geological Survey: The National Map (TNM). Available at:
<https://viewer.nationalmap.gov/basic/>. Accessed 3 April 2018.

Winter T.C., Harvey J.W., Franke O.L., Alley W.M. (1998) Ground water and surface water – a single resource. United States Geological Survey Circular 1139, 80 p.