Authors reply to Editor

Topical Editor Decision: Publish subject to minor revisions (review by editor) (25 Feb 2019) by Chris DeBeer

Comments to the Author:

Dear authors,

Thank you for submitting your revised manuscript, for your efforts to address the reviewer comments, and for your additional contributions to the archived dataset. This is an improvement. However, there are a number of edits and corrections still required, as outlined below. I encourage the authors to carry out a careful review of the manuscript, as I had found many errors, but may have missed some.

Specific Comments:

Editors comments	Authors response
Page 1, Abstract: Please remove the CCRN preamble from the abstract (lines 10-16). This is not relevant here and the site predates CCRN.	Done.
Page 1, Abstract: the abstract should be revised to better explain the context and history of the site and the data collection activities here, as well as describing the general characteristics of the dataset.	We have rewritten the abstract to address this point.
Page 1, line 17: What do you mean "for the prairie research site"? This needs to be revised.	NA – abstract revised.
Page 1, line 23: remove the "s" from "positions"	Done
Page 2, line 10: correct the phrase "…to ephemeral ponds that annually dry out annually."	Done
Page 2, line 21: the comment by reviewer #3 about wetland drainage has not been addressed. Was there any drainage before 1968?	We have changed the sentence to read "As far as we are aware, no wetland drainage has occurred on the site, though we cannot be certain about what happened prior to 1968 when the site was established as a National Research Area"
Page 2, line 29: the word "activities" should be added after "research"	Done.
Page 2, 3, Introduction: the introduction section jumps around a lot and needs to be better organized. i.e. paragraphs 2, 4, and 6 deal with the site and its history of research activity, while paragraphs 1,3, and 5 deal with the landscape and physiographic setting.	We have tried to improve the structure of the introduction. We start by introducing the prairies (para 1), then we introduce the site (para 2) then we talk about land use (para 3) and soils/geology (para

	4), then we end with a summary research at the site and the focus of the paper (para 5).
Page 3, line 28: be careful about the term "net solar radiation". Is this correct? I'm not sure, as the CNR4 measures the balance of incoming and outgoing short- and long-wave radiation.	The editor is correct - the CNR4 measures both longwave and shortwave components of radiation. We have deleted "solar".
Page 4, line 9 and Figure 2: Where does the snowfall data come from? There is mention later on of a Geonor installed in 2015, but where is the 2014-17 snowfall data from?	The Geonor was actually installed in 2014, which we have corrected in the text. We have also removed the snowfall data from the plot because it is not part of the published dataset.
Page 4, line 18: Could you add a reference for the ESC snow tube? See https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2015RG000481 for more information.	Done.
Page 5, line 26 and Figure 4: I am not sure it is appropriate to call these hydrographs as the graphs show pond level fluctuations over time. A hydrograph shows discharge rate against time.	Agreed. We changed the caption to "Pond level fluctuations over time in Wetlands 1, 50 and 109"
Page 6, line 22: the "229 probes" reference could be clearer, following a comment by reviewer #3.	A reference to the instruction manual was added.
Page 6, line 26: Fig 5 shows time series of EC. This should refer to Fig. 6.	Changed and checked all other references to figures.
Page 6, line 27: Where is transect 1 in Fig 1? And what is this, the snow survey transect? This should be more clear.	This should actually refer to soil profile 1. We have added numbers to the soil profile markers in Figure 1.
Page 7, lines3-4: the phrase "…comprising a shallow and relatively high permeability weathered till layers…" does not make sense. Is this plural? Then remove "a".	Removed "a" to correct this.
Page 7, line 11: Delete "The" before "Figure 8"	Done.
Page 8, paragraph 2: What is the difference between V-SMOW and V-SMOW2, and SLAP and SLAP2? This could be more clear.	These are different reference waters, and we distinguish them for precision. This is clear in

	the references we provide. See note * below for further details.
Page 9, line 10-11: Why is there a reference to Fig. 9? Should this be to Fig. 2 instead?	Corrected to Figure 2
Page 9, line 23: again, I question whether these should be called hydrographs.	Corrected
Page 10, line 2: why is there a reference to Fig. 4, which shows pond level fluctuations?	This should have referred to Figure 5. It has been changed (and all other references checked for accuracy).
Page 10, line 10: the comment by reviewer #3 was not fully addressed. The correction was to have included the word "fraction" after "saturated water content"	The error was the water "saturated" – i.e. we are referring to the water content at freeze-up. This has been corrected.
Page 11: Acknowledgment: Please acknowledge the efforts of the Canadian Consortium for Lidar Environmental Applications Research (C-CLEAR) team for the lidar acquisition.	Done.
Page 17, Figure 2: you should be more clear what station the data plotted in each panel are from. Is the data in part (d) from a 2 m height?	Air temperature in parts (c) and (d) was measured at 2 m at the mast tower. The rainfall data is from the mast tower and evaporation data from the scaffold tower. The caption has been amended.
Dataset:	
Reviewer #3 had a comment about the headers of the .csv files having non-ASCII characters. Please clarify what was done in response and what changes were made.	The isotope files initially included a per mil symbol, which has been removed and replaced with the word "permil".

* Regarding the difference between V-SMOW and V-SMOW2 and SLAP and SLAP2, the Consultants' Meeting on Stable Isotope Standards and Intercalibration in Hydrology and in Geochemistry recommended that oxygen and hydrogen isotope ratios be normalized on the VSMOW-SLAP scale, where the consensus value for δ^{18}O and δ^{2}H SLAP (V-SMOW: δ^{2}H = 0.0 and δ^{18}O = 0.0) and Standard Light Antarctic Precipitation (SLAP: δ^{2}H = –428.0 ‰ and δ^{18}O = –55.5 ‰). Due to the consumption of the original VSMOW and SLAP reference waters, two replacement reference waters, VSMOW2 and SLAP2, were developed. No significant difference between the original and replacement water δ^{18}O and δ^{2}H values has been detected and therefore VSMOW and SLAP are considered synonymous with VSMOW2 and SLAP2 when referring to the normalization of waters on the VSMOW-SLAP scale.

Meteorological, soil moisture, surface water, and groundwater data from the St. Denis National Wildlife Area, Saskatchewan, Canada

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Abstract. The St. Denis National Wildlife Area is located in the seasonally frozen and semi-arid Canadian prairies, close to Saskatoon, Saskatchewan. The site has a hummocky terrain and is underlain by clay-rich glacial tills. Though the site is only 4 km^2 it contains hundreds of wetlands containing pond which range in size, in permanence (from ephemeral to permanent) and in their interactions with groundwater (recharge and discharge ponds are present). The site was established as a research area in 1968, and has long-term records of hydrological observations, including meteorological, snow, soil moisture, surface water (ponds) and groundwater data. Some records, notably the pond level and chemistry data, span the period 1968 to present. Other datasets, notably water level observations from networks of piezometers, have been collected sporadically at different locations and times. Some datasets are collected manually on an annual basis, including pond surveys and snow surveys. Meteorological data have been collected by automatic weather stations since 1989 and have been maintained and upgraded over time, with a flux tower added to the site in 2011. Automatically logged soil moisture profiles and collocated piezometers have been running since 2013. A Lidar survey from 2005 provides a 1 m resolution digital elevation map (DEM) of the site and surrounding landscape. The compiled data are available at https://doi.org/10.20383/101.0115.

1 Introduction

The Canadian portion of the North American Prairies is bounded to the west by the Rocky Mountains, and the north and east by the Boreal Forest. It contains around 80% of Canada's agricultural area, with an annual crop market value in 2016 of $41 billion (Statistics Canada, 2017). The region is characterized by a semi-arid, seasonally frozen climate, with colder and wetter conditions moving from southwest to northeast. The surficial geology is dominated by glacial till, interspersed with glacio-lacustrine sand and gravel deposits, and the glaciated landscape is generally flat or gently rolling, with thousands of depressions. Due to the low amounts of precipitation, drainage networks are poorly developed, and precipitation excess tends to form lakes and wetlands in surface depressions (Hayashi et al., 2016). Surface water bodies in the depressions have widely

Moved down [1]: Long-term meteorological, soil moisture, surface water and groundwater data provide information on past climate change, most notably information that can be used to ana past changes in precipitation and groundwater availability in a re

Deleted: These data are also valuable to test, calibrate and vali hydrological and climate models. CCRN (Changing Cold Region Network) is a collaborative research network that brought togeth team of over 40 experts from 8 universities and 4 federal governm agencies in Canada for 5 years (2013-18) through the Climate Change and Atmospheric Research (CCAR) initiative of the Natu Sciences and Engineering Research Council of Canada (NSERC) The working group aimed to integrate existing and new data with improved predictive and observational tools to understand, diagn and predict interactions amongst the cryospheric, ecological, hydrological and climatic components of the changing Earth syst at multiple scales, with a geographic focus on the rapidly changin cold interior of Western Canada.

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database includes atmosphere, soil, surface water and groundwat data for the prairie research site. The meteorological measuremen are observed every 5 seconds, and half-hourly mean values (or to values) are logged. Soil moisture data comprises volumetric wate content, soil temperature, electrical conductivity and matric poten for probes installed at depths of 5 cm, 20 cm, 50 cm, 100 cm, 200 and 300 cm in all soil profiles. Additional data on snow surveys, pond and groundwater levels, surface water chemistry and water isotopes collected on an intermittent basis between 1968 and 201 also presented, including information on the dates, ground surfac elevations (in meters above sea level), and geographical positions coordinates used to construct hydraulic heads. The spatial data ta provide the geographical coordinates of piezometers and wetland that are relevant to the interpretation of the records and the

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varying sizes, from large permanent lakes, such as Redberry Lake, Saskatchewan (van der Kamp et al., 2008), to ponds that rarely dry out, to ephemeral ponds that dry out annually. Farming practices over the past century include widespread artificial wetland drainage in some portions of the region (Rashford et al., 2011).

Within this prairie landscape, the St. Denis National Research Area (Figure 1) was established in 1968 by the Canadian Wildlife Service for research on how agricultural practices affect waterfowl production. The site was primarily selected because it was a cultivated land parcel with an abundance of wetlands close to the City of Saskatoon. The St. Denis National Research Area was officially listed in the Canada Gazette with an amendment to the Wildlife Area Regulations in 1978 (SOR/78-466). The St. Denis National Research Area is the only site in the Environment and Climate Change Canada protected areas network to bear the title of "National Research Area", however, the colloquial name of the reserve is St. Denis National Wildlife Area (SDNWA).

At the time of establishment, nearly 60% of the 361.5 hectares in the SDNWA were under cultivation, with the remainder a mix of native grasslands, shrublands, and wetlands. As far as we are aware, no wetland drainage has occurred on the site, though we cannot be certain about what happened prior to 1968 when the site was established as a National Research Area. Lease agreements with local farmers are used to keep the annual cropland in production with wheat, barley, and canola, while the remainder of the vegetation remains undisturbed. In 1977, a program was initiated to convert 97 hectares of cultivated land to a perennial forage mix of smooth brome (*Bromus inermis*) and alfalfa (*Medicago sativa*) (van der Kamp et al.,1999). The program was to minimize erosion on sloping and light textured soils from tillage activities, to provide nesting cover and food for wildlife, and was consistent with land use changes in the surrounding region. There were minor changes in land cover until 2015 when a seeding program began to convert the remaining cropland back to permanent grassland cover.

The SDNWA and surrounding landscape area is hummocky, with local relief of the order of 15m. The area lies within and near the lower end of a 2,400 ha closed watershed for which detailed Lidar elevation data are available. Aspen bluffs occupy some of the larger depressions in the drainage basin. Soils are predominantly Dark Brown Chernozems and Orthic Regosols; both developed from glacial till (Miller et al., 1985). The glacial stratigraphy of the site is well-documented: roughly one hundred meters of clay-rich glacial till of low permeability lies under the soils, interspersed with isolated sand lenses and a continuous thin layer of sand at about 25 to 30 m depth (Hayashi et al., 1998).

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The SDNWA is a site that is unrivaled in the Canadian Prairies for the length and breadth of hydrological observations (Pennock et al., 2013, provide a good summary of the site and the research history). Over the past 50 years, field research has been undertaken at SD NWA by hydrologists, hydrogeologists, biologists, ecologists,
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Over the past 50 years, field research has been undertaken at SD NWA by hydrologists, hydrogeologists, biologists, ecologists, soil scientists and others, and there have been more than 100 papers published on this site. Many of these studies were based on short-term field experiments, which have produced snapshots of data in time. Here, we focus on the continuous monitoring program, which is ongoing and is the foundation of much of the short-term research. The longest records are of pond levels and chemistry, dating back to 1968. Soil and groundwater observations have been recorded continuously since 2013 (before this there are large amounts of groundwater data, but those observations are not continuous to present).

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Figure 1: Map and location of St. Denis National Wildlife Area. The grey area on the inset map represents the extent of Prairie Pothole Region in North America.

2 Meteorological data

There are two climate stations at the St. Denis National Wildlife Area. The older, a 10 m mast tower, is at an elevation of 554 masl at 52.2037°N 106.1067°W located on the upland south of Pond 50 surrounded by brome-alfalfa grassland (Figure 1). This station was initially deployed in the spring of 1989 as part of the Wetlands Ecosystem Vulnerability Study (WEVS). It was initially used to evaluate the water budgets of prairie wetlands, particularly Pond 50 (Woo and Rowsell, 1993). From 1991 to 1998 operation of the station was transferred to the Meteorological Service of Canada. In 1998, the equipment was transferred to the Canadian Wildlife Service (CWS), for continuing use as a WEVS facility. Reorganization of the CWS in 2006 prompted responsibility of the tower to be transferred to the Water Directorate of the Science and Technology Branch of Environment and Climate Change Canada. These transfers sometimes resulted in substantial breaks in the period of record. In 2011, a second climate tower was constructed that was capable of supporting eddy covariance equipment for measuring turbulent energy and carbon fluxes and all component net radiation. This is a 10 m scaffolding tower located at 52.2089°N 106.0889°W at a local high point in a field currently supporting dense nesting cover (Figure 1). The specifics of each tower, including variables and units and sensor types and heights, are summarized in Table 1. Three-dimensional wind speeds, air temperature, water vapour content, and carbon dioxide density are measured at 10 Hz with turbulent fluxes calculated over a half hour period on the Campbell Scientific CR3000 logger. The turbulent flux data within these records is uncorrected and should be treated with caution. All meteorological data are observed every 5 seconds, and half-hourly averages (or totals) are currently logged on Campbell Scientific CR1000 (mast tower) and CR3000 (scaffolding tower) data loggers. Rainfall data, measured with Texas Electronics TE525M tipping bucket rain gauges, are reported as the hourly or half-hourly totals. It is important to note that while the tipping bucket rain gauges are in operation all year and may record precipitation during the winter months, they only supply reliable measurements of liquid precipitation when not accompanied by freezing or frozen precipitation. Figure 2 shows the record of yearly rainfall (which may be significantly less than total precipitation) and air temperature at the site.

Figure 2: Meteorological data from SDNWA: a) the total annual rainfall for the period of record (1991-2017) measured at the mast tower; b) cumulative total rainfall (mast tower) and evaporation (scaffold tower) for the 2016-2017 hydrologic year; c) mean monthly air temperature at 2 m (mast tower) for the period of record (1991-2017); and d) daily air temperature at 2 m (mast tower) for the 2016-2017 hydrologic year.

3 Snow surveys

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Snow surveys have been conducted at SDNWA by Environment and Climate Change Canada (ECCC) since 1994. Snow depths and densities are measured along three transects (Figure 1) and converted to snow water equivalent (SWE) and then generalized over the whole site (Figure 3). The snow surveys are performed once each year in March to estimate the SWE on the ground before snowmelt begins. One of the snow surveys consists of two perpendicular transects that cross in the centre of Pond 109. Each transect is approximately 250 m. Snow depth is measured at every 5 to 10 m. At every fifth depth measurement, a density sample is collected using an Eastern Snow Conference snow tube (ESC-30, Goodison et al., 1987). This survey measures snow accumulation in the grass, wetland vegetation, trees, and an ice-covered pond. The other snow survey is a 700 m transect that runs east to west through cropped and grass fields across the western portion of the SDNWA. Snow depths are measured every 15 - 20 m and density samples are taken every fifth depth measurement. SWE values are calculated for each point and then averaged to calculate mean SWE for each land cover. The average SWE over the entire SDNWA is estimated by calculating a weighted mean by a land cover fraction of the total area.

Figure 3. Weighted mean of snow water equivalent (SWE) of snowpack before melt over SDNWA. The blue line represents the 24-year mean of snow accumulation.

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4 Pond water level, chemistry and bathymetry data

At the St. Denis National Wildlife Area pond water depths in wetlands have been monitored since 1968. These wetlands generally have areas between 0.1 and 10 hectares and contain ponds that range in class from vernal to ephemeral to permanent. SDNWA wetlands were initially mapped based on aerial photography (Hogan and Conly, 2002) and numbered. The major wetlands were numbered 1 to 147 and smaller wetlands adjacent or adjoined to the larger depressions were sub-labeled with letters a, b, c, and d.

The record of pond depth measurements dates from 1968 to 2017 and includes measurements from 135 ponds. Canadian Wildlife Service staff began monitoring 76 of the SDNWA wetlands in 1968; an additional 57 started being monitoring after 2011. The frequency of measurement varies annually and among wetlands. Monitoring typically begins in spring and extends through to the fall. Measurements are not conducted during the winter because many ponds will freeze to the sediment and because snow and ice accumulation on ponds influence water depth under ice. There are some wetlands with data available for every year from 1968 to the present (Pond 25, Pond 50, Pond 65, Pond 90, Pond 109, and Pond 120). Many were dry during the drought of 1999-2002. In 2015, a long-term monitoring plan was developed jointly with researchers from the University of Saskatchewan and ECCC to monitor pond depths, stable isotopes and water quality of 25 wetlands once each in May, July, and October.

The methodology for collecting pond depth data is described in Conly et al. (2004). The lowest bottom elevation in the wetland depression is used as the relative datum and the geodetic elevations of these points have been determined for many of the wetlands. Measurements are made by wading into the pond and using a measuring rod to measure water depth at monitoring markers (usually a metal T-bar installed deep into pond sediments to prevent heaving or movement). The measuring rod is attached to a 6-cm diameter circular base to prevent the rod from being pushed into the sediment. Shallow seasonal and ephemeral ponds require only a single marker. Deeper ponds that vary considerably in flooded area and depth have multiple markers installed at various elevations to ensure a measurement can be made when markers installed at lower elevations are flooded. Depth measurements are taken at the same time at multiple markers to ensure markers are tied to the local datum. Point measurements at single markers (in smaller wetlands) are generally within 25 mm of those measured with conventional survey equipment and benchmarks. The accuracy in larger wetlands is considered to be within 50 mm (Conly et al., 2004). The year-to-year and seasonal variations in pond water levels are apparent from the long-term record (Figure 4).

Figure 4: Pond level fluctuations over time in, Wetlands 1, 50 and 109.

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Water chemistry of ponds and groundwater have been measured in a number of studies at St Denis National Wildlife Area (e.g., Hayashi et al., 1998; Berthold et al., 2004; Waiser 2006; Heagle et al., 2007, 2013; Pennock et al., 2010, 2013). The record consists of measurements of individual ions and overall solute load measures, i.e., electrical conductivity (*EC*, Figure 5) and total dissolved solids (*TDS*). The details of the equipment and methods are described in Hayashi et al. (1998), Berthold et al. (2004), Waiser (2006), Heagle et al. (2007& 2013) and Pennock et al. (2010).

Figure 5: Time series of pond water electrical conductivity (log scale) at St. Denis showing multi-year variations in pond water chemistry.

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Detailed elevation surveys were carried out in 1994, 1998, 1999, 2008, and 2009 on twenty-six wetlands depressions using electronic total stations within the St. Denis NWA. The catchment extent of the wetlands and depressions, vegetation, soil, and the hydroperiods of ponds in the respective wetlands are published in Hayashi and van der Kamp (2000) and Minke et al. (2010). Survey points were spaced horizontally at 10–15 m intervals in the uplands, 5–10 m intervals in the wetlands, and 2–5 m intervals in small depressions. The estimated measurement error is within a few centimeters for elevation and within a few tens of centimeters for horizontal location (Hayashi and van der Kamp, 2000; Minke et al., 2010). The water depth data for these wetlands (Figure 4) can be presented as water surface elevation for comparison with groundwater levels.

5 Soil moisture data

There are four soil moisture profiles at SDNWA where continuous observations of water content, matric potential, temperature, and electrical conductivity have been made since July 2013. Three of these profiles are located along a lowland transect between ephemeral ponds (107 and 108a) adjacent to Pond 109 and one profile is located towards the top of a hillslope east of Pond 1 (Figure 1). In each case, piezometers are collocated with the soil moisture profiles, as described below.

Hydra Probe sensors (Hydra II, Stevens Water Monitoring Systems Inc, 2007) are impedance sensors that simultaneously measure soil volumetric water content, soil temperature, and electrical conductivity. The probes were installed at depths of 5 cm, 20 cm, 50 cm, 100 cm, 200 cm and 300 cm in all soil profiles. During soil freezing the dielectric constant of ice is much lower than that of liquid water, so the instrument is likely to give a reasonable measure of the liquid water content (Spaans and Baker, 1995). The soil matric potential is measured using the heat dissipation sensors (229 probes, Campbell Scientific Inc. 2009) at depths of 5 cm, 20 cm, 50 cm, and 100 cm. The heat dissipation sensor is a porous block sensor which measures the pressure of dry soil and has a working range of -10 kPa to -2500 kPa. Tensiometers (T4e, Decagon Devices) are used to measure the pressure of wet soil at the depths of 100 cm, 200 cm, and 300 cm. The working range of the tensiometer is +100 kPa to -85 kPa. The soil freezing temperature and moisture content for three profiles at 20 cm near Pond 109 is shown in Figure 6(a-b). Figure 7 shows the observed soil water content and soil freezing characteristic of profile 1 (Figure 1) at 5 cm and 20 cm depths at St. Denis.

Figure 6: Soil freezing depth for three profiles near Pond 109.

Figure 7: Observed soil water content and soil freezing characteristic of profile 1 at 5 cm and 20 cm depths at St. Denis.

6 Groundwater level data

The hydrogeology of St. Denis is reasonably complex, comprising shallow and relatively high permeability weathered till layers overlying unweathered till aquitards and coarse-grained inter-till confined aquifers. A large number of piezometers were installed in all three of these units, mostly for individual short-term projects, and as a result most of the data are discontinuous. These data are none-the-less available and provide useful insights into the spatially and temporally variable interactions between groundwater and surface water bodies. Continuous monitoring of the water table started in 2013 at a piezometer near Pond 109 collocated with the soil moisture transects. Two piezometers were installed in a confined aquifer and instrumented in November 2013. These are the deepest piezometers on the site (39 and 41 m below ground level). Unvented Solinst Leveloggers are used to monitor water levels, corrected for changes in barometric pressure with a Solinst BaroLogger placed at the scaffolding climate tower. Figure 8 shows ground and surface water levels at SDNWA for 2014 to 2016.

Figure 8: Groundwater and surface water levels in St. Denis.

7 Water isotope data

Stable isotopes of water (δ^{18}O and δ^{2}H) have been measured sporadically for some of the ponds at St. Denis since 1993. These data are complemented by campaign-based samples of rainfall, snow (mainly in the period 2013-2014) and groundwater (sporadic measurements between 1993 and 2014, and covering depths between 1.2 – 41 m below ground level). Furthermore, continuous snow and rainfall samples from Saskatoon, 35 km away, are available for the period 1993 to 2014. Isotope ratios of δ^{2}H and δ^{18}O of all samples were measured at the National Hydrology Research Centre in Saskatoon, Canada. The sampling and analysis methodology is described in detail in Lis et al. (2008). Isotope ratios of tritium were measured at the Rafter Radiocarbon Laboratory, National Isotope Centre, GNS Science in New Zealand. The stable isotope ratios of water were analyzed using three instruments: Micromass Optima continuous flow mass spectrometer, Micromass IsoPrime dual inlet/continuous flow mass spectrometers, and off-axis integrated cavity output spectroscopy (OA-ICOS) laser.

Between 1993 and 2007, the precipitation, ponds, and groundwater samples were analyzed for δ^{2}H and δ^{18}O using the isotope-ratio mass spectrometers (IRMS). The protocols for the isotope-ratio mass spectrometer analysis follow the standard methods

(Begley and Scrimgeour, 1997; Coleman et al., 1982; Eiler and Kitchen, 2001; Epstein and Mayeda, 1953; Karhu, 1997; Kelly et al., 2001; Socki, 1999). The $^{18}O/^{16}O$ ratio in the water samples were analyzed by the equilibration of water samples with CO_2 gas at 25 ± 0.1 ˚C for 24 h to produce CO_2 gas (Epstein and Mayeda, 1953). After the equilibration, the CO_2 gas was extracted and purified through a vacuum cryogenic line. The $^2H/^1H$ ratio was analyzed by the production of hydrogen gas using Cr at 850 ˚C (Coleman et al., 1982). The $^{18}O/^{16}O$ and $^2H/^1H$ ratios were measured against the internal standards which were calibrated using Vienna-Standard Mean Ocean Water (V-SMOW: δ^2H = 0.0 and $\delta^{18}O$ = 0.0) and Standard Light Antarctic Precipitation (SLAP: δ^2H = –428.0 ‰ and $\delta^{18}O$ = –55.5 ‰). The results were normalized to the VSMOW-SLAP scale and reported in the delta notation as decribed in Coplen (1988). The analytical reproducibility is ± 0.1 ‰ and ±1.0 ‰ for $\delta^{18}O$ and δ^2H. Both offline dual-inlet (i.e., zinc reduction or uranium reduction) and continuous flow IRMS methods (i.e., Cr reduction or C) have measurement accuracies of the order of (± 0.5 to ± 4 ‰) for δ^2H and the automated CF-IRMS methods, such as C-reduction to CO and CO_2-H_2O equilibration, are between ± 0.1 and ± 0.4 ‰ for $\delta^{18}O$ (Lis et al., 2008).

A Los Gatos Research DLT-100 liquid water isotope analyzer system coupled with a CTC LC-PAL liquid autosampler (Los Gatos Inc., California) was employed in stable isotope analyses done between 2008 and 2018. The analysis follows the methods described in Lis et al. (2008) and IAEA manual (2009). Laboratory standards (INV1: δ^2H = -220.0 ‰, $\delta^{18}O$ = -28.5 ‰ and ROD3: δ^2H = -8.0 ‰, $\delta^{18}O$ = -1.2 ‰) were calibrated with Vienna-Standard Mean Ocean Water (V-SMOW2) and Standard Light Antarctic Precipitation (SLAP2) reference waters. INV1 and ROD3 were used to normalize the results to the VSMOW2-SLAP2 scale by assigning $\delta^{18}O$ and δ^2H values of -55.5 ‰ and -427.5 ‰, respectively, to the SLAP2 reference water. Consequently, all measured values reported are relative to VSMOW/SLAP δ scale. Samples, standards and control samples (river water) were analyzed repeatedly six times. The laboratory precision was ±1.0 ‰ for δ^2H and ± 0.2 ‰ for $\delta^{18}O$.

Tritium samples (^3H) samples were shipped to Rafter Radiocarbon Laboratory, National Isotope Centre, GNS Science in New Zealand for ultra-low-level tritium counting using electrolytic enrichment and liquid scintillation counting (LSC). The ^3H concentrations are expressed in tritium units (TU); the precision at an average tritium concentration of New Zealand rain of 4 TU is ± 0.06 TU (98.5 %), and the detection limit is ±0.025 TU (Morgenstern and Taylor, 2009). Details of the analytical procedure are provided in Morgenstern and Taylor (2009). A summary of the stable isotope data is shown in Figure 9.

Figure 9: A scatter plot of δ^2H versus $\delta^{18}O$ at St. Denis, Saskatchewan.

8 Spatial data

Elevation data of the SDNWA and surrounding area were collected during a Light Detection and Ranging (Lidar) survey conducted by the Canadian Consortium for Lidar Environmental Applications Research (C-CLEAR) on 9 August 2005. The exact methods of the Lidar data survey and processing of the digital elevation model (DEM) are described in Toyra et al. (2008). The generated DEM is provided in UTM Zone 13 NAD83 and the elevations are orthometric heights based on the CGG05 geoid model. The elevations are tied to a local benchmark near Pond 1. The ground data points were interpolated into a 1 m DEM using the Inverse Distance Weighted (IDW) algorithm. The Lidar DEM was evaluated based on in situ survey data (GPS points and total station surveys). The results indicate that the accuracy of Lidar DEM in the agricultural fields or grasses is 0.13m, while the accuracy in the shrubs and trees surrounding the wetland ponds is 0.17m.

9 Overview of content

The record from both climate towers shows strong seasonality of incoming radiation and turbulent fluxes at the SDNWA. Maximum incoming solar radiation (typically ~ 350 Wm^{-2}) occurs in June near the summer solstice. Conversely, minimum solar radiation of 10 W m^{-2} is in December. There is very little seasonal lag between incoming solar radiation and net radiation, which ranges from 200 W m^{-2} to -30 Wm^{-2} between June and December. The record does include several spikes in the radiation and turbulent flux data that should be removed prior to any analysis. The mean of hourly wind speed over the period of record (1992 - 2018) is 3.8 ms^{-1}. The period of record includes half-hourly mean wind speeds as high as 16.9 ms^{-1}. Daily maximum air temperatures often reach +27 °C in July and can be well below -30 °C anytime between November and February (Figure 2). These cold air temperatures are also associated with dry air with relative humidity often less than 50% in late winter. The measurements of relative humidity were some of those that suffered from the changing agencies responsible for the towers. The near 30-year length of the record provides an excellent perspective on the cycles of rainfall in the central Canadian Prairie. The record drought from 1999-2002 (van der Kamp and Hayashi, 2009) during which annual rainfall averaged 20 mm is well documented and is in stark contrast to a recent wet period (Dumanski et al., 2015) when annual rainfall averaged 330 mm from 2005-2013. A recent addition to the towers was a Geonor total precipitation gauge in 2014, but the record is too short to allow for a description of the entire precipitation regime at the site.

The mean maximum spring SWE as measured during the March snow surveys was 62 mm throughout the recorded period (1994-2017). There was a sustained period of lower than average SWE from 1998 to 2003, followed by an above-average period from 2004-2009. The spring snowpack in 2013 was 120 mm and the largest in the 24-year period.

The water level variations in wetlands 1, 50 and 109 follow a distinct annual cycle that has a peak in pond level at the end of the snowmelt period followed by a gradual decline during summer months. Wetland 109 contains a seasonal pond that dries out completely in some summers; may carry water over between years during wetter periods and has reached spill elevation occasionally in recent wet years. The larger wetlands, 1 and 50, have permanent and semi-permanent ponds, respectively. Wetland 1 receives inflow in most years from a roughly 1000 ha watershed and spills to lower-lying ponds in most years, while Wetland 50 has never spilled during the period of record.

Wetland pond chemistry in the prairies is controlled primarily by water balance components of evaporation, plant transpiration and groundwater discharge. The long-term fluctuations in the chemistry of wetland ponds are caused by multi-year, wet-dry cycles associated with meteorological forcing and land-use in the region (Cressey et al., 2016; Goldhaber et al., 2016, 2014; LaBaugh et al., 2016, Nachshon et al., 2014). During extreme wet conditions groundwater discharge and surface runoff of salts from an upland area into freshwater ponds results in freshwater ponds becoming salinized (e.g., Pond 109 and 120, Figure 5). In addition to these water balance controls, geochemical and biochemical interactions within a wetland pond and underlying wetland soils also add or remove solutes from the wetland pond water (Heagle et al., 2007; LaBaugh et al., 2016; Pennock et al., 2014). Inadequate knowledge of the climate history and land use change around a particular pond could lead to a misinterpretation of the pond's hydrological function by short-term observations of pond chemistry.

The maximum frost table depth is ~1.2 m and corresponds with cold surface air temperature and low snowpack accumulation (Hayashi et al., 2003). The frost table depth is affected by antecedent soil water content during fall before the freeze (Pan et al., 2017). The saturated water content at freeze-up is usually 0.5 with a high residual of liquid water content during frozen conditions. The variation in the water content values in different years might be attributed to heterogeneity and hydrological variation within the study area.

The stable water isotope compositions of precipitation, snowmelt, groundwater and surface water (ponds) are similar to isotope values of water taken from surface ponds and glacial deposits throughout southern Saskatchewan and central Canada (Fortin et al., 1991; Fritz et al., 1987; Jasechko et al., 2014, 2017; Kelley & Holmden, 2001). The data show distinct differences between the different sources. The precipitation data from SDNWA fall on the Saskatoon local meteoric water line (LMWL), but show distinct seasonal variability with winter measurements (snow) more depleted than summer rainfall. The pond water isotopes show evaporation like many surface waters. The shallow groundwater data are relatively similar to the pond data, but subject to less evaporation. The intertill aquifer data is biased towards the snow end of the spectrum of precipitation.

10 Data availability

The SDNWA dataset is stored at the Federated Research Data Repository (FRDR) and can be accessed from the FRDR at: https://doi.org/10.20383/101.0115.

11 Final remarks

The data from the SDNWA have contributed significantly to our understanding of groundwater-surface water interactions in prairie environments. The long-term dataset can be used to examine the inter-annual variability of hydrological fluxes, climate change impact on wetlands and groundwater resources. The unique dataset will be valuable to prairie hydrological research communities for various purposes such as inter-site comparison of hydrogeological processes or hydrological model testing.

12 Competing interests

The authors declare that they have no conflicting interest.

13 Acknowledgment

The field program at SDNWA was assisted by field assistants, scientists, and institutions who are too many to name. We especially grateful to the graduate students and post-doctoral fellows from the University of Saskatchewan who conducted hydrological research projects at the SDNWA over the years. We also thank research and field technicians who took responsibility for data collection and quality control, especially Randy Schmidt, and Branko Zdravkovic and Amber Peterson who assisted with data transfer and archiving. The efforts of the Canadian Consortium for Lidar Environmental Applications Research (C-CLEAR) team is also acknowledged for the Lidar data acquisition. The program has been funded by Natural Sciences and Engineering Research Council (Discovery Grant, CCRN), National Hydrology Research Institute, Saskatoon, Global Institute for Water Security, University of Saskatchewan, and Environment and Climate Change Canada.

14 Author contributions

EKPB provided the stable water isotopes and groundwater data, described sample collection, measurement, summarized the entirety of all the data and put together the final drafts of the manuscript for comments. RB put together pond levels and snow surveys and meteorological data and plots, and aerial map for SDNWA. SB compiled the soil moisture data, created plots and wrote on instrumentation for the soil moisture data. AI discussed the relevant context of the hydrological data and wrote on the site description and hydrogeology, and provided edits and comments on the manuscript. CS wrote the introduction, described the instrumentation for the meteorological data and provided editorial comments on drafts. GV read through the final drafts of the manuscript and provided editorial help and reviews.

References

Begley, I. S. and Scrimgeour, C. M.: High-precision δ 2 H and δ 18 O measurement for water and volatile organic compounds by continuous-flow pyrolysis isotope ratio mass spectrometry, Anal. Chem., 69(8), 1530–1535, doi:10.1021/ac960935r, 1997.

Berthold, S., Bentley, L. R., and Hayashi, M.: Integrated hydrogeological and geophysical study of depression-focused groundwater recharge in the Canadian prairies, Water Resour. Res., 40, W06505, 2004.

Cressey, R.L., Austin, J.E., and Stafford, J.D.: Three Responses of Wetland Conditions to Climatic Extremes in the Prairie Pothole Region, Wetlands, 36, 357–370, doi:10.1007/s13157-016-0818-8, 2016.

Campbell Scientific Inc. 229 Heat Dissipation Matric Water Potential Sensor Instruction Manual. Revision: 5/09, 2009.

Coleman, M. L., Shepherd, T. J., Durham, J. J., Rouse, J. E., and Moore, G. R.: Reduction of water with zinc for hydrogen isotope analysis, Anal. Chem., 54(6), 993–995, doi:10.1021/ac00243a035, 1982.

Conly, F. M., Su, M., van der Kamp, G., and Millar, J. B.: A practical approach to monitoring water levels in prairie wetlands, Wetlands, 24(1), 219-226, 2004.

Coplen, T. B.: Normalization of oxygen and hydrogen isotope data, Chem. Geol., 72(4), 293–297, doi:10.1016/0168-9622(88)90042-5, 1988.

Dumanski, S., Pomeroy, J. W., and Westbrook, C. J.: Hydrological regime changes in a Canadian Prairie basin, Hydrol. Process., 29, 3893-3904, 2015.

Eiler, J. M. and Kitchen, N.: Hydrogen-isotope analysis of nanomole (picoliter) quantities of H2O, Geochemica Cosmochim. Acta, 65(24), 4467–4479, doi:10.1021/jp312364c, 2001.

Epstein, S. and Mayeda, T.: Variation of O18 content of waters from natural sources, Geochim. Cosmochim. Acta, 4(5), 213–224, doi:10.1016/0016-7037(53)90051-9, 1953.

Fortin, G., van der Kamp, G., and Cherry, J. A.: Hydrogeology and hydrochemistry of an aquifer-aquitard system within glacial deposits, Saskatchewan, Canada, J. Hydrol., 126(3-4), 262-292, 1991.

Fritz, P., Drimmie, R.J., Frape, S.K., and O'Shea, K.: The isotopic composition of precipitation and groundwater in Canada, Isot. Tech. Water Resour. Dev., 143, 539–549, doi:10.1016/0022-1694(93)90212-R, 1987.

Hayashi, M. and van der Kamp, G.: Simple equations to represent the volume–area–depth relations of shallow wetlands in small topographic depressions, J. Hydrol., 237 (1–2), 74-85, 2000.

Goldhaber, M.B., Mills, C.T., Morrison, J.M., Stricker, C.A., Mushet, D.M., and LaBaugh, J.W.: Hydrogeochemistry of prairie pothole region wetlands: Role of long-term critical zone processes, Chem. Geol. 387, 170–183, doi:10.1016/j.chemgeo.2014.08.023, 2014.

Goldhaber, M.B., Mills, C.T., Mushet, D.M., McCleskey, B.B., and Rover, J.: Controls on the Geochemical Evolution of Prairie Pothole Region Lakes and Wetlands over Decadal Time Scales, Wetlands, 36, 255–272, doi:10.1007/s13157-016-0854-4, 2016.

Goodison, B.E., Glynn, J.E., Harvey, K.D., and Slater, J.E.: Snow surveying in Canada: A perspective, Can. Water Resour. J., 12(2), 27-42, 1987.

Hayashi, M., van der Kamp, G., and Rosenberry, D. O.: Hydrology of prairie wetlands: Understanding the integrated surface-water and groundwater processes, Wetlands, Supplemental Issue: Midcontinent prairie-pothole wetlands and climate change, 36 (Suppl. 2), S237–S254, doi:10.1007/s13157-016-0797-9, 2016.

Hayashi, M., van der Kamp, G., and Rudolph, D. L.: Water and solute transfer between a prairie wetland and adjacent uplands, 1. Water balance, J. Hydrol., 207, 42-55, 1998.

Hayashi, M., van der Kamp, G., and Schmidt, R.: Focused infiltration of snowmelt water in partially frozen soil under small depressions, J. Hydrol., 270(3–4), 214–229, 2003.

Heagle, D.J., Hayashi, M., and van der Kamp, G.: Use of solute mass balance to quantify geochemical processes in a prairie recharge wetland, Wetlands, 27(4), 806-818, 2007.

Heagle, D., Hayashi, M., and van der Kamp, G.: Surface–subsurface salinity distribution and exchange in a closed-basin prairie wetland, J. Hydrol, 478, 1–14, doi:10.1016/j.jhydrol.2012.05.054, 2013.

Hogan, J. M. and Conly, F. M.: St. Denis National Wildlife Area land cover classification: 1997, Canadian Wildlife Service, Prairie and Northern Region, Saskatoon, SK, Canada, Technical Report Series No. 384, 2002.

IAEA: Laser spectroscopic analysis of liquid water samples for stable hydrogen and oxygen isotopes, Isot. Hydrol. Sect. Int. At. Energy Agency, 49, 2009.

Jasechko, S., Gibson, J. J., and Edwards, T. W. D.: Stable isotope mass balance of the Laurentian Great Lakes, J. Great Lakes Res., 40(2), 336-346, 2014.

Jasechko, S., Wassenaar, L. I., and Mayer, B.: Isotopic evidence for widespread cold-season-biased groundwater recharge and young streamflow across central Canada, Hydrol. Process., 31(12), 2196-2209, 2017.

Karhu, J. A.: Catalytic reduction of water to hydrogen for isotopic analysis using zinc containing traces of sodium, Anal. Chem., 69(22), 4728–4730, doi:10.1021/ac9704467, 1997.

Kelly, S. D., Heaton, K. D., and Brereton, P.: Deuterium/hydrogen isotope ratio measurement of water and organic samples by continuous-flow isotope ratio mass spectrometry using chromium as the reducing agent in an elemental analyser, Rapid Commun. Mass Spectrom., 15(15), 1283–1286, doi:10.1002/rcm.303, 2001.

Koopmans, R. W. R. and Miller, R. D.: Soil freezing and soil water characteristic curvesm, Soil Sci. Soc. Am. J., 30(6), 680, 1966.

LaBaugh, J.W., Mushet, D.M., Rosenberry, D.O., Euliss, N.H., Goldhaber, M.B., Mills, C.T., and Nelson, R.D.: Changes in Pond Water Levels and Surface Extent Due to Climate Variability Alter Solute Sources to Closed-Basin Prairie-Pothole Wetland Ponds, 1979 to 2012, Wetlands, 36, 343–355, doi:10.1007/s13157-016-0808-x, 2016.

Lis, G., Wassenaar, L. I., and Hendry, M. J.: High-precision laser spectroscopy D/H and 18O/16O measurements of microliter natural water samples, Anal. Chem., 80(1), 287–93, doi:10.1021/ac701716q, 2008.

Miller, J. J., Acton, D.F., and St. Arnaud, R. J.: The effect of groundwater on soil formation in a morainal landscape in Saskatchewan, Can. J. Soil Sci., 65, 293-307, 1985.

Minke, A. G., Westbrook, C. J., and van der Kamp, G.: Simplified volume-area-depth method for estimating water storage of prairie potholes, Wetlands, 30(3), 541-551, 2010.

Morgenstern, U. and Taylor, C. B.: Ultra low-level tritium measurement using electrolytic enrichment and LSC, Isotopes Environ. Health Stud., 45(2), 96–117, doi:10.1080/10256010902931194, 2009.

Pan, X., Helgason, W., Ireson, A., and Wheater, H.: Field-scale water balance closure in seasonally frozen conditions, Hydrol. Earth Syst. Sci., 21(11), 5401–5413, 2017.

Nachshon, U., Ireson, A., van der Kamp, G., Davies, S., and Wheater, H.S.: Impacts of climate variability on wetland salinization in the North American prairies, Hydrol. Earth Syst. Sci., 18, 1251–1263, doi:10.5194/hess-18-1251-2014, 2014.

Pennock, D., Henderson, D., Naschon, U., Spence, C., van der Kamp, G., Waiser, M., Wilson, H., and Bedard-Haughn, A.: Where it all comes together – 45 years of research on the hydrology-ecosystem interactions at the St. Denis National Wildlife Area. Report completed for the Global Institute for Water Security, University of Saskatchewan, 84 pp, 2013.

Pennock, D., Yates, T., Bedard-Haughn, A., Phipps, K., Farrell, R. and McDougal, R.: Landscape controls on N2O and CH4 emissions from freshwater mineral soil wetlands of the Canadian Prairie Pothole region, Geoderma, 155, 308-319, 2010.

Rashford, B. S., Bastian, C. T. and Cole, J. G.: Agricultural land-use change in prairie Canada: implications for wetlands and waterfowl habitat conservation, Can. J. Agr. Econ., 59, 185-205, 2011.

Spaans, E. J. A. and Baker, J. M.: Examining the use of time domain reflectometry for measuring liquid water content in frozen
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Spaans, E. J. A. and Baker, J. M.: Examining the use of time domain reflectometry for measuring liquid water content in frozen
Spaans, E. J. A. and Baker, J. M.: Examining the use of time domain reflectometry for measuring liquid water content in frozen soil TDR Calibration, Water Resour. Res., 31(12), 2917–2925, 1995.

Socki, R. A.: On-line technique for measuring stable oxygen and hydrogen isotopes from microliter quantities of water, Anal. Chem., 71(11), 2250–2253, doi:10.1021/ac981140i, 1999.

Statistics Canada.: Table 002-0004 - Agriculture value added account, annual (dollars), CANSIM (database), Web service, 2017, accessed: April 24, 2018.

Stevens Water Monitoring Systems Inc.: The Hydra Probe ® soil sensor user’s manual, July, 1–63, 2007.

van der Kamp, G. and Hayashi, M.: Groundwater-wetland ecosystem interaction in the semiarid glaciated plains of North America, Hydrogeol. J., 17(1), 203-214, 2009.

Töyrä, J., Pietroniro, A., Craymer, M., and Véronneau, M: Evaluation of LiDAR-derived ground surface digital elevation model (DEM) in low-relief regions: Case study on the Canadian Prairies, in: Hydroscan: Airborne laser mapping of hydrologic features and resources, edited by: Hopkinson, C., Pietroniro, A. and Pomeroy, J.W., 301-326.

van der Kamp, G., Keir, D., and Evans, M.S.: Long-term water level changes in closed-basin lakes of the Canadian prairies, Can. Water Resour. J., 33(1), 23-38, 2008.

van der Kamp, G., Stolte, W. J., and Clark, R.G.: Drying out of small prairie wetlands after conversion of their catchments from cultivation to permanent brome grass, Hydrol. Sci. J., 44(3), 387-397, 1999.
Waiser, M. J.: Relationship between hydrological characteristics and dissolved organic carbon concentration and mass in northern prairie wetlands using a conservative tracer approach, J. Geophys. Res., 111, doi:10.1029/2005JG000088, 2006.
Woo, M.K. and Rowsell, R.D.: Hydrology of a prairie slough, J. Hydrol., 146, 175-207, 1993.

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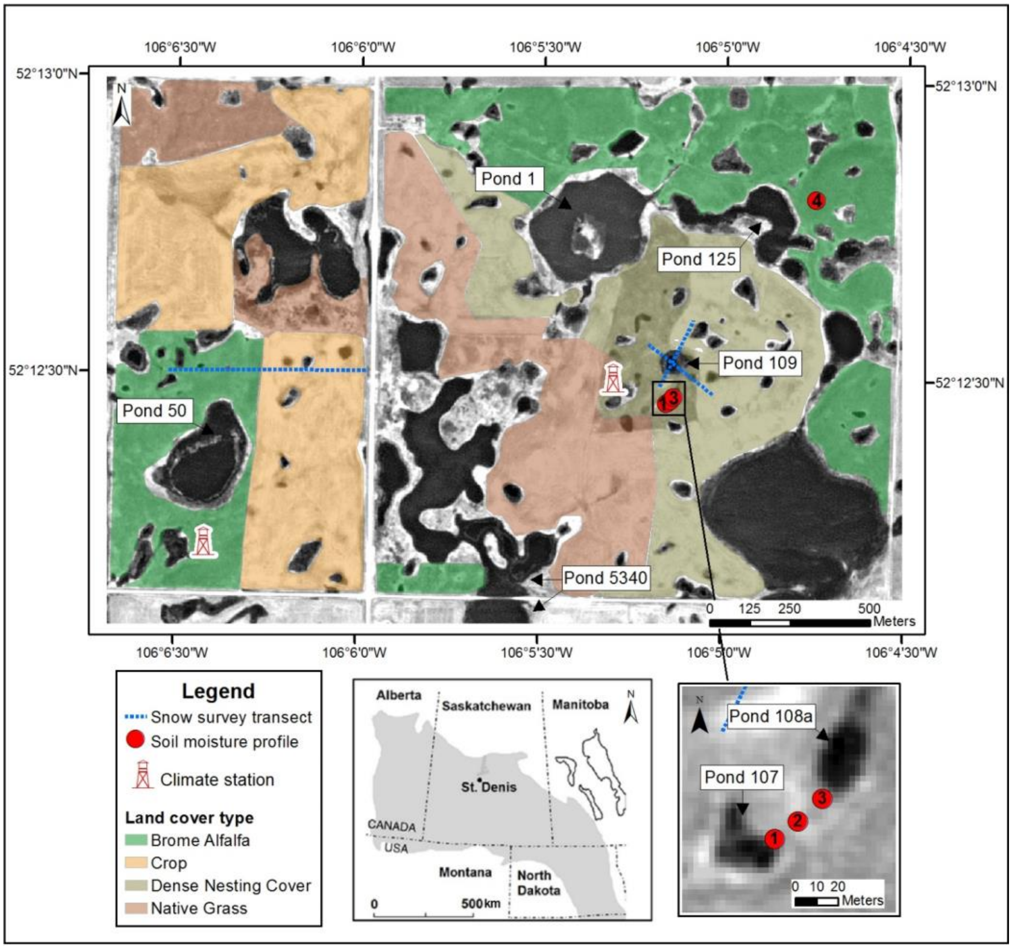

Figure 1: Map and location of St. Denis National Wildlife Area. The grey area on the inset map represents the extent of Prairie Pothole Region in North America

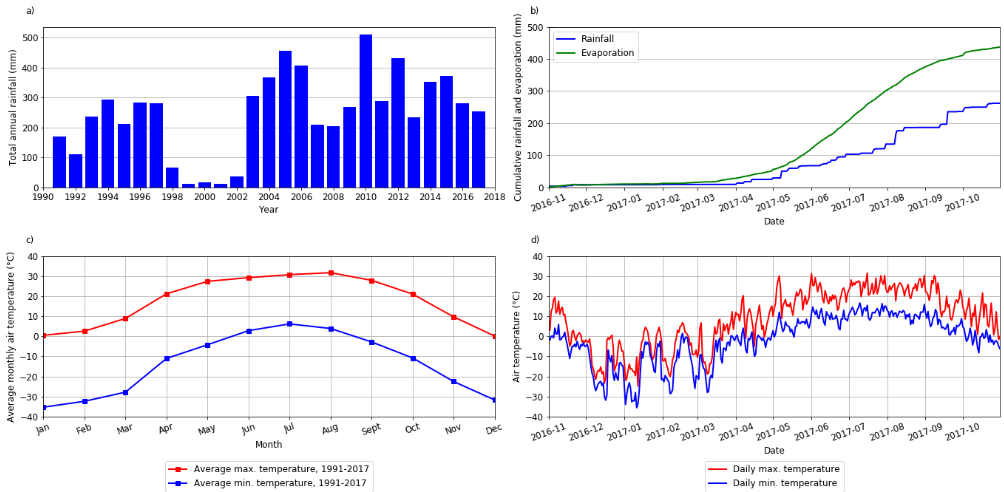

Figure 2: Meteorological data from SDNWA: a) the total annual rainfall for the period of record (1991-2017) measured at the mast tower; b) cumulative total rainfall (mast tower) and evaporation (scaffold tower) for the 2016-2017 hydrologic year; c) mean monthly air temperature at 2 m (mast tower) for the period of record (1991-2017); and d) daily air temperature at 2 m (mast tower) for the 2016-2017 hydrologic year.

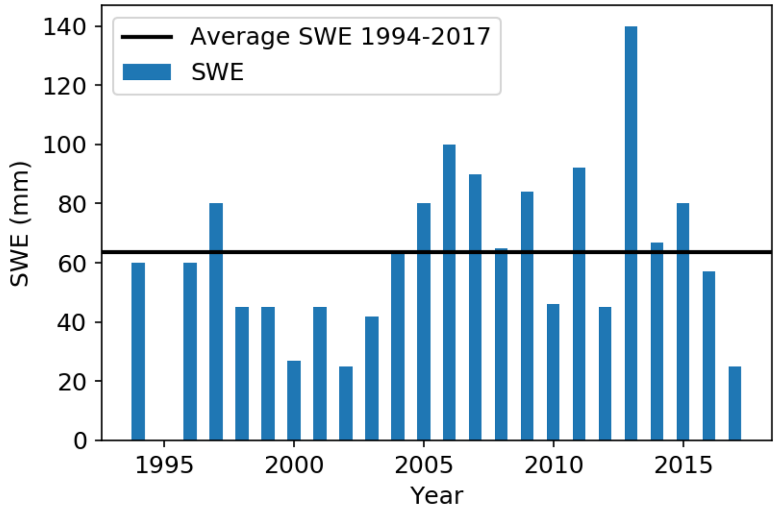

Figure 3: Weighted mean snow water equivalent (SWE, blue bars) of snowpack before melt over SDNWA. The black line represents the 24-year average of snow accumulation.

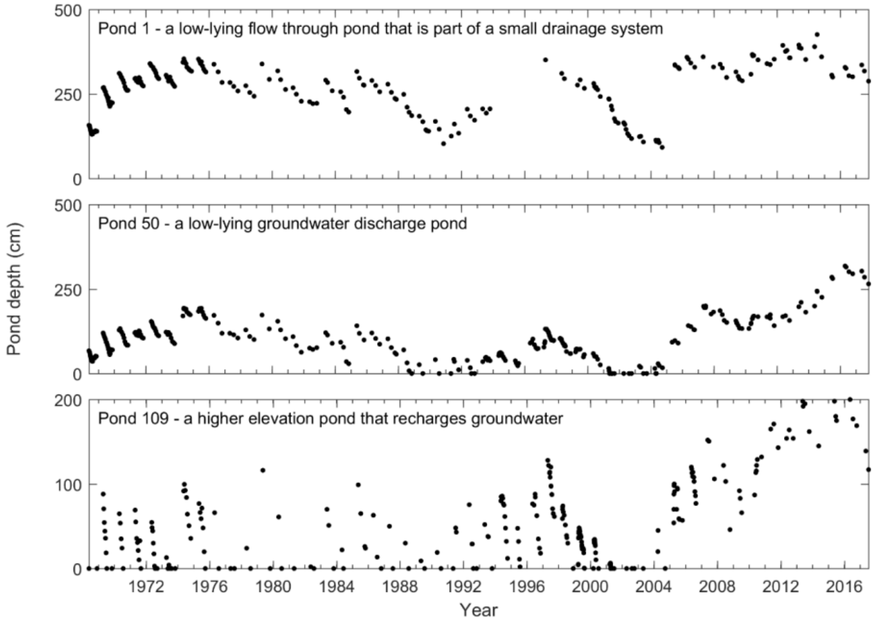

Figure 4: Pond level fluctuations with time in Wetlands 1, 50 and 109.

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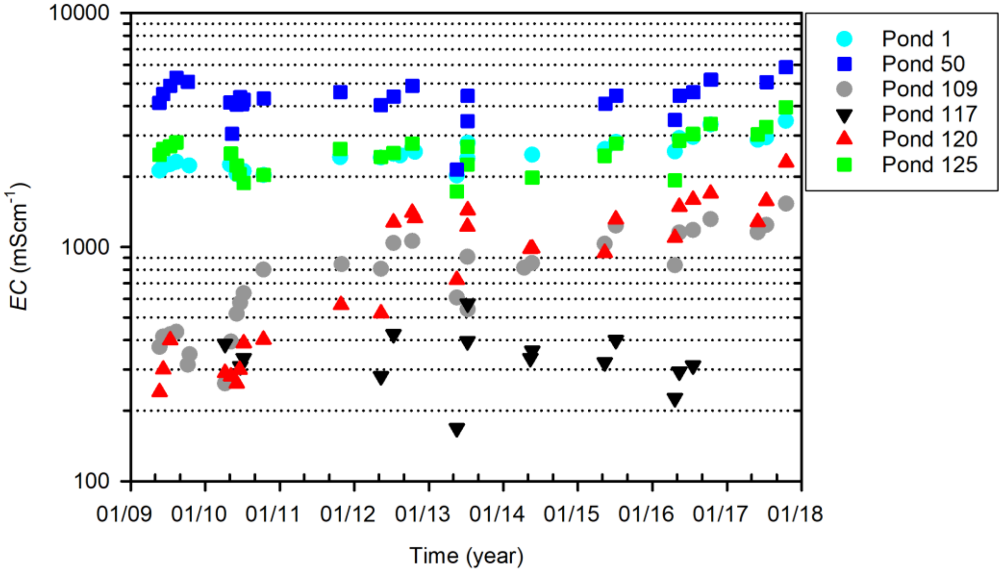

Figure 5: Time series of pond water electrical conductivity (log scale) at St. Denis showing the variations in pond salinity.

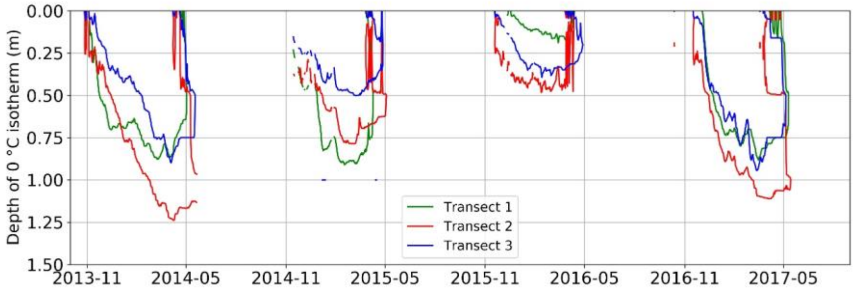

Figure 6: Soil freezing depths in three soil profiles near Pond 109.

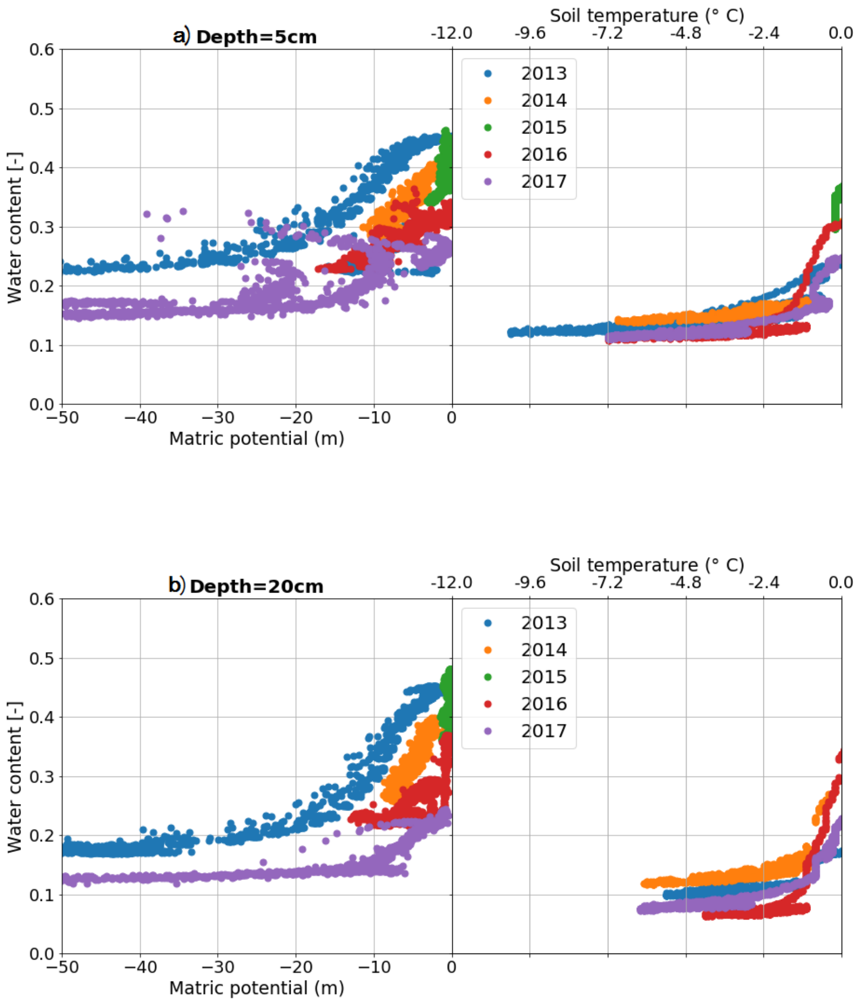

Figure 7: Observed soil water content and soil freezing characteristic of the Upslope profile at 5 cm and 20 cm depths at St. Denis.

Note that the water content data for the freezing condition of 2015 is not recorded in Fig. 7b since soil temperature at 20 cm depth was always above 0 ^{0}c.

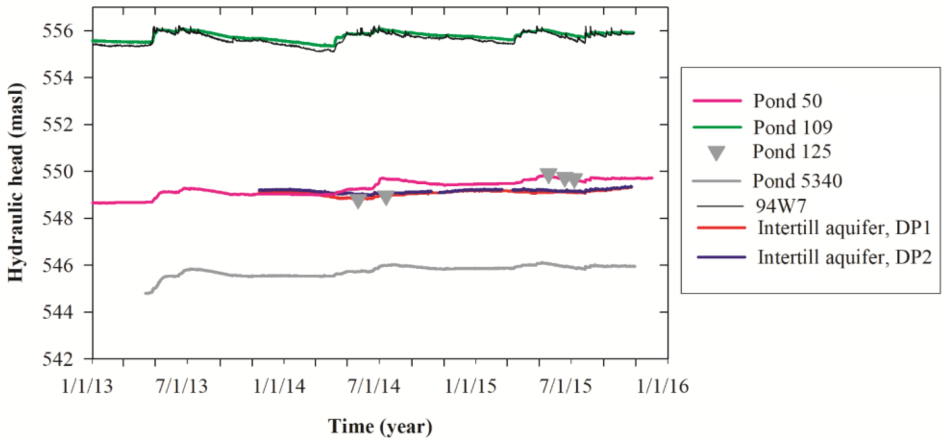

Figure 8: Groundwater and surface water levels in St. Denis.

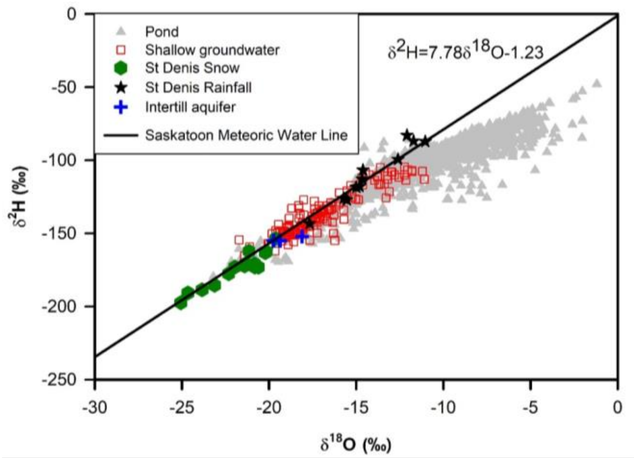

Figure 9: A scatter plot of δ^2H versus $\delta^{18}O$ at St. Denis, Saskatchewan.

Tables

Table 1: Long-term meteorological instrumentation at St. Denis National Wildlife Area

10 m mast		
Variable	*Height (m)*	*Sensor*
Wind speed (ms^{-1})	10	RM Young 5103
Wind direction (°)	10	RM Young 5103
Air temperature/ Relative humidity (°C /%)	2	Vaisala HMP series
Photosynthetically active radiation (Wm^{-2})	1	LiCor Li190SB
Incoming solar radiation (Wm^{-2})	1	LiCor Li200X
Rainfall (mm)	0.5	Texas Electronics TE525M
10 m scaffolding tower		
Variable	*Height (m)*	*Sensor*
Wind speed (ms^{-1})	2	Met One 14A
Wind direction (°)	10	NRG
Air temperature/ Relative humidity (°C /%)	10	Vaisala HMP series
Air temperature/ Relative humidity (°C /%)	1.5	Vaisala HMP series
All component radiation (Wm^{-2})	10	Kipp and Zonen CNR4
Turbulent fluxes (C, Qe, Qh) (Wm^{-2})	10	Campbell Scientific CSAT3; EC150
Rainfall (mm)	10	Texas Electronics TE525M

AUTHORS RESPONSE TO REVIEWERS

The authors reply to reviewers are in bullet and highlighted in red

REVIEWER 1:

This is a very useful document that describes the impressive monitoring work that has been done in the Canadian prairies, particularly at the St. Denis natural research area, in Saskatchewan. Over the last decades, and mainly over the last few years a lot of environmental data has been collected at the St. Denis research site. The data includes meteorological data, hydrological information, soil measurements, isotopes analyses, and more. All of this data is well organized and available for any one who is willing to use it. The St. Denis site represents the natural (and cultivated) environment of the Canadian prairies and the availability of the data to the scientific community is priceless. The MS is well written and should be published.

- We thank the Referee #1, Dr. Nachshon for the encouraging comments on this manuscript.

I know that there is also chemical (major ions) information about the ponds water and I do not think the authors mentioned it. They briefly mentioned the stable isotopes, but I would recommend the authors to elaborate on the chemistry information that they have.

This is a good suggestion, and we have now included pond water chemistry data in the revised data set. We have taken note of the importance and usefulness of the data and have thus elaborated on how this data is collected in the revised manuscript's Section 7 (Water isotope data and surface water chemistry) page 8.

- On top of that - I found few minor typos: P1, L20: "isotope isotopes" P3, L1: "biologist,s," P3, L2: "on," - delete the comma At the isotopes section there are many acronyms and I'm not sure all of them were explained.
- These corrections have been made.

REVIEWER 2:

General comments

It is great to see the data of this prairie monitoring site being made available to all. As the authors mention, there are timeseries of varying observation frequency and duration. Together they paint a very detailed picture of hydrological dynamics of prairie wetlands and their surroundings. The dataset fits very well into the scope of EESD.

- We thank the Referee # 2 Dr W. Appels for taking time to review the manuscript and also the encouraging comments

Please consider the comments below to clarify some of the descriptions. Specific comments

Page 3, line 5: Are you able to include the long-term pond chemistry data in the open dataset? If not, may be mention that briefly here.

- We have included the long-term pond chemistry data and elaborated on the data collection and source in Section 7 of the revised manuscript. A new plot on the variation of pond EC among various ponds has also been added and brief note included under the data overview section (i.e, section 8).

Figure 1: Inset with location of the site: what does the grey shading indicate?

- We thank the reviewer for this note. The grey shading is the prairie region of North America; this has been clarified in the Figure 1 label.

Section 3: Please describe when in the winter the SWE data was collected. The wording of the caption of Figure 3 is not 100% clear to me: are the points the cumulative SWE of snow fallen or the content of the snow pack before melt? Are they averages of multiple days as well as of multiple locations in the landscape? If not, maybe include the date of each survey in the csv file as well.

- The snow survey is done once a year in the spring. We have added the date of the annual snow survey to the csv file. We have also updated the text in section 3 to indicate that the snow survey is performed once each year and that the values in figure 3 are an average SWE for the whole site.
- Figure 3 caption has been revised to indicate that the values shown are the average SWE of the snowpack before melt.

Technical comments page 3, line 1, typo: biologists

- Typo corrected

Figure 2 - temperature plots: use degree symbol in the axis labels

- Corrected

Figure 6: consider changing the point types/sizes to show some of the 2015 freezing characteristic. Or is it missing/compromised?

- In 2015 there was negligible freezing at 20 cm, and only a small amount of freezing at 5 cm, as can be seen in Figure 5. Therefore Fig 6 provide an accurate depiction of the data in 2015.
- The data was not compromised or miising, rather it was not recorded, because the soil temperature at 20 cm below ground was always above 0 ^{0}c.

REVIEWER 3:

Interactive comment on “Meteorological, soil moisture, surface water, and groundwater data from the St Denis National Wildlife Area, Saskatchewan, Canada” by Edward K. P. Bam et al.

Anonymous Referee #3 Received and published: 2 January 2019 General comments

The data set for St Denis NWA is very useful as it represents an unusually complete set of variables for the region. The atmospheric data are at high frequency, and include variables such as the turbulent fluxes, which are rarely found. The many researchers who laboured to collect the data are to be thanked for their hard work, as are the authors who have collected and presented the data sets. Unfortunately, the writing is marked by vagueness and colloquialisms.

The following terms need to be fixed: By “average” you are usually referring to mean values.

Use of the words “high” and “low” is colloquial, unless you mean some type of elevation. You are referring to things which are either “large” or “small” Comparative words like “colder”, “higher”, or “greater” imply that you are comparing a value to another value, which in many cases is not specified. This needs to be fixed.

- The authors are grateful for the comments by the reviewer and have made necessary changes to the language.

Specific comments

Page 1 Line 21 “ground elevations (datum) used”. The term “elevations” is plural; “datum” is singular.

- This sentence has been edited for clarity.

Line 29 “dominated by glacial till, as well as coarser grained fluvial deposits,” This implies that the fluvial deposits are coarser than the till.

- This sentence has been edited to convey that there are sand/gravel deposits within the glacial till.

Page 2 Line 2 “ponds that annually dry out” A better phrasing would be “ponds that dry out annually” Line 3 “Farming practices over the past century include widespread artificial wetland drainage in some portions of the region.” This statement should be backed up by a reference.

- Reference added.

Line 6 “The site was selected because it was primarily a cultivated...” A better phrasing would be “The site was selected primarily because it was a cultivated...”

- Agreed and fixed.

Line 12 “No wetland drainage has occurred on the site since 1968.” Did any drainage occur before this year? Line 27 “The area is hummocky” Which area? This is a poor word to use, as “area” has a mathematical meaning. Do you mean the general region, or the NWA?

- We mean both NWA and the region near the NWA. The sentence has been revised.

Line 28 “for which detailed Lidar elevation data are available.” Is this dataset available to other researchers? I don’t see it in the provided data sets.

- We have added the LiDAR DEM data to the open dataset and included a short description of the dataset in a new section 8.

Page 3 Line 1 "In the past 50 years" Would be better to replace "In" with "Over" as the activity continues to the present.

- Accepted, replaced

Line 11 As there are 2 stations, the word "oldest" should be replaced by "older"

- Ok, replaced

Line 20 Insert the word "energy" after "turbulent" as the carbon fluxes are also turbulent. Insert the word "solar" after "net" to identify the type of radiation. Also, insert a dash between "all" and "component"

- Ok, replaced

Line 24 The manufacturer of the logger is specified in Line 26, so it should be included here, too.

- Ok, replaced.

Line 26 According to Table 1, and to the headers of the .csv files, the "precipitation" data are actually tipping bucket rainfalls – why would they be corrected for the effects of wind speed on snowfall? Please insert a complete description here of the data. Referring this data as "precipitation" is very confusing.

- This paragraph has been changed to indicate that the precipitation data is measured with tipping bucket gauges, which only provide accurate rainfall data. This is why we call the data 'rainfall'. We have removed the word 'precipitation' from this description. However, the data we provide is raw and covers the entire year. Users will need to determine the precipitation phase using other data.

Page 4 Line 7 Replace "second" with "other" before "snow survey", as the other snow survey site was not numbered.

- Ok, replaced

Line 27 "Generally, monitoring typically" Pick one, either "generally" or "typically".

- agreed and change effected.

Page 5 Line 4 "in (Conly et al., 2004)", should be "by Conly et al. (2004)"

- Ok.

Line 19 "For the wetlands" This is not required – delete.

- Ok, deleted.

Page 6 Line 2 "During soil freezing the dielectric constant of ice is much lower than that of liquid water, so the instrument is likely to give a reasonable measure of the liquid water content" This sentence is problematic. It is unclear whether you are referring to the liquid water phase in frozen soils or to the completely unfrozen soils. It needs to be re-written. Replace "lower" with "smaller" Insert "more" between "is" and "likely"

- The sentence was rewritten for clarity and refers to the liquid phase in frozen soil. The new sentence reads, "In frozen soil, the dielectric constant of ice is much smaller than that of liquid water, so the instrument is more likely to give a reasonable measure of the liquid water content".

Line 3 What does the number in "229 probes" refer to? Is it the number of probes that were installed, or is it a model number?

- The ''229 probes'' here refer to the name of the heat dissipation sensors which measure the soil matric potential. The sensor is manufactured by the Campbell Scientific, Canada.

Line 14 "shallow high permeability weathered till layers" I think that it is important to indicate that the high permeability is relative to other types of till, so it would be a good idea to insert the word "relatively" before "high"

- Ok.

Line 27 "Stables" should be "Stable"

- Ok.

Page 8 Line 4 "There is little lag in net radiation" What does this mean? What it is lagging with respect to? Are you saying that there is little seasonal lag between the incoming short-wave radiation and the net all-wave radiation?

- Yes, that is what we are saying, and we have edited the sentence for clarity.

Line 6 "Wind speeds average ..." Over what time periods? Are these daily values?

- This is the mean of hourly wind speed over the period of record. This has been clarified in the text.

Line 20 "Wetlands 1, 50 and 109 are representative of prairie wetlands" What do the other ones represent, mountain wetlands?

- We have rephrased this sentence to avoid confusion.

Line 28 What is the "freeze back"? I am not familiar with this term.

- The sentence was rephrased for clarity. The new sentence reads, "The frost table depth is also affected by antecedent soil water content".

Line 29 "The saturated water content at freeze-up is usually 0.5" What does this mean? What is the saturated water content 0.5 of? Do you mean that the saturation fraction is 0.5?

- The 'fraction' term was added in the sentence. The new sentence reads, "The saturated water content fraction at freeze –up is usually 0.5 with a high residual of liquid water content during frozen conditions".

Figures

Figure 1 The soil moisture profile points near Pond 109 are so large that they overlap, so it is hard to see them all. It would be better to use smaller markers.

- We have added an inset detail map to the figure to show the soil moisture profiles near Pond 109. The profiles are too close together to show with non-overlapping markers at the scale of the site map unless the markers are so small that they become difficult to see.

Figure 2 This figure is not referenced in the text. Which set of air temperatures is plotted, the 2m or 5m? Please include the elevation, or the name of the site in the y-axis label. Also, include the time-step of the values plotted, i.e. either daily or monthly. If you are going to refer to a value as a flux (the evaporation and precipitation) then it needs to have the units of a flux, i.e. as a mass (or depth) per unit time. It looks like you are plotting values which are accumulated over a time. The axis title in the bottom-right plot is confusing. As it states "Month", it implies that monthly values are plotted. It might be better to title it as simply "Date", as these are daily values. You could indicate the date format as "(Year-month)", if you like.

- We have added a reference to this figure in the text in the Overview of content section. The figure has been revised….

Figure 3 The blue line is the mean value. The use of the word "average" is confusing as a) it is incorrect and b) the individual SWE values are weighted averages.

- Ok.

Figure 4 “Hydrograph” should be plural.

- Ok.

Data sets

The headers of the isotope .csv files contain non-ASCII characters, which are problematic for many programs to read, particularly as there is no indication as to how the files are encoded. It would be a good idea to change these characters to their closest ASCII equivalents.

- Ok.

Meteorological, soil moisture, surface water, and groundwater data from the St. Denis National Wildlife Area, Saskatchewan, Canada

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Abstract. Long-term meteorological, soil moisture, surface water and groundwater data provide information on past climate change, most notably information that can be used to analyze past changes in precipitation and groundwater availability in a region. These data are also valuable to test, calibrate and validate hydrological and climate models. CCRN (Changing Cold Regions Network) is a collaborative research network that brought together a team of over 40 experts from 8 universities and 4 federal government agencies in Canada for 5 years (2013-18) through the Climate Change and Atmospheric Research (CCAR) initiative of the Natural Sciences and Engineering Research Council of Canada (NSERC). The working group aimed to integrate existing and new data with improved predictive and observational tools to understand, diagnose and predict interactions amongst the cryospheric, ecological, hydrological and climatic components of the changing Earth system at multiple scales, with a geographic focus on the rapidly changing cold interior of Western Canada. The St. Denis National Wildlife Area database includes atmosphere, soil, surface water and groundwater data for the prairie research site. The meteorological measurements are observed every 5 seconds, and half-hourly mean values (or total values) are logged. Soil moisture data comprises volumetric water content, soil temperature, electrical conductivity and matric potential for probes installed at depths of 5 cm, 20 cm, 50 cm, 100 cm, 200 cm and 300 cm in all soil profiles. Additional data on snow surveys, pond and groundwater levels, surface water chemistry and water isotopes collected on an intermittent basis between 1968 and 2018 are also presented, including information on the dates, ground surface elevations (in meters above sea level), and geographical positions coordinates used to construct hydraulic heads. The spatial data tables provide the geographical coordinates of piezometers and wetlands that are relevant to the interpretation of the records and the digital elevation map (DEM) of the site and surrounding landscape. The compiled data are available at https://doi.org/10.20383/101.0115.

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1 Introduction

The Canadian portion of the North American Prairies is bounded to the west by the Rocky Mountains, and the north and east by the Boreal Forest. It contains around 80% of Canada's agricultural area, with an annual crop market value in 2016 of $41 billion (Statistics Canada, 2017). The region is characterized by a semi-arid, seasonally frozen climate, with colder and wetter conditions moving from southwest to northeast. The surficial geology is dominated by glacial till, interspersed with glacio-lacustrine sand and gravel deposits, and the glaciated landscape is generally flat or gently rolling, with thousands of depressions. Due to the low amounts of precipitation, drainage networks are poorly developed, and precipitation excess tends to form lakes and wetlands in surface depressions (Hayashi et al., 2016). Surface water bodies in the depressions have widely varying sizes, from large permanent lakes, such as Redberry Lake, Saskatchewan (van der Kamp et al., 2008), to ponds that rarely dry out, to ephemeral ponds that annually dry out annually. Farming practices over the past century include widespread artificial wetland drainage in some portions of the region (Rashford et al., 2011).

The St. Denis National Research Area (Figure 1) was established in 1968 by the Canadian Wildlife Service for research on how agricultural practices affect waterfowl production. The site was primarily selected because it was a cultivated land parcel with an abundance of wetlands close to the City of Saskatoon. The St. Denis National Research Area was officially listed in the Canada Gazette with an amendment to the Wildlife Area Regulations in 1978 (SOR/78-466). The St. Denis National Research Area is the only site in the Environment and Climate Change Canada protected areas network to bear the title of "National Research Area", however, the colloquial name of the reserve is St. Denis National Wildlife Area (SDNWA).

At the time of establishment, nearly 60% of the 361.5 hectares in the SDNWA were under cultivation, with the remainder a mix of native grasslands, shrublands, and wetlands. No wetland drainage has occurred on the site since 1968. Lease agreements with local farmers are used to keep the annual cropland in production with wheat, barley, and canola, while the remainder of the vegetation remains undisturbed. In 1977, a program was initiated to convert 97 hectares of cultivated land to a perennial forage mix of smooth brome (*Bromus inermis*) and alfalfa (*Medicago sativa*) (van der Kamp et al. 1999). The program was to minimize erosion on sloping and light textured soils from tillage activities, to provide nesting cover and food for wildlife, and was consistent with land use changes in the surrounding region. There were minor changes in land cover until 2015 when a seeding program began to convert the remaining cropland back to permanent grassland cover.

Much inventory, monitoring, and research have occurred at SDNWA, consistent with the original purpose of the site. Research efforts have been diverse and growing, with an emphasis on migratory bird ecology, wetland hydrology, and soil science. SDNWA has grown in value to the research community because of the accumulated long-term data collected consistently. It is a site that is unrivaled in the Canadian Prairies for the length and breadth of hydrological observations. Pennock et al. (2013) provide a good summary of the site and the research history.

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The SDNWA and surrounding landscape area is hummocky, with local relief of the order of 15m. The area lies within and near the lower end of a 2,400 ha closed watershed for which detailed Lidar elevation data are available. Aspen bluffs occupy some of the larger depressions in the drainage basin. Soils are predominantly Dark Brown Chernozems and Orthic Regosols; both developed from glacial till (Miller et al., 1985). The glacial stratigraphy of the site is well-documented: roughly one hundred meters of clay-rich glacial till of low permeability lies under the soils, interspersed with isolated sand lenses and a continuous thin layer of sand at about 25 to 30 m depth (Hayashi et al., 1998).

Over the past 50 years, field research has been undertaken at SD NWA by hydrologists, hydrogeologists, biologists, ecologists, soil scientists and others, and there have been more than 100 papers published on this site. Many of these studies were based on short-term field experiments, which have produced snapshots of data in time. Here, we focus on the continuous monitoring program, which is ongoing and is the foundation of much of the short-term research. The longest records are of pond levels and chemistry, dating back to 1968. Soil and groundwater observations have been recorded continuously since 2013 (before this there are large amounts of groundwater data, but those observations are not continuous to present).

Figure 1: **Map and location of St. Denis National Wildlife Area. The grey area on the inset map represents the extent of Prairie Pothole Region in North America.**

2 Meteorological data

There are two climate stations at the St. Denis National Wildlife Area. The older, a 10 m mast tower, is at an elevation of 554 masl at 52.2037°N 106.1067°W located on the upland south of Pond 50 surrounded by brome-alfalfa grassland (Figure 1). This station was initially deployed in the spring of 1989 as part of the Wetlands Ecosystem Vulnerability Study (WEVS). It was initially used to evaluate the water budgets of prairie wetlands, particularly Pond 50 (Woo and Rowsell, 1993). From 1991 to 1998 operation of the station was transferred to the Meteorological Service of Canada. In 1998, the equipment was transferred to the Canadian Wildlife Service (CWS), for continuing use as a WEVS facility. Reorganization of the CWS in 2006 prompted responsibility of the tower to be transferred to the Water Directorate of the Science and Technology Branch of Environment and Climate Change Canada. These transfers sometimes resulted in substantial breaks in the period of record. In 2011, a second climate tower was constructed that was capable of supporting eddy covariance equipment for measuring turbulent energy and carbon fluxes and all component net solar radiation. This is a 10 m scaffolding tower located at 52.2089°N 106.0889°W at a local high point in a field currently supporting dense nesting cover (Figure 1). The specifics of each tower, including variables and units and sensor types and heights, are summarized in Table 1. Three-dimensional wind speeds, air temperature, water vapour content, and carbon dioxide density are measured at 10 Hz with turbulent fluxes calculated over a half hour period on the Campbell Scientific CR3000 logger. The turbulent flux data within these records is uncorrected and

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should be treated with caution. All meteorological data are observed every 5 seconds, and half-hourly averages (or totals) are currently logged on Campbell Scientific CR1000 (mast tower) and CR3000 (scaffolding tower) data loggers. Rainfall data, measured with Texas Electronics TE525M tipping bucket rain gauges, are reported as the hourly or half-hourly totals. It is important to note that while the tipping bucket rain gauges are in operation all year and may record precipitation during the winter months, they only supply reliable measurements of liquid precipitation when not accompanied by freezing or frozen precipitation. The Figure 2 shows total and accumulated precipitation, evaporation and the temperature records at 2 m for the at the SDNWA.

Figure 2: Meteorological data from SDNWA: a) the total annual rainfall for the period of record (1991-2017) and annual snowfall (only available 2014-2017); b) cumulative total precipitation (rain and snow) and evaporation for the 2016-2017 hydrologic year; c) mean monthly air temperature at 2 m for the period of record (1991-2017); and d) daily air temperature for the 2016-2017 hydrologic year.

3 Snow surveys

Snow surveys have been conducted at SDNWA by Environment and Climate Change Canada (ECCC) since 1994. Snow depths and densities are measured along three transects (Figure 1) and converted to snow water equivalent (SWE) and then generalized over the whole site (Figure 3). The snow surveys are performed once each year in March to estimate the SWE on the ground before snowmelt begins. One of the snow surveys consists of two perpendicular transects that cross in the centre of Pond 109. Each transect is approximately 250 m. Snow depth is measured at every 5 to 10 m. At every fifth depth measurement, a density sample is collected using an Eastern Snow Conference snow tube. This survey measures snow accumulation in the grass, wetland vegetation, trees, and an ice-covered pond. The other snow survey is a 700 m transect that runs east to west through cropped and grass fields across the western portion of the SDNWA. Snow depths are measured every 15 - 20 m and density samples are taken every fifth depth measurement. SWE values are calculated for each point and then averaged to calculate mean SWE for each land cover. The average SWE over the entire SDNWA is estimated by calculating a weighted mean by a land cover fraction of the total area.

Figure 3. Weighted mean of snow water equivalent (SWE) of snowpack before melt over SDNWA. The blue line represents the 24-year mean of snow accumulation.

4 Pond water level, chemistry and bathymetry data

At the St. Denis National Wildlife Area pond water depths in wetlands have been monitored since 1968. These wetlands generally have areas between 0.1 and 10 hectares and contain ponds that range in class from vernal to ephemeral to permanent. SDNWA wetlands were initially mapped based on aerial photography (Hogan and Conly, 2002) and numbered. The major

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wetlands were numbered 1 to 147 and smaller wetlands adjacent or adjoined to the larger depressions were sub-labeled with letters a, b, c, and d.

The record of pond depth measurements dates from 1968 to 2017 and includes measurements from 135 ponds. Canadian Wildlife Service staff began monitoring 76 of the SDNWA wetlands in 1968; an additional 57 started being monitoring after 2011. The frequency of measurement varies annually and among wetlands. Monitoring typically begins in spring and extends through to the fall. Measurements are not conducted during the winter because many ponds will freeze to the sediment and because snow and ice accumulation on ponds influence water depth under ice. There are some wetlands with data available for every year from 1968 to the present (Pond 25, Pond 50, Pond 65, Pond 90, Pond 109, and Pond 120). Many were dry during the drought of 1999-2002. In 2015, a long-term monitoring plan was developed jointly with researchers from the University of Saskatchewan and ECCC to monitor pond depths, stable isotopes and water quality of 25 wetlands once each in May, July, and October.

The methodology for collecting pond depth data is described in Conly et al. (2004). The lowest bottom elevation in the wetland depression is used as the relative datum and the geodetic elevations of these points have been determined for many of the wetlands. Measurements are made by wading into the pond and using a measuring rod to measure water depth at monitoring markers (usually a metal T-bar installed deep into pond sediments to prevent heaving or movement). The measuring rod is attached to a 6-cm diameter circular base to prevent the rod from being pushed into the sediment. Shallow seasonal and ephemeral ponds require only a single marker. Deeper ponds that vary considerably in flooded area and depth have multiple markers installed at various elevations to ensure a measurement can be made when markers installed at lower elevations are flooded. Depth measurements are taken at the same time at multiple markers to ensure markers are tied to the local datum. Point measurements at single markers (in smaller wetlands) are generally within 25 mm of those measured with conventional survey equipment and benchmarks. The accuracy in larger wetlands is considered to be within 50 mm (Conly et al., 2004). The year-to-year and seasonal variations in pond hydrographs are apparent from the long-term record (Figure 4).

Figure 4: Hydrographs of ponds in Wetlands 1, 50 and 109.

Water chemistry of ponds and groundwater have been measured in a number of studies at St Denis National Wildlife Area (e.g., Hayashi et al., 1998; Berthold et al., 2004; Waiser 2006; Heagle et al., 2007, 2013; Pennock et al., 2010, 2013). The record consists of measurements of individual ions and overall solute load measures, i.e., electrical conductivity (*EC*, Figure 4) and total dissolved solids (*TDS*). The details of the equipment and methods are described in Hayashi et al. (1998), Berthold et al. (2004), Waiser (2006), Heagle et al. (2007& 2013) and Pennock et al. (2010).

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Figure 5: Time series of pond water electrical conductivity (log scale) at St. Denis showing multi-year variations in pond water chemistry.

Detailed elevation surveys were carried out in 1994, 1998, 1999, 2008, and 2009 on twenty-six wetlands depressions using electronic total stations within the St. Denis NWA. The catchment extent of the wetlands and depressions, vegetation, soil, and the hydroperiods of ponds in the respective wetlands are published in Hayashi and van der Kamp (2000) and Minke et al. (2010). Survey points were spaced horizontally at 10–15 m intervals in the uplands, 5–10 m intervals in the wetlands, and 2–5 m intervals in small depressions. The estimated measurement error is within a few centimeters for elevation and within a few tens of centimeters for horizontal location (Hayashi and van der Kamp, 2000; Minke et al., 2010). The water depth data for these wetlands (Figure 4) can be presented as water surface elevation for comparison with groundwater levels.

5 Soil moisture data

There are four soil moisture profiles at SDNWA where continuous observations of water content, matric potential, temperature, and electrical conductivity have been made since July 2013. Three of these profiles are located along a lowland transect between ephemeral ponds (107 and 108a) adjacent to Pond 109 and one profile is located towards the top of a hillslope east of Pond 1 (Figure 1). In each case, piezometers are collocated with the soil moisture profiles, as described below.

Hydra Probe sensors (Hydra II, Stevens Water Monitoring Systems Inc, 2007) are impedance sensors that simultaneously measure soil volumetric water content, soil temperature, and electrical conductivity. The probes were installed at depths of 5 cm, 20 cm, 50 cm, 100 cm, 200 cm and 300 cm in all soil profiles. During soil freezing the dielectric constant of ice is much lower than that of liquid water, so the instrument is likely to give a reasonable measure of the liquid water content (Spaans and Baker, 1995). The soil matric potential is measured using the heat dissipation sensors (229 probes, Campbell Scientific) at depths of 5 cm, 20 cm, 50 cm, and 100 cm. The heat dissipation sensor is a porous block sensor which measures the pressure of dry soil and has a working range of -10 kPa to -2500 kPa. Tensiometers (T4e, Decagon Devices) are used to measure the pressure of wet soil at the depths of 100 cm, 200 cm, and 300 cm. The working range of the tensiometer is +100 kPa to -85 kPa. The soil freezing temperature and moisture content for three profiles at 20 cm near Pond 109 is shown in Figure 5(a-b). Figure 7 shows the observed soil water content and soil freezing characteristic of Transect 1 (Figure 1) at 5 cm and 20 cm depths at St. Denis.

Figure 6: Soil freezing depth for three profiles near Pond 109.

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Figure 7: Observed soil water content and soil freezing characteristic of Transect 1 at 5 cm and 20 cm depths at St. Denis.

6 Groundwater level data

The hydrogeology of St. Denis is reasonably complex, comprising a shallow and relatively high permeability weathered till layers overlying unweathered till aquitards and coarse-grained inter-till confined aquifers. A large number of piezometers were installed in all three of these units, mostly for individual short-term projects, and as a result most of the data are discontinuous. These data are none-the-less available and provide useful insights into the spatially and temporally variable interactions between groundwater and surface water bodies. Continuous monitoring of the water table started in 2013 at a piezometer near Pond 109 collocated with the soil moisture transects. Two piezometers were installed in a confined aquifer and instrumented in November 2013. These are the deepest piezometers on the site (39 and 41 m below ground level). Unvented Solinst Leveloggers are used to monitor water levels, corrected for changes in barometric pressure with a Solinst BaroLogger placed at the scaffolding climate tower. The Figure 8 shows ground and surface water levels at SDNWA for 2014 to 2016.

Figure 8: Groundwater and surface water levels in St. Denis.

7 Water isotope data

Stable isotopes of water (δ^{18}O and δ^{2}H) have been measured sporadically for some of the ponds at St. Denis since 1993. These data are complemented by campaign-based samples of rainfall, snow (mainly in the period 2013-2014) and groundwater (sporadic measurements between 1993 and 2014, and covering depths between 1.2 – 41 m below ground level). Furthermore, continuous snow and rainfall samples from Saskatoon, 35 km away, are available for the period 1993 to 2014. Isotope ratios of δ^{2}H and δ^{18}O of all samples were measured at the National Hydrology Research Centre in Saskatoon, Canada. The sampling and analysis methodology is described in detail in Lis et al. (2008). Isotope ratios of tritium were measured at the Rafter Radiocarbon Laboratory, National Isotope Centre, GNS Science in New Zealand. The stable isotope ratios of water were analyzed using three instruments: Micromass Optima continuous flow mass spectrometer, Micromass IsoPrime dual inlet/continuous flow mass spectrometers, and off-axis integrated cavity output spectroscopy (OA-ICOS) laser.

Between 1993 and 2007, the precipitation, ponds, and groundwater samples were analyzed for δ^{2}H and δ^{18}O using the isotope-ratio mass spectrometers (IRMS). The protocols for the isotope-ratio mass spectrometer analysis follow the standard methods (Begley and Scrimgeour, 1997; Coleman et al., 1982; Eiler and Kitchen, 2001; Epstein and Mayeda, 1953; Karhu, 1997; Kelly et al., 2001; Socki, 1999). The ^{18}O/^{16}O ratio in the water samples were analyzed by the equilibration of water samples with CO_2 gas at 25 ± 0.1 ˚C for 24 h to produce CO_2 gas (Epstein and Mayeda, 1953). After the equilibration, the CO_2 gas was extracted and purified through a vacuum cryogenic line. The ^{2}H/^{1}H ratio was analyzed by the production of hydrogen gas using Cr at 850 ˚C (Coleman et al., 1982). The ^{18}O/^{16}O and ^{2}H/^{1}H ratios were measured against the internal standards which

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were calibrated using Vienna-Standard Mean Ocean Water (V-SMOW) and Standard Light Antarctic Precipitation (SLAP). The results were normalized to the VSMOW-SLAP scale and reported in the delta notation as decribed in Coplen (1988). The analytical reproducibility is ± 0.1 ‰ and ±1.0 ‰ for δ^{18}O and δ^{2}H. Both offline dual-inlet (i.e., zinc reduction or uranium reduction) and continuous flow IRMS methods (i.e., Cr reduction or C) have measurement accuracies of the order of (± 0.5 to ± 4 ‰) for δ^{2}H and the automated CF-IRMS methods, such as C-reduction to CO and CO_2-H_2O equilibration, are between ± 0.1 and ± 0.4 ‰ for δ^{18}O (Lis et al., 2008).

A Los Gatos Research DLT-100 liquid water isotope analyzer system coupled with a CTC LC-PAL liquid autosampler (Los Gatos Inc., California) was employed in stable isotope analyses done between 2008 and 2018. The analysis follows the methods described in Lis et al. (2008) and IAEA manual (2009). Laboratory standards (INV1: δ^{2}H = -220.0 ‰, δ^{18}O = -28.5 ‰ and ROD3: δ^{2}H = -8.0 ‰, δ^{18}O = -1.2 ‰) were calibrated with Vienna-Standard Mean Ocean Water (V-SMOW2) and Standard Light Antarctic Precipitation (SLAP2) reference waters. INV1 and ROD3 were used to normalize the results to the VSMOW2-SLAP2 scale by assigning δ^{18}O and δ^{2}H values of -55.5 ‰ and -428.0 ‰, respectively, to the SLAP2 reference water. Consequently, all measured values reported are relative to VSMOW/SLAP δ scale. Samples, standards and control samples (river water) were analyzed repeatedly six times. The laboratory precision was ±1.0 ‰ for δ^{2}H and ± 0.2 ‰ for δ^{18}O.

Tritium samples (^{3}H) samples were shipped to Rafter Radiocarbon Laboratory, National Isotope Centre, GNS Science in New Zealand for ultra-low-level tritium counting using electrolytic enrichment and liquid scintillation counting (LSC). The ^{3}H concentrations are expressed in tritium units (TU); the precision at an average tritium concentration of New Zealand rain of 4 TU is ± 0.06 TU (98.5 %), and the detection limit is ±0.025 TU (Morgenstern and Taylor, 2009). Details of the analytical procedure are provided in Morgenstern and Taylor (2009). A summary of the stable isotope data is shown in Figure 9.

Figure 8: A scatter plot of δ^{2}H versus δ^{18}O at St. Denis, Saskatchewan.

8 Spatial data

Elevation data of the SDNWA and surrounding area were collected during a Light Detection and Ranging (Lidar) survey conducted by the Canadian Consortium for Lidar Environmental Applications Research (C-CLEAR) on 9 August 2005. The exact methods of the Lidar data survey and processing of the digital elevation model (DEM) are described in Toyra et al. (2008). The generated DEM is provided in UTM Zone 13 NAD83 and the elevations are orthometric heights based on the CGG05 geoid model. The elevations are tied to a local benchmark near Pond 1. The ground data points were interpolated into a 1 m DEM using the Inverse Distance Weighted (IDW) algorithm. The Lidar DEM was evaluated based on in situ survey

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data (GPS points and total station surveys). The results indicate that the accuracy of LiDAR DEM in the agricultural fields or grasses is 0.13m, while the accuracy in the shrubs and trees surrounding the wetland ponds is 0.17m.

9 Overview of content

The record from both climate towers shows strong seasonality of incoming radiation and turbulent fluxes at the SDNWA. Maximum incoming solar radiation (typically ~ 350 Wm^{-2}) occurs in June near the summer solstice. Conversely, minimum solar radiation of 10 $W m^{-2}$ is in December. There is very little seasonal lag between incoming solar radiation and net radiation, which ranges from 200 $W m^{-2}$ to -30 Wm^{-2} between June and December. The record does include several spikes in the radiation and turbulent flux data that should be removed prior to any analysis. The mean of hourly wind speed over the period of record (1992 - 2018) is 3.8 ms^{-1}. The period of record includes half-hourly mean wind speeds as high as 16.9 ms^{-1}. Daily maximum air temperatures often reach +27 °C in July and can be well below -30 °C anytime between November and February (Figure 9). These cold air temperatures are also associated with dry air with relative humidity often less than 50% in late winter. The measurements of relative humidity were some of those that suffered from the changing agencies responsible for the towers. The near 30-year length of the record provides an excellent perspective on the cycles of rainfall in the central Canadian Prairie. The record drought from 1999-2002 (van der Kamp and Hayashi, 2009) during which annual rainfall averaged 20 mm is well documented and is in stark contrast to a recent wet period (Dumanski et al., 2015) when annual rainfall averaged 330 mm from 2005-2013. A recent addition to the towers was a Geonor total precipitation gauge in 2015, but the record is too short to allow for a description of the entire precipitation regime at the site.

The mean maximum spring SWE as measured during the March snow surveys was 62 mm throughout the recorded period (1994-2017). There was a sustained period of lower than average SWE from 1998 to 2003, followed by an above-average period from 2004-2009. The spring snowpack in 2013 was 120 mm and the largest in the 24-year period.

The hydrographs of wetlands 1, 50 and 109 follow a distinct annual cycle that has a peak in pond level at the end of the snowmelt period followed by a gradual decline during summer months. Wetland 109 contains a seasonal pond that dries out completely in some summers; may carry water over between years during wetter periods and has reached spill elevation occasionally in recent wet years. The larger wetlands, 1 and 50, have permanent and semi-permanent ponds, respectively. Wetland 1 receives inflow in most years from a roughly 1000 ha watershed and spills to lower-lying ponds in most years, while Wetland 50 has never spilled during the period of record.

Wetland pond chemistry in the prairies is controlled primarily by water balance components of evaporation, plant transpiration and groundwater discharge. The long-term fluctuations in the chemistry of wetland ponds are caused by multi-year, wet-dry cycles associated with meteorological forcing and land-use in the region (Cressey et al., 2016; Goldhaber et al., 2016, 2014;

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LaBaugh et al., 2016, Nachshon et al., 2014). During extreme wet conditions groundwater discharge and surface runoff of salts from an upland area into freshwater ponds results in freshwater ponds becoming salinized (e.g., Pond 109 and 120, Figure 4). In addition to these water balance controls, geochemical and biochemical interactions within a wetland pond and underlying wetland soils also add or remove solutes from the wetland pond water (Heagle et al., 2007; LaBaugh et al., 2016; Pennock et al., 2014). Inadequate knowledge of the climate history and land use change around a particular pond could lead to a misinterpretation of the pond's hydrological function by short-term observations of pond chemistry.

The maximum frost table depth is ~1.2 m and corresponds with cold surface air temperature and low snowpack accumulation (Hayashi et al., 2003). The frost table depth is affected by antecedent soil water content during fall before the freeze (Pan et al., 2017). The saturated water content at freeze-up is usually 0.5 with a high residual of liquid water content during frozen conditions. The variation in the water content values in different years might be attributed to heterogeneity and hydrological variation within the study area.

The stable water isotope compositions of precipitation, snowmelt, groundwater and surface water (ponds) are similar to isotope values of water taken from surface ponds and glacial deposits throughout southern Saskatchewan and central Canada (Fortin et al., 1991; Fritz et al., 1987; Jasechko et al., 2014, 2017; Kelley & Holmden, 2001). The data show distinct differences between the different sources. The precipitation data from SDNWA fall on the Saskatoon local meteoric water line (LMWL), but show distinct seasonal variability with winter measurements (snow) more depleted than summer rainfall. The pond water isotopes show evaporation like many surface waters. The shallow groundwater data are relatively similar to the pond data, but subject to less evaporation. The intertill aquifer data is biased towards the snow end of the spectrum of precipitation.

10 Data availability

The SDNWA dataset is stored at the Federated Research Data Repository (FRDR) and can be accessed from the FRDR at: https://doi.org/10.20383/101.0115

11 Final remarks

The data from the SDNWA have contributed significantly to our understanding of groundwater-surface water interactions in prairie environments. The long-term dataset can be used to examine the inter-annual variability of hydrological fluxes, climate change impact on wetlands and groundwater resources. The unique dataset will be valuable to prairie hydrological research communities for various purposes such as inter-site comparison of hydrogeological processes or hydrological model testing.

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12 Competing interests

The authors declare that they have no conflicting interest.

13 Acknowledgment

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14 Author contributions

EKPB provided the stable water isotopes and groundwater data, described sample collection, measurement, summarized the entirety of all the data and put together the final drafts of the manuscript for comments. RB put together pond levels and snow surveys and meteorological data and plots, and aerial map for SDNWA. SB compiled the soil moisture data, created plots and wrote on instrumentation for the soil moisture data. AI discussed the relevant context of the hydrological data and wrote on the site description and hydrogeology, and provided edits and comments on the manuscript. CS wrote the introduction, described the instrumentation for the meteorological data and provided editorial comments on drafts. GV read through the final drafts of the manuscript and provided editorial help and reviews.

References

Begley, I. S. and Scrimgeour, C. M.: High-precision δ 2 H and δ 18 O measurement for water and volatile organic compounds by continuous-flow pyrolysis isotope ratio mass spectrometry, Anal. Chem., 69(8), 1530–1535, doi:10.1021/ac960935r, 1997.

Berthold, S., Bentley, L. R., and Hayashi, M.: Integrated hydrogeological and geophysical study of depression-focused groundwater recharge in the Canadian prairies, Water Resour. Res., 40, W06505, 2004.

Cressey, R.L., Austin, J.E., Stafford, J.D., 2016. Three Responses of Wetland Conditions to Climatic Extremes in the Prairie Pothole Region. Wetlands 36, 357–370. doi:10.1007/s13157-016-0818-8

Coleman, M. L., Shepherd, T. J., Durham, J. J., Rouse, J. E., and Moore, G. R.: Reduction of water with zinc for hydrogen isotope analysis, Anal. Chem., 54(6), 993–995, doi:10.1021/ac00243a035, 1982.

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Conly, F. M., Su, M., van der Kamp, G., and Millar, J. B.: A practical approach to monitoring water levels in prairie wetlands, Wetlands, 24(1), 219-226, 2004.

Coplen, T. B.: Normalization of oxygen and hydrogen isotope data, Chem. Geol., 72(4), 293–297, doi:10.1016/0168-9622(88)90042-5, 1988.

Dumanski, S., Pomeroy, J. W., and Westbrook, C. J.: Hydrological regime changes in a Canadian Prairie basin, Hydrol. Process., 29, 3893-3904, 2015.

Eiler, J. M. and Kitchen, N.: Hydrogen-isotope analysis of nanomole (picoliter) quantities of H2O, Geochemica Cosmochim. Acta, 65(24), 4467–4479, doi:10.1021/jp312364c, 2001.

Epstein, S. and Mayeda, T.: Variation of O18 content of waters from natural sources, Geochim. Cosmochim. Acta, 4(5), 213–224, doi:10.1016/0016-7037(53)90051-9, 1953.

Fortin, G., van der Kamp, G., and Cherry, J. A.: Hydrogeology and hydrochemistry of an aquifer-aquitard system within glacial deposits, Saskatchewan, Canada, J. Hydrol., 126(3-4), 262-292, 1991.

Fritz, P., Drimmie, R.J., Frape, S.K., O'Shea, K., 1987. The isotopic composition of precipitation and groundwater in Canada. Isot. Tech. Water Resour. Dev. 143, 539–549. doi:10.1016/0022-1694(93)90212-R

Hayashi, M. and van der Kamp, G.: Simple equations to represent the volume–area–depth relations of shallow wetlands in small topographic depressions, J. Hydrol., 237 (1–2), 74-85, 2000.

Goldhaber, M.B., Mills, C.T., Morrison, J.M., Stricker, C.A., Mushet, D.M., LaBaugh, J.W., 2014. Hydrogeochemistry of prairie pothole region wetlands: Role of long-term critical zone processes. Chem. Geol. 387, 170–183. doi:10.1016/j.chemgeo.2014.08.023

Goldhaber, M.B., Mills, C.T., Mushet, D.M., McCleskey, B.B., Rover, J., 2016. Controls on the Geochemical Evolution of Prairie Pothole Region Lakes and Wetlands Over Decadal Time Scales. Wetlands 36, 255–272. doi:10.1007/s13157-016-0854-4

Hayashi, M., van der Kamp, G., and Rosenberry, D. O. Hydrology of prairie wetlands: Understanding the integrated surface-water and groundwater processes, Wetlands, Supplemental Issue: Midcontinent prairie-pothole wetlands and climate change, 36 (Suppl. 2), S237–S254, doi:10.1007/s13157-016-0797-9, 2016.

Hayashi, M., van der Kamp, G., and Rudolph, D. L.: Water and solute transfer between a prairie wetland and adjacent uplands, 1. Water balance, J. Hydrol., 207, 42-55, 1998.

Hayashi, M., van der Kamp, G., and Schmidt, R.: Focused infiltration of snowmelt water in partially frozen soil under small depressions. J. Hydrol., 270(3–4), 214–229, 2003.

Heagle, D.J., Hayashi, M., and van der Kamp, G.: Use of solute mass balance to quantify geochemical processes in a prairie recharge wetland, Wetlands, 27(4), 806-818, 2007.

Heagle, D., Hayashi, M., Kamp, G. Van Der, 2013. Surface–subsurface salinity distribution and exchange in a closed-basin prairie wetland. J. Hydrol. 478, 1–14. doi:10.1016/j.jhydrol.2012.05.054

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Hogan, J. M. and Conly, F. M.: St. Denis National Wildlife Area land cover classification: 1997, Canadian Wildlife Service, Prairie and Northern Region, Saskatoon, SK, Canada, Technical Report Series No. 384, 2002.

IAEA: Laser spectroscopic analysis of liquid water samples for stable hydrogen and oxygen isotopes, Isot. Hydrol. Sect. Int. At. Energy Agency, 49, 2009.

Jasechko, S., Gibson, J. J., and Edwards, T. W. D.: Stable isotope mass balance of the Laurentian Great Lakes, J. Great Lakes Res., 40(2), 336-346, 2014.

Jasechko, S., Wassenaar, L. I., and Mayer, B.: Isotopic evidence for widespread cold-season-biased groundwater recharge and young streamflow across central Canada, Hydrol. Process., 31(12), 2196-2209, 2017.

Karhu, J. A.: Catalytic reduction of water to hydrogen for isotopic analysis using zinc containing traces of sodium, Anal. Chem., 69(22), 4728–4730, doi:10.1021/ac9704467, 1997.

Kelly, S. D., Heaton, K. D., and Brereton, P.: Deuterium/hydrogen isotope ratio measurement of water and organic samples by continuous-flow isotope ratio mass spectrometry using chromium as the reducing agent in an elemental analyser, Rapid Commun. Mass Spectrom., 15(15), 1283–1286, doi:10.1002/rcm.303, 2001.

Koopmans, R. W. R. and Miller, R. D.: Soil freezing and soil water characteristic curves. Soil Sci. Soc. Am. J., 30(6), 680, 1966.

LaBaugh, J.W., Mushet, D.M., Rosenberry, D.O., Euliss, N.H., Goldhaber, M.B., Mills, C.T., Nelson, R.D., 2016. Changes in Pond Water Levels and Surface Extent Due to Climate Variability Alter Solute Sources to Closed-Basin Prairie-Pothole Wetland Ponds, 1979 to 2012. Wetlands 36, 343–355. doi:10.1007/s13157-016-0808-x

Lis, G., Wassenaar, L. I., and Hendry, M. J.: High-precision laser spectroscopy D/H and 18O/16O measurements of microliter natural water samples, Anal. Chem., 80(1), 287–93, doi:10.1021/ac701716q, 2008.

Miller, J. J., Acton, D.F. and St. Arnaud, R. J.: The effect of groundwater on soil formation in a morainal landscape in Saskatchewan, Can. J. Soil Sci., 65, 293-307, 1985.

Minke, A. G., Westbrook, C. J., and van der Kamp, G.: Simplified volume-area-depth method for estimating water storage of prairie potholes, Wetlands, 30(3), 541-551, 2010.

Morgenstern, U. and Taylor, C. B.: Ultra low-level tritium measurement using electrolytic enrichment and LSC, Isotopes Environ. Health Stud., 45(2), 96–117, doi:10.1080/10256010902931194, 2009.

Pan, X., Helgason, W., Ireson, A., and Wheater, H.: Field-scale water balance closure in seasonally frozen conditions, Hydrol. Earth Syst. Sci., 21(11), 5401–5413, 2017.

Nachshon, U., Ireson, A., van der Kamp, G., Davies, S., Wheater, H.S., 2014. Impacts of climate variability on wetland salinization in the North American prairies. Hydrol. Earth Syst. Sci. 18, 1251–1263. doi:10.5194/hess-18-1251-2014

Pennock, D., Henderson, D., Naschon, U., Spence, C., van der Kamp, G., Waiser, M., Wilson, H., and Bedard-Haughn, A.: Where it all comes together – 45 years of research on the hydrology-ecosystem interactions at the St. Denis National Wildlife Area. Report completed for the Global Institute for Water Security, University of Saskatchewan, 84 pp, 2013.

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Deleted: et al. 2013.…Where it all comes together – 45 years o research on the hydrology-ecosystem interactions at the St. Denis National Wildlife Area. Report completed for the Global Institute Water Security, University of Saskatchewan, . …4 pp, 2013..

Pennock, D., Yates, T., Bedard-Haughn, A., Phipps, K., Farrell, R. and McDougal, R.: Landscape controls on N2O and CH4 emissions from freshwater mineral soil wetlands of the Canadian Prairie Pothole region, Geoderma,155, 308-319, 2010.

Rashford, B. S., Bastian, C. T. and Cole, J. G.: Agricultural land-use change in prairie Canada: implications for wetlands and waterfowl habitat conservation, Can. J. Agr. Econ., 59, 185-205, 2011.

Spaans, E. J. A. and Baker, J. M.: Examining the use of time domain reflectometry for measuring liquid water content in frozen soil TDR Calibration, Water Resour. Res., 31(12), 2917–2925, 1995.

Socki, R. A.: On-line technique for measuring stable oxygen and hydrogen isotopes from microliter quantities of water, Anal. Chem., 71(11), 2250–2253, doi:10.1021/ac981140i, 1999.

Statistics Canada.: Table 002-0004 - Agriculture value added account, annual (dollars), CANSIM (database), Web service, 2017. Accessed: April 24, 2018.

Stevens Water Monitoring Systems Inc.: The Hydra Probe ® soil sensor user's manual, July, 1–63, 2007.

van der Kamp, G. and Hayashi, M.: Groundwater-wetland ecosystem interaction in the semiarid glaciated plains of North America, Hydrogeol. J., 17(1), 203-214, 2009.

Töyrä, J., Pietroniro, A., Craymer, M., and Véronneau, M: Evaluation of LiDAR-derived ground surface digital elevation model (DEM) in low-relief regions: Case study on the Canadian Prairies, in: Hydroscan: Airborne laser mapping of hydrologic features and resources, edited by: Hopkinson, C., Pietroniro, A. and Pomeroy, J.W., 301-326.

van der Kamp, G., Keir, D., and Evans, M.S.: Long-term water level changes in closed-basin lakes of the Canadian prairies. Can. Water Resour. J., 33(1), 23-38, 2008.

van der Kamp, G., Stolte, W. J. and Clark, R.G.: Drying out of small prairie wetlands after conversion of their catchments from cultivation to permanent brome grass. Hydrol. Sci. J., 44(3), 387-397, 1999.

Waiser, M. J.: Relationship between hydrological characteristics and dissolved organic carbon concentration and mass in northern prairie wetlands using a conservative tracer approach, J. Geophys. Res., 111, doi:10.1029/2005JG000088, 2006.

Woo, M.K. and Rowsell, R.D.: Hydrology of a prairie slough, J. Hydrol., 146, 175-207, 1993.

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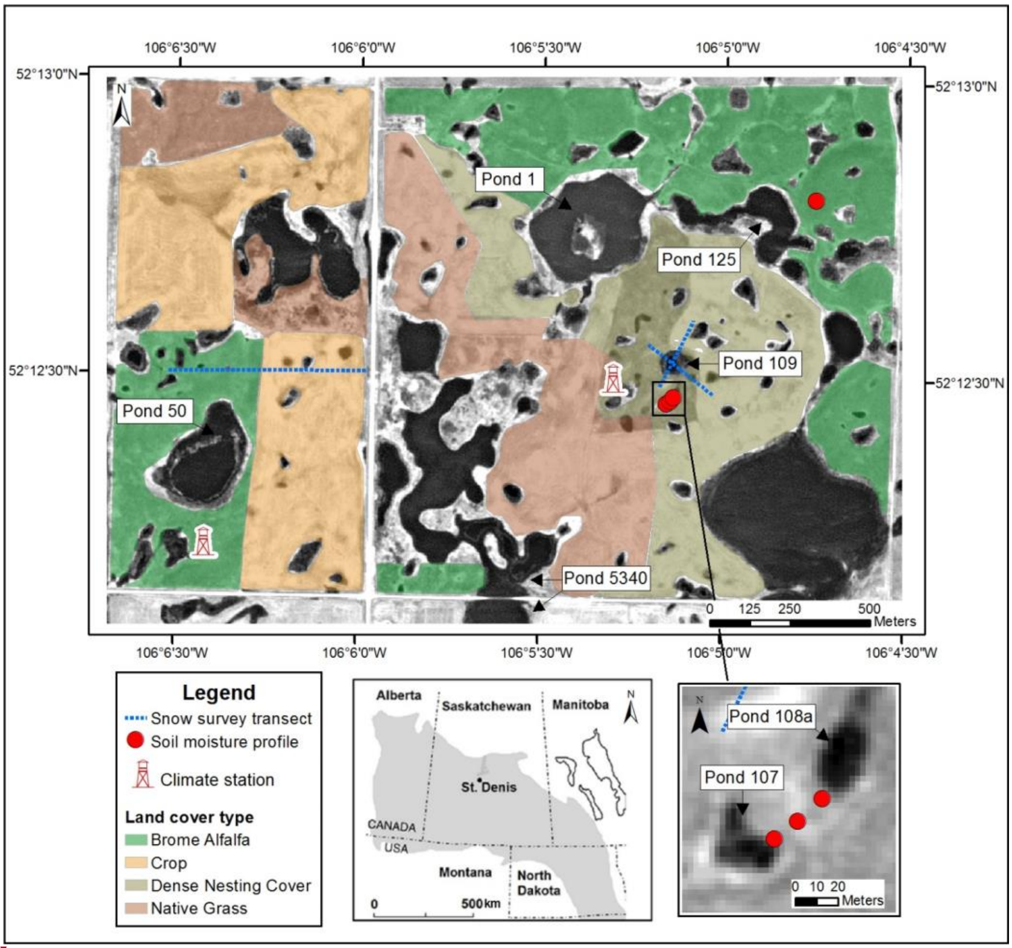

Figure 1: Map and location of St. Denis National Wildlife Area. The grey area on the inset map represents the extent of Prairie Pothole Region in North America.

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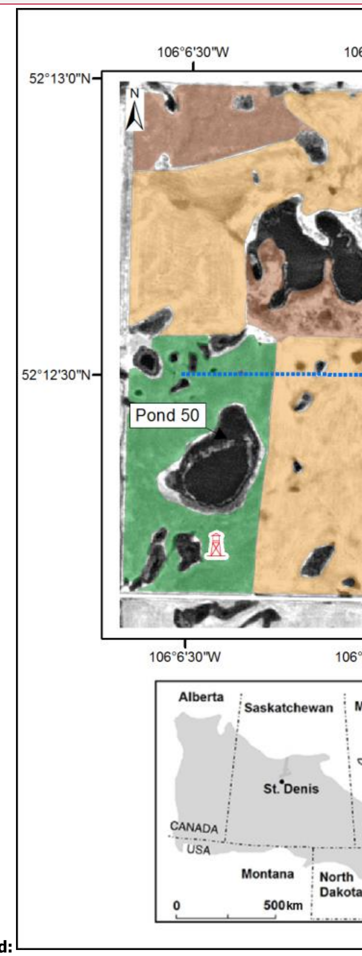

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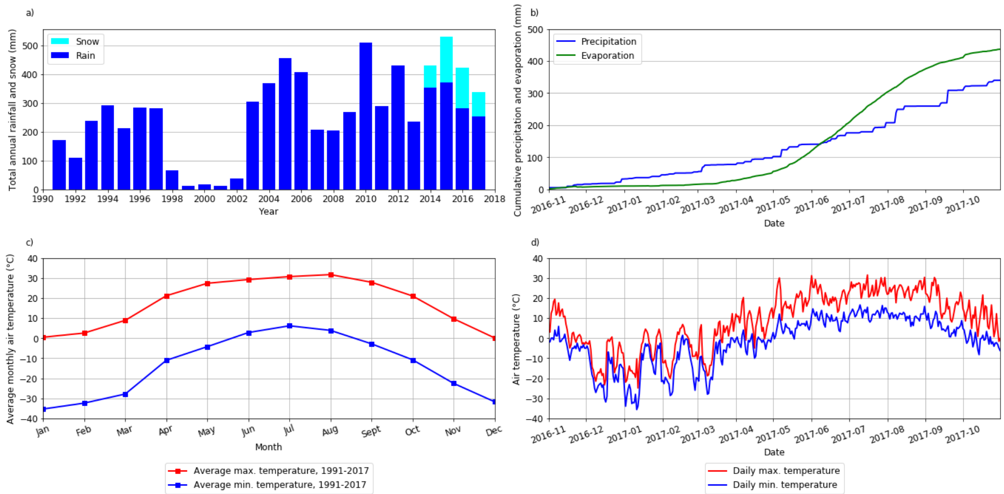

<u>**Figure 2: Meteorological data from SDNWA: a) the total annual rainfall for the period of record (1991-2017) and annual snowfall (only available 2014-2017); b) cumulative total precipitation (rain and snow) and evaporation for the 2016-2017 hydrologic year; c) mean monthly air temperature at 2 m for the period of record (1991-2017); and d) daily air temperature for the 2016-2017 hydrologic year.**</u>

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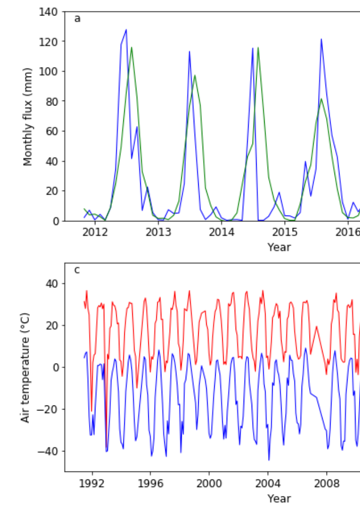

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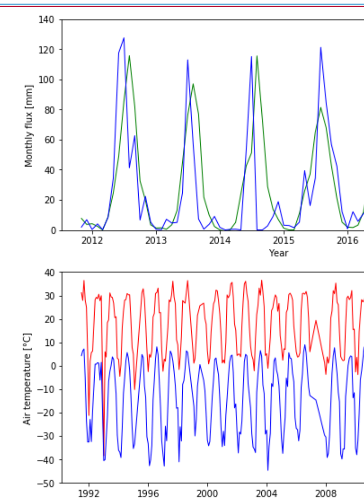

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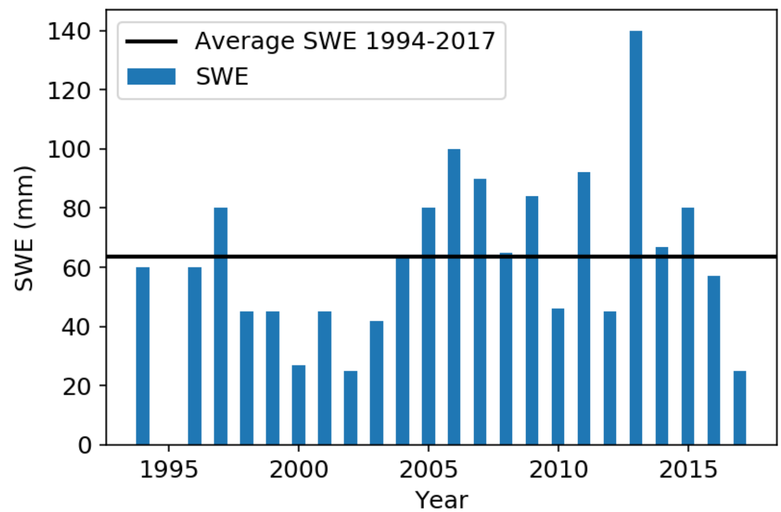

Figure 3: Weighted mean snow water equivalent (SWE, blue bars) of snowpack before melt over SDNWA. The black line represents the 24-year average of snow accumulation.

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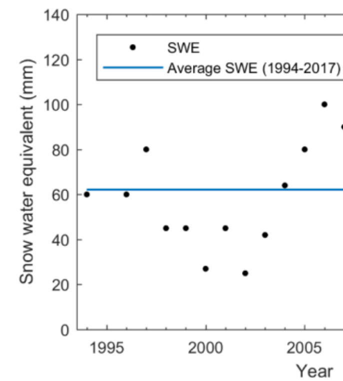

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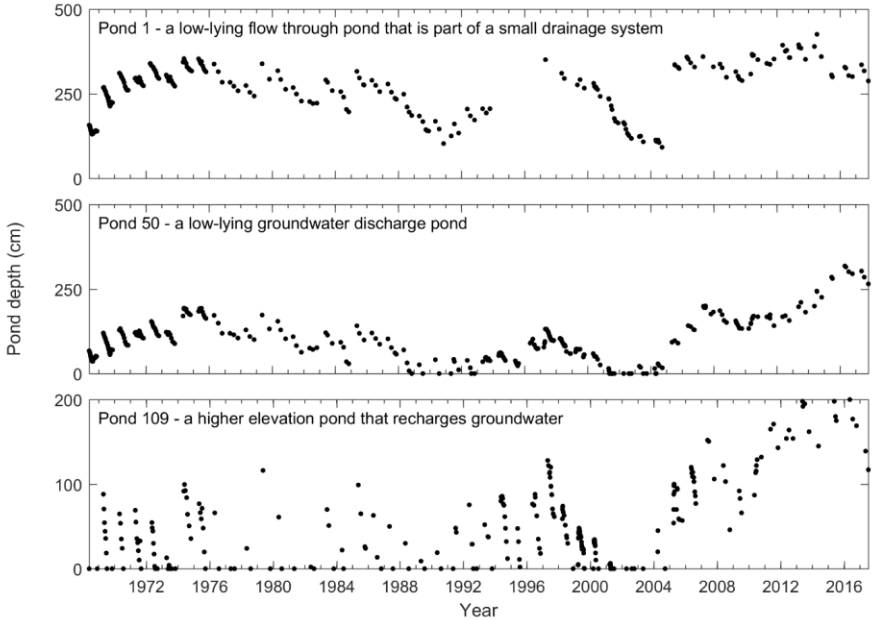

Figure 4: Hydrographs of ponds in Wetlands 1, 50 and 109.

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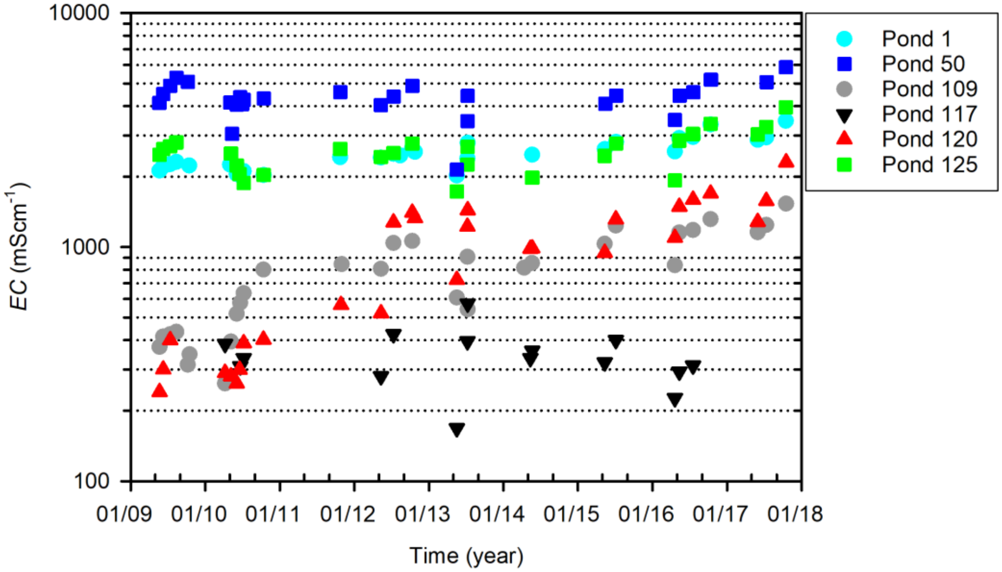

Figure 5: Time series of pond water electrical conductivity (log scale) at St. Denis showing the variations in pond salinity.

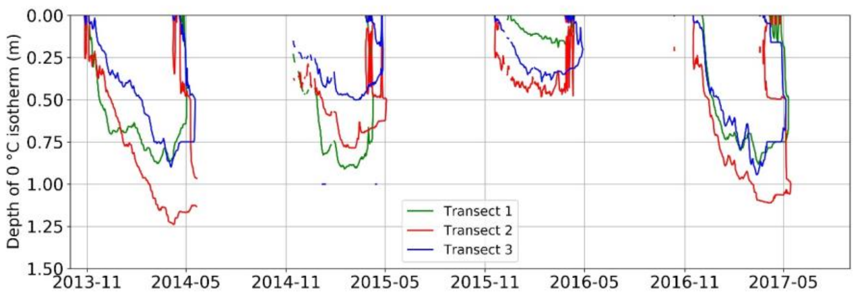

Figure 6: Soil freezing depths in three soil profiles near Pond 109

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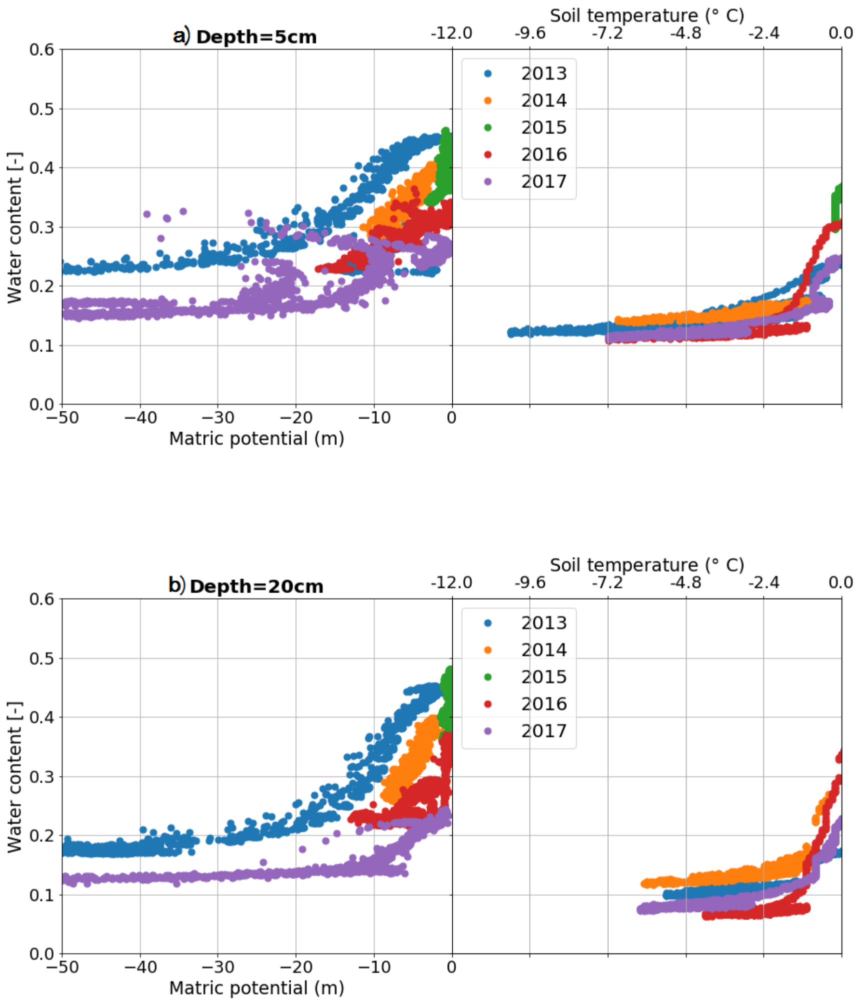

Figure 7: Observed soil water content and soil freezing characteristic of the Upslope profile at 5 cm and 20 cm depths at St. Denis.

Note that the water content data for the freezing condition of 2015 is not recorded in Fig. 7b since soil temperature at 20 cm depth was always above 0 ^{0}c.

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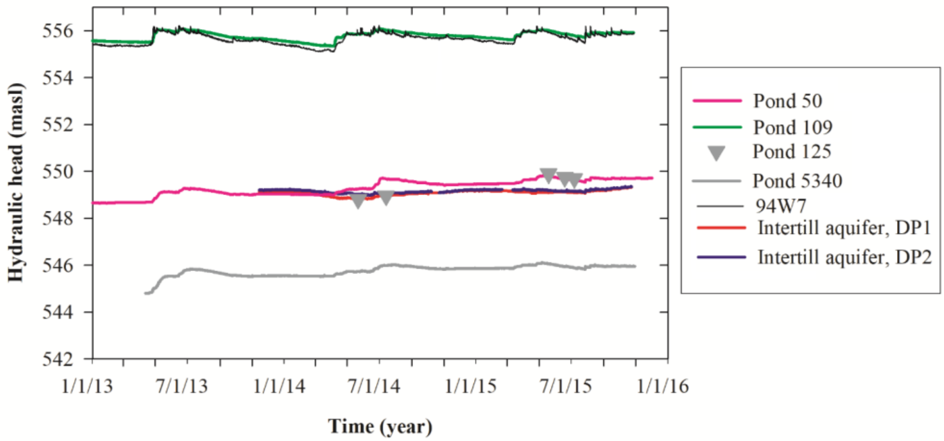

Figure 8: Groundwater and surface water levels in St. Denis.

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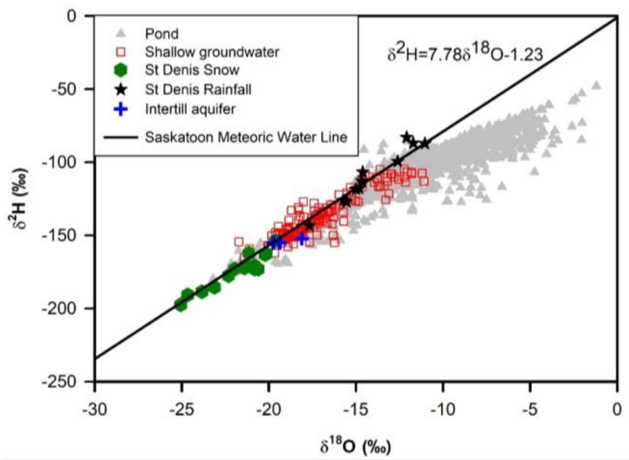

Figure 9: A scatter plot of δ^2H versus δ^{18}O at St. Denis, Saskatchewan.

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Tables

Table 1: Long-term meteorological instrumentation at St. Denis National Wildlife Area

10 m mast		
Variable	*Height (m)*	*Sensor*
Wind speed (ms^{-1})	10	RM Young 5103
Wind direction (°)	10	RM Young 5103
Air temperature/ Relative humidity (°C /%)	2	Vaisala HMP series
Photosynthetically active radiation (Wm^{-2})	1	LiCor Li190SB
Incoming solar radiation (Wm^{-2})	1	LiCor Li200X
Rainfall (mm)	0.5	Texas Electronics TE525M
10 m scaffolding tower		
Variable	*Height (m)*	*Sensor*
Wind speed (ms^{-1})	2	Met One 14A
Wind direction (°)	10	NRG
Air temperature/ Relative humidity (°C /%)	10	Vaisala HMP series
Air temperature/ Relative humidity (°C /%)	1.5	Vaisala HMP series
All component radiation (Wm^{-2})	10	Kipp and Zonen CNR4
Turbulent fluxes (C, Qe, Qh) (Wm^{-2})	10	Campbell Scientific CSAT3; EC150
Rainfall (mm)	10	Texas Electronics TE525M

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