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2014 Update on Baseline Hydrological Monitoring at Big Meadow Bog, Brier Island, Nova Scotia

G. W. Kennedy, J. Drage and C. Nixon

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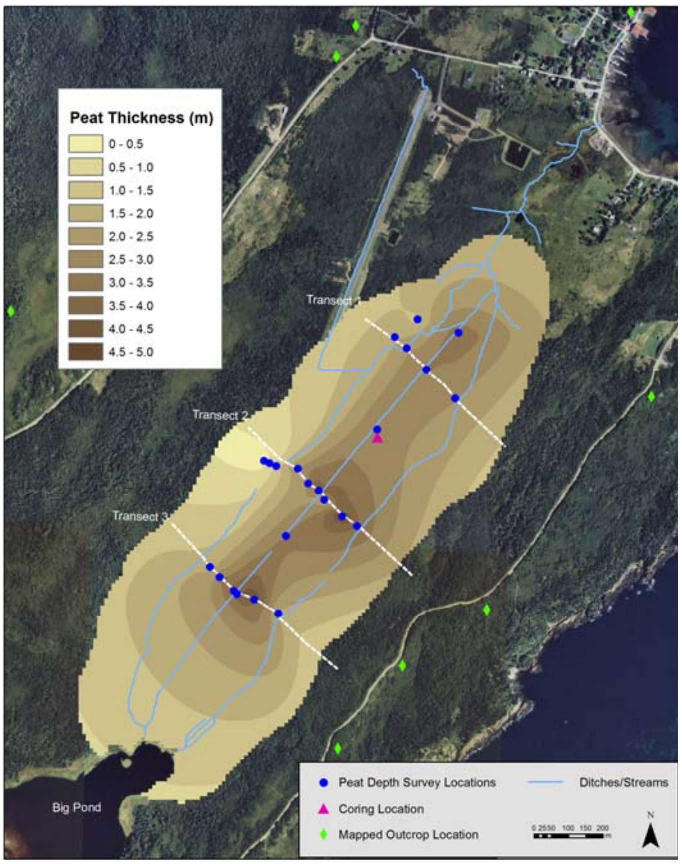

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Introduction

The Geological Services Division of the Nova Scotia Department of Natural Resources (DNR) is assisting with the baseline hydrological characterization of the Big Meadow Bog on Brier Island, Digby County. Big Meadow Bog is an approximately 40 ha wetland complex that has been impacted by drainage activities, especially in the late 1950s when drainage ditches were dug and modifications to natural drainage channels were made in order to cultivate a berry and/or celery farm. The baseline hydrological characterization work was initiated in the summer of 2013, and the results of this work, including additional details about the site and disturbances, are available in Kennedy and Drage (2015). The Nature Conservancy of Canada owns approximately one quarter of the central basin bog and is interested in managing the wetland complex to preserve its high ecological value. Of special ecological interest associated with the wetland complex are rare and unusual plant species, including various orchids, curly grass fern (*Schizaea pusilla*), livid sedge (*Carex livida*), northern dwarf birch (*Betula michauxii*) and eastern mountain avens (*Geum peckii*) (Hill, 2014).

Eastern mountain avens was first identified in Big Meadow Bog in 1949 (Atlantic Canada Conservation Data Centre, 2013), and is one of the most globally rare plants occurring in Atlantic Canada. The only important populations of eastern mountains avens are found on Brier Island, at Harris Lake (located approximately 20 km northeast of Brier Island on Digby Neck), and in the White Mountains of central New Hampshire (COSEWIC, 2010). The plant is listed as a species at risk on Schedule 1 of the federal *Species at Risk Act* and endangered under the Nova Scotia *Endangered Species Act*. Although avens populations have persisted in the wetland complex, there is concern that the extensive agricultural ditching of Big Meadow Bog that took place in the 1950s will ultimately result in the peatland transitioning to a drier, terrestrial environment, which may threaten the long-term survivability of the plant. An interpretation of hydrological changes observed at the site over the past 90 years, and a brief literature review of the impacts of drainage ditches on bogs and rewetting techniques are available in Kennedy and Drage (2015).

As part of the recovery strategy for eastern mountain avens (Environment Canada, 2010), GSD staff are working to develop an understanding of the current hydrology of Big Meadow Bog. The objective of the 2014 work was to continue the characterization of hydrologic change and baseline hydrological conditions in order to evaluate options to stabilize or restore the peatland and limit the threat of avens habitat degradation.

Study Site

Big Meadow Bog is located on Brier Island, a small (1700 ha) island off the western-most tip of Nova Scotia, where the Bay of Fundy meets the Gulf of Maine (Fig. 1). Big Meadow Bog is a wetland complex, with the wetland type varying with elevation from upland slope swamp and fen to a central basin bog (NWWG, 1997). The basin bog has an elongate shape, is 350 to 450 m wide and stretches approximately 1800 m from the community of Westport in the northeast to Big Pond in the southwest (Fig. 1). The wetland complex drains to Grand Passage to the northeast, and to a barrachois connected to the Gulf of Maine to the southwest. Historical air photos indicate that the barrachois has experienced episodic barrier breaches.

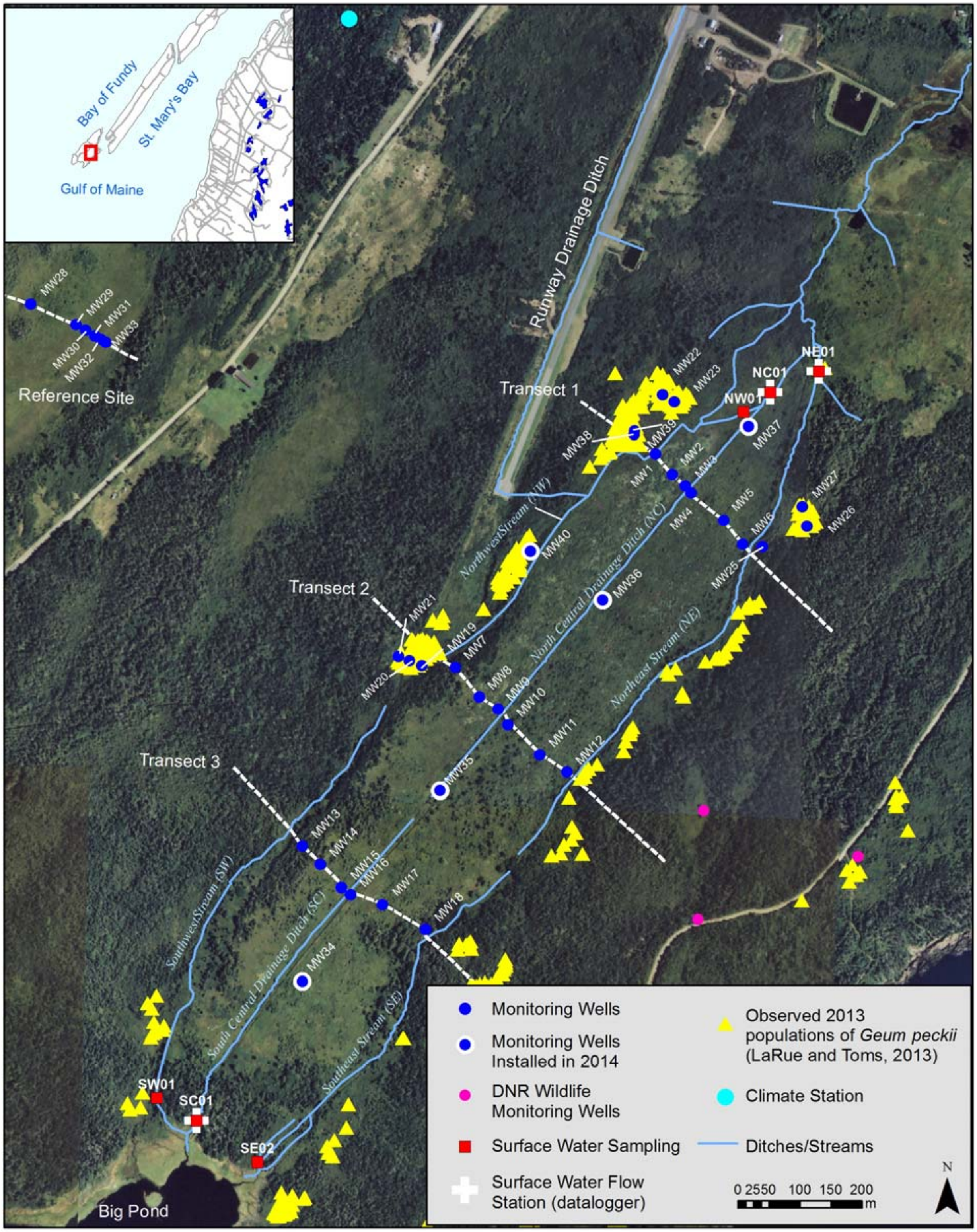

Figure 1. Air photo of Big Meadow Bog, showing location of monitoring wells, surface water stations and transects, and eastern mountain avens (*Geum peckii*) populations based on the 2013 population survey. The peripheral streams define the approximate extent of the basin bog.

An undisturbed reference site located northwest of Big Meadow Bog is incorporated into the baseline study (Fig. 1). It is classified as a fen-bog peatland complex and has similar dimensions as Big Meadow Bog. Climate normals are not available for the island; however, available records from Environment Canada (2014) show that total annual precipitation between 1988 and 1992 averaged 1146 mm, and annual mean temperature was 6.6^{o}C using monthly data from the Environment Canada climate station located in the Village of Westport (Station ID 8206260). These climate data also show that August is typically the driest month of the year and October the wettest.

Depositional History

Big Meadow Bog occupies a bedrock depression of unknown depth in Triassic North Mountain Formation basalt (Kontak and Webster, 2010). The surrounding region is mantled by discontinuous, stony till-plain deposits that were deposited by the Laurentide Ice Sheet during the last glacial maximum (~20,000 years ago; Stea *et al*., 1992). The modern surface elevation of the bog ranges from about 6-10 m above mean sea level (msl) and has a domed profile.

The stratigraphic profile of Big Meadow Bog was recently characterized at a central location in the bog (Fig. 2) by digging a 1.1 m pit and subsequently coring to 3.2 m depth using a vibracore (Spooner *et al*., 2014; Spooner, pers. comm., January 24, 2015). The stratigraphic profile is generally described as 2.4 m of *Sphagnum* peat underlain by marine sand. Cyclical successional changes over time along a marsh-swamp-fen-bog gradient are recorded in the profile. An 8 m core collected from a bog (‘Lighthouse Bog’) approximately 1 km west of Big Meadow Bog shows 5 m of peat underlain by 2.3 m of gyttja (organic-rich clayey sediments), which in turn overlies ~0.7 m of sand and gravel (Stea and Mott, 1998). Radiocarbon dates on shell fragments enclosed in the basal marine sand and gravel from this core (15,180-16,580 calibrated years before present; henceforth cal BP) are consistent with the timing of deglaciation of the outer Bay of Fundy (~14,800-15,500 cal BP; Shaw *et al*., 2006; Stea *et al*., 2011). The elevation of relative sea level (RSL) at the time of deglaciation (i.e. marine limit) has not been mapped on Brier Island, but was likely around 20-30 m above modern mean sea level (Shaw *et al*., 2002; Stea *et al*., 2001). The shell fragments in the marine sand are ~7.5 m above modern mean sea level and were thus deposited in water depths of ~17-18 m.

Following deglaciation, glacioisostatic rebound would have been initially rapid, forcing RSL to fall to a lowstand of -20 to -30 m (Shaw *et al*., 2002). The timing of the lowstand is unknown, but in the northwestern Gulf of Maine, USA, Kelley *et al*. (2010) report rapidly falling RSL (approximately -4 cm/year) from deglaciation to ~12,300 cal BP when a lowstand of -60 m was reached (Kelley *et al*., 2010; Kelley *et al*., 2013). The decreasing RSL trend was followed by a period of rapidly rising RSL (20 cm/year), a ‘slowstand’, and finally a slow but steady rise to the present mean sea level.

Much of the modern extent of Brier Island, including Big Meadow Bog and the Lighthouse Bog to the west, would have been submerged during the deglacial and early postglacial periods. As RSL fell and then rose to modern msl, Brier Island transitioned to a variety of terrestrial environments. A detailed, local RSL curve is required to determine the precise timing of the transition of Big Meadow Bog from marine to terrestrial; however, the shelly sand and gravel observed at the base of the core from the Lighthouse Bog is clearly marine. As RSL fell several tens of metres offshore and then rose back up to modern msl, stagnant, but fresh water, and the return of vegetation to the newly deglaciated terrain would have allowed for the slow accumulation of peat in the central basin lowland of the island. Spooner *et al*. (2014) suggested that during the late Holocene (i.e. last ~4000 years), climate variability in Nova Scotia, particularly changes in precipitation, created significant fluctuations in effective groundwater levels, which would have influenced the types of plant species able to colonize the wetland as well as the nature of sedimentation into the lowland.

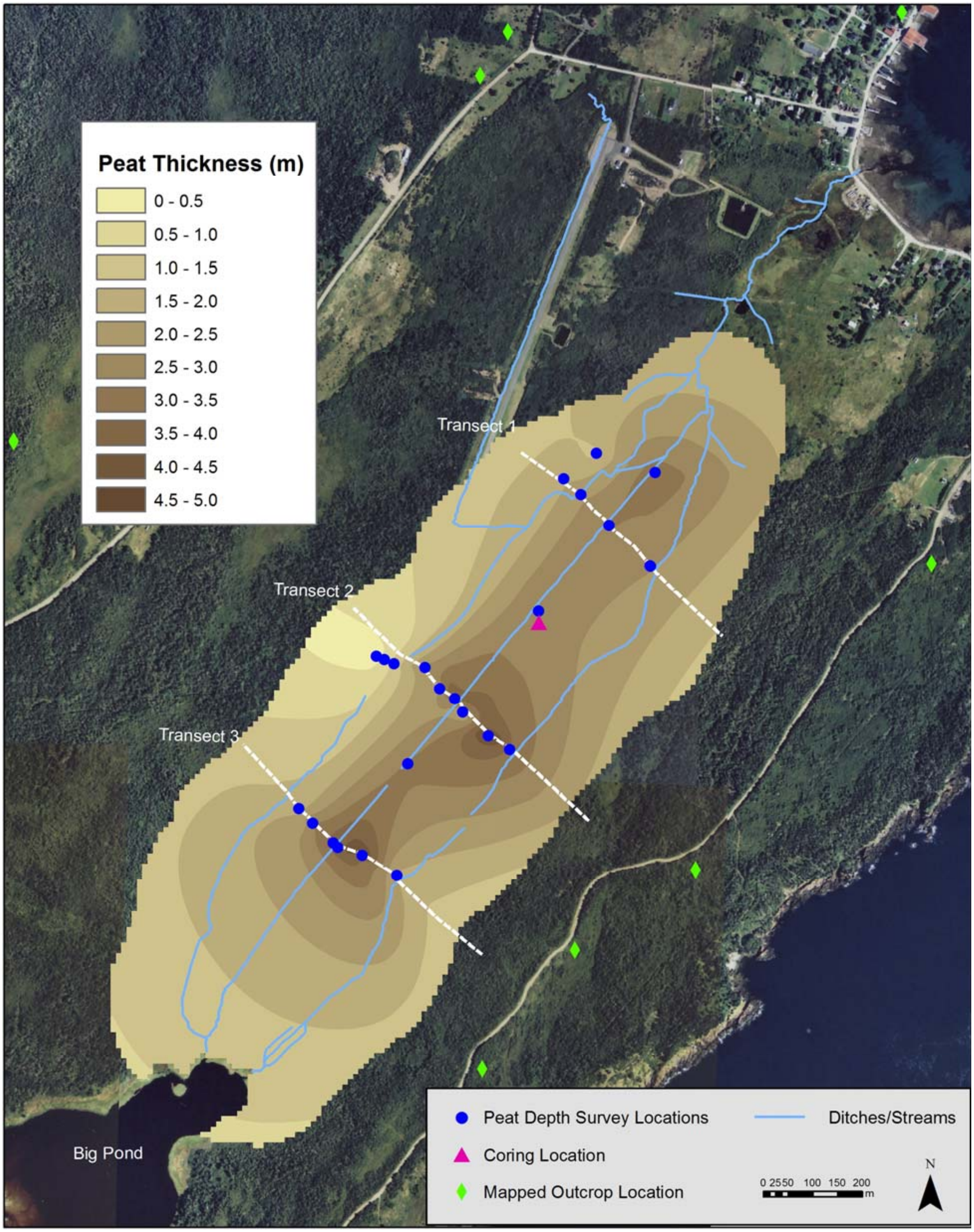

Figure 2. Interpolated (natural neighbour) peat thickness.

Methods

Climate Data

Daily precipitation records (April 30th to October 31st, 2014) were obtained from an Environment Canada climate station (Environment Canada, 2014; station ID 8200604) located near the northern tip of Brier Island and from a local climate station operated by the Applied Geomatics Research Group (AGRG) (Fig. 1). A description of the AGRG climate station instrumentation is available in Webster *et al*. (2015). Potential evapotranspiration was calculated by AGRG using the FAO Penman-Monteith equation (Allen *et al*., 1998), and used as input into the MIKE-11 hydrodynamic model to calculate actual evapotranspiration, which was dependent on the modelled degree of saturation of the root zone.

Monitoring Wells

Additional monitoring wells were installed in 2014 to improve the resolution of groundwater-level mapping (Fig. 1). Details on 2013 well installation and site instrumentation are available in Kennedy and Drage (2015). In 2014, four monitoring wells were installed in hand-augered boreholes along a longitudinal transect for the collection of groundwater-level and -chemistry information. A well was installed near a population of eastern mountain avens located in the western fen margin of Big Meadow Bog between Transect 1 and 2. The wells were all 1.5 m in length and were constructed using 25 mm diameter PVC pipe. The PVC pipe was perforated by drilling 5 mm diameter holes at 5 cm intervals starting 30 cm from the top of the well and continuing to the bottom of the pipe. The bottom of the wells were capped with a PVC pipe-cap to prevent the well from in-filling with peat during installation. The elevations of the monitoring wells were surveyed by DNR staff in 2014 using a Leica Viva GS14 Global Navigation Satellite System. The base station was located over a control monument on Brier Island (monument ID 225862), previously re-surveyed using a nearby high-precision network (HPN) survey monument located on Long Island (monument ID 204271). An additional eight monitoring wells equipped with automatic dataloggers were located in botanical reference wetlands on Brier Island (three bogs, three fens and two shrub swamps) by DNR Wildlife and Biodiversity Division staff (Fig. 1) to help characterize the ecological niche of eastern mountain avens.

Each monitoring well was purged of at least one well volume following installation. Data collection included the measurement of water levels, pH, temperature, electrical conductivity and redox using a Hach field chemistry kit. Manual water level surveys (4) were conducted in April, June, August and October of 2014, and a field chemistry survey was conducted in June 2014. Dataloggers were re-installed in wells MW3 (April), MW9 (April), MW23 (April) and MW14 (August). In June, a new datalogger was placed in MW29, which is located at the reference site (Fig. 1). The monitoring data were assessed for groundwater chemistry and groundwater level trends.

Horizontal saturated hydraulic conductivity measurements of the peat were obtained at Big Meadow Bog in October of 2014 using the method described by Hvorslev (1951). Five tests were completed, including four bail tests (i.e. removing water from the well) at existing monitoring wells (MW1, MW4, MW8 and MW14) and one slug test (i.e. adding water to the well) at a well that was temporarily installed specifically for hydraulic conductivity testing (MW14-2). The temporary well was installed within 1 m of MW14. At least one hydraulic conductivity test was completed at each of the three transects shown in Figure 1. Water level responses during the tests were recorded manually with a water level meter and a stop watch.

Peat Thickness

A peat depth survey was carried out in June of 2014 by inserting flexible fiberglass rods (1 cm diameter) into the peat along the established well transects and measuring the depth of refusal, which was assumed to indicate bedrock (or the presence of inorganic sediments overlying bedrock). The location of peat depth measurements were surveyed as described previously for the water wells. A peat thickness isopach map was generated from these data combined with available bedrock outcrop data (Kontak and Webster, 2010) using the natural neighbour interpolation method in ArcGIS (Fig. 2).

Surface Water Chemistry

Surface water chemistry surveys were conducted in August and October of 2014, and samples were collected from the six major drainage channels associated with the wetland complex (Fig. 1). Water samples were submitted to AGAT Laboratories in Dartmouth, Nova Scotia, and analyzed for general chemistry, dissolved metals and total kjeldahl nitrogen. Surface water chemistry was then classified using major cation and anion data (Deutsch, 1997), and compared to available groundwater chemistry data on a Piper diagram.

Results and Discussion

Peatland Morphology

The peat deposit deepens toward the centre of the bog to a maximum thickness of approximately 5 m (Fig. 2). There was reasonably good agreement (±0.25 m) between the peat depth interpreted using the probe technique and the core collected near the centre of the basin bog (Spooner, pers. comm., January 24, 2015; Fig. 2). The thickness and continuity of the marine sand layer interpreted at the base of the core (2.44 to 3.20 m depth) and the lithology of the underlying material (e.g. unlithified sediments or bedrock) are not known. In the wetland adjacent to Big Meadow Bog near MW19, sandy silt was encountered at a depth of approximately 1 m during hand-augering. Marine sand can also be observed at a shallow depth (<0.5 m) underlying peat around the margin of Big Pond.

The presence of *in situ* spruce tree stumps at 90 cm below the modern surface of the bog (dating to ~1720 cal BP; Spooner *et al*., 2014) and a woody layer at the same stratigraphic level observed in the drainage ditches indicate drier, swampy conditions in the past and an approximate average peat accumulation rate of 0.05 cm/year over the past 1720 years. The woody layer is indicative of rapid and substantial fluctuations in the moisture regime and coincident environmental change (Spooner *et al*., 2014). Subsequent to drainage, it is likely that peat accumulation rates have decreased and peat subsidence is occurring in the central basin bog in response to the lowered water table, although subsidence rates have not been quantified. A comparison of the October 2013 and June 2014 top-of-well-casing elevations showed slightly higher elevations (<3 cm) during the 2014 survey (note conditions were also wetter), but elevation change was considered to be negligible given the error associated with the survey method.

Groundwater Levels

Environment Canada (2014) precipitation records for Brier Island are discontinuous; however, an analysis of mean precipitation from May to October for the 17 years with available data between 1962 and 2013 indicates that 2014 was a slightly drier growing season than is typical on Brier Island, with 5.5% less total precipitation observed in 2014 compared to historical mean totals (512 mm compared to 542 mm). The AGRG rain gauge recorded slightly less total precipitation (-2.5%) than the Environment Canada station over the monitoring period between May 14th and October 15th. Comparison of precipitation and modeled actual evapotranspiration data obtained from AGRG indicates a moisture deficit of approximately 94 mm during this period.

Water level trends for the five monitoring wells with dataloggers are shown in Figure 3. A general decreasing water level trend can be observed over the growing season, although only partial seasonal trends are available for MW14 and MW29 in 2014 due to the later installation of these dataloggers. Similarly, the manual water level surveys showed a decreasing water level trend between April 29th and October 15th in response to the seasonal moisture deficit, as shown in Figure 4 for Transect 1. The magnitude of water level changes tended to be exaggerated near the central drainage ditch (Table 1, Fig 4). The seasonal range of recorded water levels was 0.73 m and 0.46 m in MW3 and MW9, respectively, which are located adjacent to the central drainage ditch, and 0.49 m in MW23, which is located near a population of eastern mountain avens in the western fen margin of the peatland. The water level was below the shallow root zone (<0.20 m of the surface) at MW3 and MW9 for over 84% and 42% of the monitoring period, respectively. Comparatively, the water level was below the shallow root zone for 32% of the monitoring period in well MW23.

The magnitude of short-term water level fluctuation near the central drainage ditch (MW3 and MW9) in response to July wetting and drying events was approximately twice the variability observed in the fen

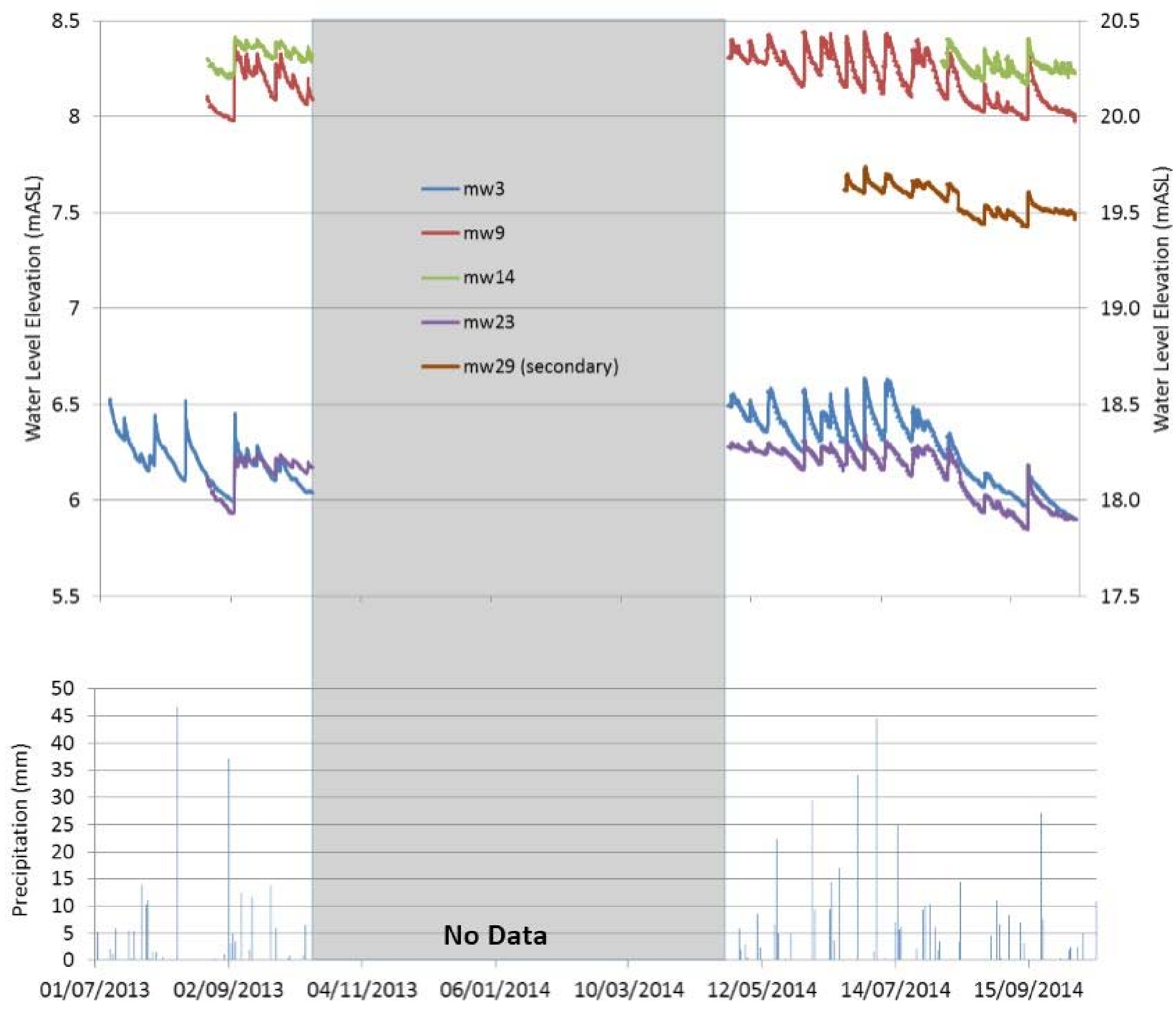

Figure 3. Well hydrographs for MW3, MW9, MW14, MW23, MW29 and rainfall over the study period.

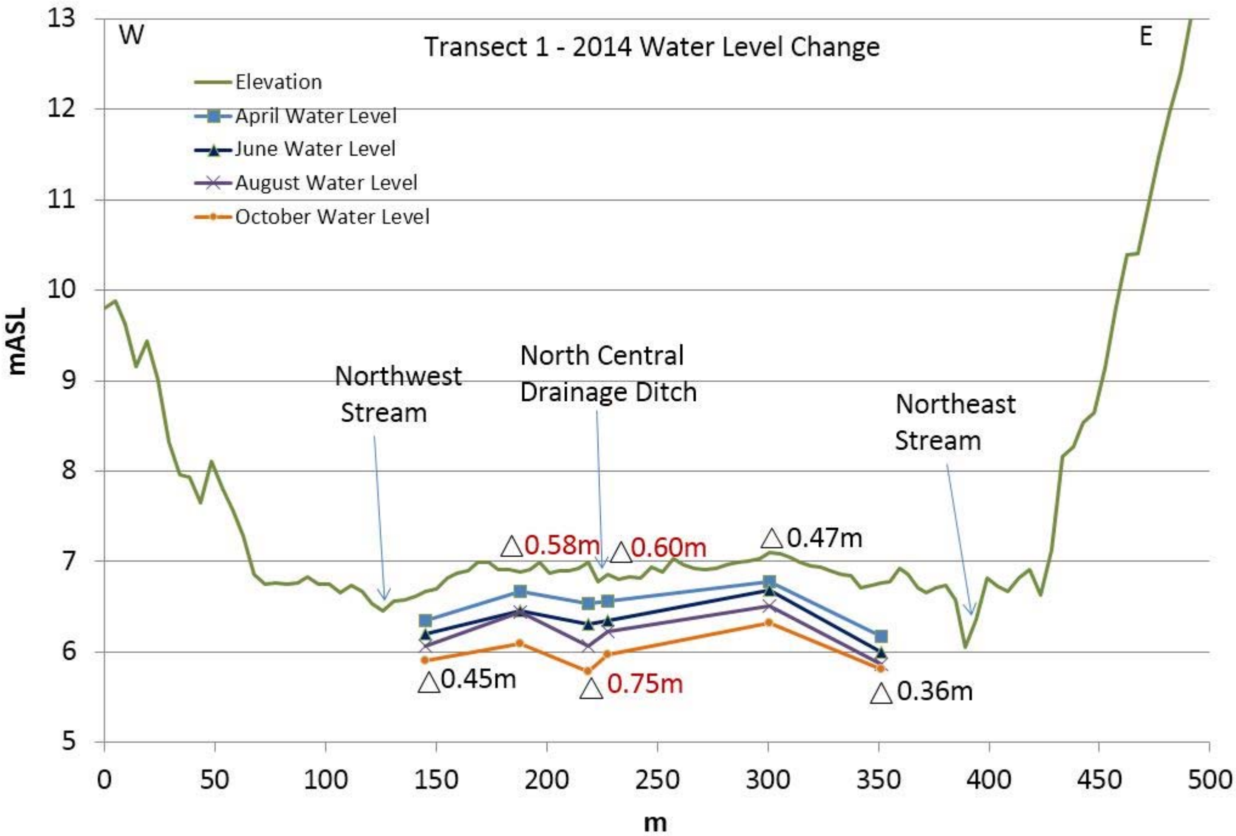

Figure 4. 2014 water level trend at Transect 1, showing greater seasonal change near the drainage ditch.

Table 1. Water level responses in dataloggers for various time periods in 2014.

Monitoring well	Location	Water Level Change (April 30–October 15)	Water Level Change (Wetting, July 5th)	Water Level Change (Drying, July 6th–July 14th)	Water Level Change (Drying, August 15–September 23)
MW3	Transect 1: bog, adjacent to central drainage ditch	0.73 m	+ 0.37 m	-0.31 m	-0.38 m
MW9	Transect 2: bog, adjacent to central drainage ditch	0.46 m	+ 0.31 m	-0.30 m	-0.35 m
MW14	Transect 3: bog, intermediate to central drainage ditch and western bog margin	ND	ND	ND	-0.24 m
MW23	Fen, adjacent to western margin of bog	0.49 m	+0.17 m	-0.15 m	-0.42 m
MW29	Bog–Fen reference site	ND	+0.14 m	-0.13 m	-0.23 m

ND: No data

margin (MW23) and reference site (MW29) (Table 1). All of the monitoring wells, however, showed a marked decline in water levels in response to the mid-August to mid-September drought, although this response was still less pronounced at the reference site (MW29) and at the monitoring well installed between the central drainage ditch and western margin of the bog (MW14) (Table 1). The larger water level decline observed in MW23 in August compared to July, relative to the water level responses observed in other wells, may indicate a change or reversal in vertical hydraulic gradient at lower groundwater levels resulting in reduced groundwater input to this area during the August drying event. Available precipitation data from AGRG (Webster *et al*., 2015) show that the water level response in the monitoring wells to rain events was almost instantaneous (< 1 hour measurement interval for water level dataloggers).

The water-level elevation interpolation using Kriging (ordinary, spherical) in ArcGIS indicates a transverse hydraulic gradient (northwest to southeast) in the southern half of the peatland (between Transect 2 and 3) and a dominant longitudinal gradient (southwest to northeast) in the northern half of the peatland (between Transect 1 and 2) (Fig. 5). The transverse hydraulic gradient across the central basin bog indicates ingress of minerotrophic water from the western upland near Transect 2. This area corresponds to a major drainage area based on modelled flow accumulation (MacDonald and Webster, 2014), conveying runoff and shallow groundwater from the western upland to the central basin bog near Transect 2.

A depth to water-level interpolation using Kriging (ordinary, spherical) for October 2014 shows that the impact of the central drainage ditch on water levels is especially evident at Transect 1 and 3, and within 50 m of the ditch (Fig. 6). Horizontal hydraulic gradients were highest adjacent to the central ditch and the eastern peripheral streams (SE and NE).

Hydraulic Conductivity

The saturated horizontal hydraulic conductivity (K_h) values ranged from $6x10^{-6}$ cm/s to $2x10^{-4}$ cm/s, with a geometric mean of approximately $7x10^{-5}$ cm/s (Table 2). These values are within the range of K_h values reported in the literature for peat 0.1 m below the ground surface, which range from 10^{-1} cm/s to 10^{-6} cm/s (Kellner, 2007). Based on the depth of the monitoring wells that were tested at Big Meadow Bog, these K_h values are generally indicative of conditions between 0.25 and 1.20 m of the ground surface. Water levels in the peatland were low during the October K-testing and the K_h values are therefore representative of deeper, catotelmic layers of the peat.

Surface Water Runoff

Webster *et al*. (2015) provides a delineation of catchment areas associated with Big Meadow Bog (Fig. 7); an interpretation of surface water levels and flows from the NC-NW, NE and SC surface water channels; and rainfall runoff response modelling using MIKE-11, a 1-D hydrodynamic model. A reliable rating-curve calibration could not be achieved for the NE01 and SC01 stations due to insufficient field measurements of discharge, low flows and dynamic channel dimensions (Webster *et al*. 2015), and the analysis presented below should therefore be used with caution. It should also be noted that the NC01 monitoring station captures discharge from the NC drainage ditch and part of the discharge from the NW peripheral stream, which divides into two branches immediately downstream of the pool feature (Fig. 7). It was generally found that baseflow was sustained throughout the summer at the three monitored outlets and that modelled flows were dependent on catchment size, such that the magnitude of discharge rates followed the trend NC-NW>NE>SC. A summary of selected stream level and modelled flow data is presented in Table 3. Minimum flows were interpreted on July 5th at all three outlets and maximum flows on November 18th. Based on the relative size of the catchment areas located within the boundary

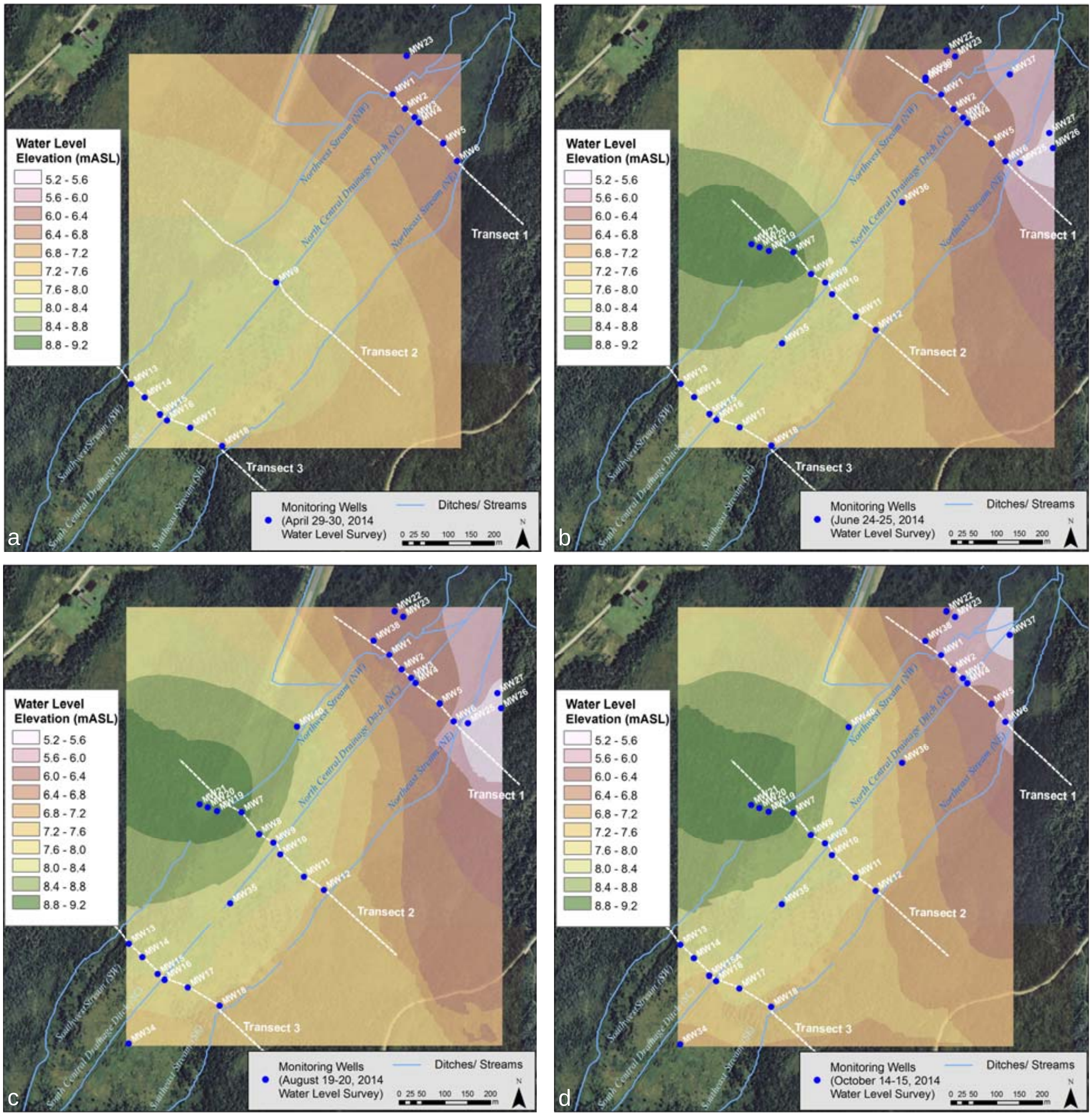

Figure 5. Interpolated (kriging) water level elevation for April (a), June (b), August (c) and October (d) of 2014.

of the central basin bog (Table 3), shallow groundwater and runoff losses from the central bog area are predicted to be greatest to the NC drainage ditch (Fig. 7). The largest modelled surface water discharge from the system occurred over the October–November period of 2014, when evapotranspiration was low and rainfall and antecedent water levels were high. It should be noted, however, that the May 17th to November 30th surface water monitoring program missed snowmelt and early spring conditions.

Two of the monitored catchments (flow stations NC01 and NE01) include runoff from upland minerotrophic areas, whereas the SC catchment (flow station SC01) is located entirely within the central basin bog. The rainfall-discharge response observed at the SC outlet is therefore markedly different from the responses observed at stations NC01 and NE01. Discharge at the SC outlet was characterized by low flows, dominated by baseflow input, with short lag (<1 hour) and recession times. At the two northern

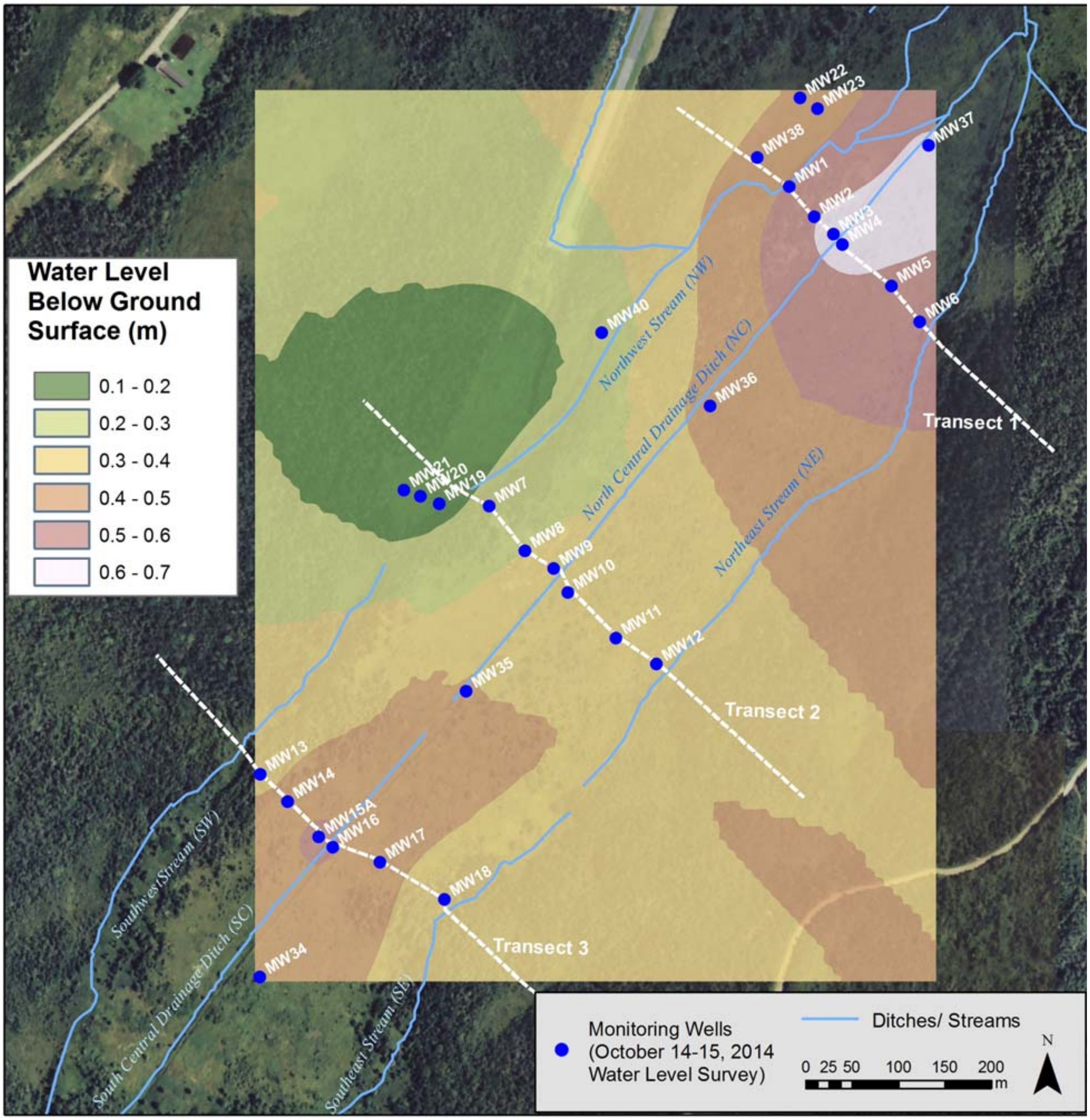

Figure 6. Interpolated (kriging) depth to water level below ground surface for October 2014.

outlets (NC01 and NE01), peak flows were higher and the lag time was longer and more variable depending on the antecedent moisture conditions, showing a 3-6 hour time lag in wet conditions, and an 8-12 hour time lag in dry conditions. In addition, a strong diurnal water-level trend was observed at station SC01, which may be attributed to a combination of tidal cycles and the effect of evapotranspiration on groundwater flow patterns (Webster *et al*. 2015). This diurnal water-level trend was not evident at the NC01 and NE01 stations. Although water levels were not monitored upstream of the confluence of the NC drainage ditch and the NW peripheral stream, the catchment associated with the NC ditch is located entirely within the central basin bog and therefore likely produces a similar rainfall response as observed at the SC outlet.

Table 2. Hydraulic conductivity test results

Monitoring Well	Hydraulic Conductivity, K (cm/s)
MW1	2.69×10^{-4}
MW4	6.10×10^{-6}
MW8	4.24×10^{-4}
MW14	2.24×10^{-5}
MW14-2	1.40×10^{-5}
Geometric Mean	7.38×10^{-5}

It should be noted that the drainage ditch adjacent to the runway redirects runoff to the northwest peripheral stream (NW) and may be an important regular source of water to the small linear pool feature identified in Figure 7. This pool is located near a population of eastern mountain avens. It was also observed that the SE peripheral stream divides into multiple branches before ultimately reconnecting near the outlet to Big Pond (Fig. 7). Although some of the catchments associated with the ditches and streams do not appear to have channelized tributaries to the peripheral streams, major drainage tracks were observed in the field as indicated in Figure 7. Visual observation of the central drainage ditch suggests that it does not behave as an efficient drain. The ditch is partially occluded due to collapsing walls and vegetation overgrowth. The raised ridge of peat cuttings directly east of the central drainage ditch (NC + SC) and the eastern peripheral streams (NE + SE), and directly west of the western peripheral streams (NW + SW) may affect runoff processes, although a more comprehensive field survey of channel configuration and runoff dynamics before and after storm events is needed to assess the connectivity of ditches (i.e. active vs. inactive) and stream features, and how rainfall is transmitted to surface water.

Geochemistry

There are limited available groundwater and surface-water chemistry data available, and previous issues with respect to the groundwater sampling protocol and high sample-turbidity are noted in Kennedy and Drage (2015). The analysis presented below should therefore be used with caution.

Groundwater

The June 2014 field chemistry survey showed a lateral gradient coincident with the swamp-fen-bog gradient with respect to pH, similar to the gradient observed in 2013. Groundwater sampling from the monitoring wells was not conducted in 2014. Nutrient, pH and alkalinity concentrations in monitoring wells sampled in 2013 are summarized in Table 4 (Kennedy and Drage, 2015). Organic nitrogen was typically an order of magnitude higher than inorganic nitrogen in groundwater samples. It was also found that the central basin bog showed lower pH and alkalinity compared to the fen margins of Big Meadow Bog, and elevated inorganic nitrogen and phosphorus concentrations compared to the reference site, fen margins, and values found in the literature (Table 4; e.g. Wind-Mulder *et al*., 1996).

Surface Water

The results of the surface water sampling showed that concentrations of nutrients are higher at the northern surface water outlets of the wetland complex compared to the southern outlets (Table 5). In

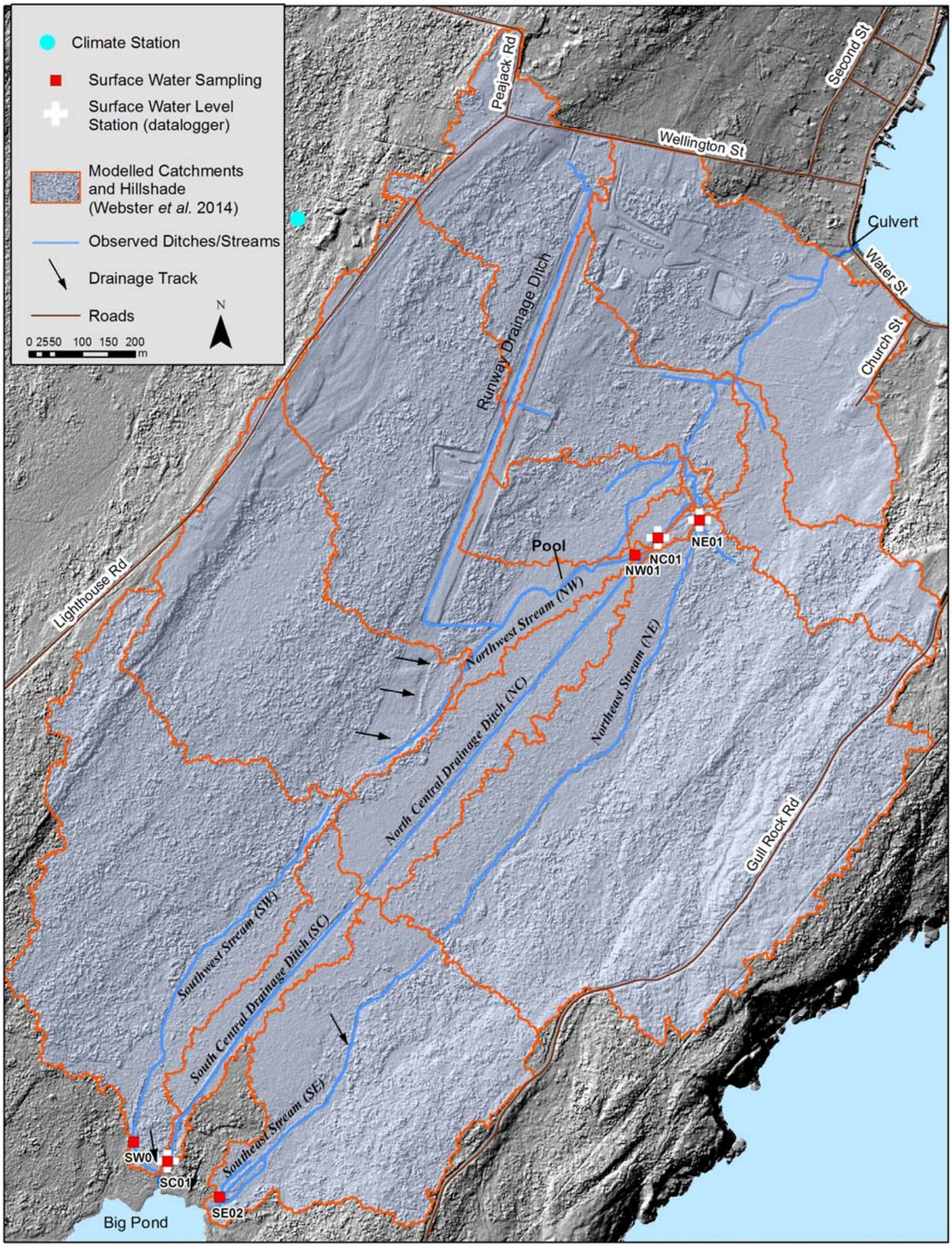

Figure 7. Catchment areas associated with the Big Meadow Bog (after Webster *et al*. 2015)

Table 3. Summary of stream level, and measured and modelled flow results.

Outlet	Approximate Contributing Catchment Size (km^2)	Approximate Sub-Catchment Size[1] (km^2)	Water Level Range (m, May 17th to November 30th)	Measured Flow Range (m^3/s, April 29h to November 3rd)	Modelled Flow Range (m^3/s, May 17th to November 30th)
NC01	0.75	0.13	0.13 to 1.15	<0.001–0.009 (n=5)	0.003–2.53
NW01	0.65	0.025	ND	ND	ND
NC02	0.10	0.10	ND	ND	ND
NE01	0.55	0.094	0.07 to 0.82	0.01–0.067 (n=5)	<0.001–0.68
SW01	0.32	0.044	ND	ND	ND
SC01	0.056	0.056	0.05 to 0.46	0.001–0.004 (n=5)	<0.001–0.083
SE02	0.22	0.071	ND	ND	ND

Area of catchment within approximate boundary of central basin bog
ND: No data

Table 4. Summary of nutrient, pH and alkalinity concentrations from the 2013 groundwater sampling program.

	Inorganic Nitrogen[1] (mg/L)	Organic Nitrogen[2] (mg/L)	Phosphorus (mg/L)	Alkalinity (mg/L)	pH
Central Bog Wells					
Transect 1	1.7–7.2	–	7.2–15.0	<5–22	4.0–5.5
Transect 2	0.5–4.3	5.6–27.0	0.4–12.0	<5–8	3.9–5.0
Transect 3	0.3–3.4	4.7–10.5	0.3–3.7	<5	4.0–4.5
Fen Margin Wells	0.2–1.2	6.8–44.8	0.1–0.8	<5–44	4.4–6.5
Reference Site Wells	0.2–0.4	7.1–10.3	0.3–0.4	<5	3.9–4.1

[1] $NH_3 + NO_3 + NO_2$ (as N)
[2] TKN (total kjeldahl nitrogen) – NH_3

terms of nitrogen fractions, organic nitrogen was generally found to be higher than inorganic nitrogen. Based on limited data with respect to surface water flow and chemistry, the greatest total export of nutrients from the basin bog was likely from the NC drainage ditch and NE peripheral stream. High variability of surface water pH was observed, especially between the August and November sampling events at the southern outlets, with higher pHs generally associated with the summer sampling event (low flow conditions). The lower pH (~1-3 units) measured in the fall should be verified with additional sampling, but could be attributed to a greater relative contribution of groundwater discharge from the bog compared to minerotrophic upland areas when the conditions are wetter.

Water Types

A comparison of water types was conducted using a Piper diagram (Fig. 8). Samples collected from surface water were generally sodium dominated (Na-Cl or Na-HCO_3-Cl type), whereas groundwater samples from the central areas of Big Meadow Bog were generally either Na-Cl or Ca-Na-Cl type. In comparison, samples collected at the reference site were Ca-Na-Cl type. The samples collected from monitoring wells installed in the fen margins of Big Meadow Bog were mainly Na-Cl type, but samples

Table 5. Summary of nutrient, pH and alkalinity concentrations from the 2014 (August and October) surface water sampling program.

	Inorganic Nitrogen[1] (mg/L)	Organic Nitrogen[2] (mg/L)	Phosphorus (mg/L)	Alkalinity (mg/L)	pH
Northeast (NE) Stream System	0.2–1.0	0.2–0.9	0.2	<5–47	5.3–6.9
North-central (NC) Drainage Ditch	0.3–2.4	1.4–3.2	2.0–5.0	<5	3.3–4.7
Northwest (NW) Stream System	0.6–1.3	1.1–4.4	0.7–2.6	<5	3.1–4.9
Southeast (SE) Stream System	0.1–0.4	1.1–1.7	0.2–0.3	<5–22	4.3–6.7
South-central (SC) Drainage Ditch	0.2–1.6	1.2–2.2	0.5–0.6	<5–55	4.4–7.3
Southwest (SW) Stream System	<0.2	1.1–1.5	<0.2	<5–10	4.4–6.4

[1]$NH_3 + NO_3 + NO_2$ (as N)
[2]TKN (total kjeldahl nitrogen) – NH_3

from two wells (MW20 and MW23) showed a greater relative contribution of calcium and bicarbonate alkalinity (Ca-Na-HCO_3-Cl type), similar to the bedrock aquifer water sample. Higher background concentrations of sodium and chloride are expected at Big Meadow Bog compared to inland peatland sites due to the local deposition of sea-salt aerosols.

Summary and Perspectives

A more rigorous delineation of wetland types and morphology associated with the Big Meadow Bog wetland complex is needed; however, a simplified cross-section illustrating the conceptual understanding of the wetland system's structure and hydrological functioning is presented in Figure 9. The trends in water levels were similar in 2013 and 2014. The impaired ability of the peatland to regulate water level responses is highlighted by comparing water level responses in wells located along the central ditch to those at the reference site and at locations intermediate to the central ditch and peripheral streams (e.g. MW14).

Lowered water levels in the central area of Big Meadow Bog due to the effect of the site drainage modifications can be clearly observed. The water level depression is especially evident at Transect 1 and 3, and during periods of high moisture deficit (Kennedy and Drage, 2015). The magnitudes of water level impacts are difficult to quantify without pre-disturbance baseline data. Nevertheless, the basin bog clearly shows more water-level variability compared to the reference site (~2 X), and water level change is exaggerated toward the centre of the transects near the central drainage ditch. The greatest water level variability was observed at Transect 1, whereas water levels along Transect 2 were the highest and most stable, which may be attributed to inefficient drainage and water accumulation from adjacent upland areas. The fen margins of the bog, which host eastern mountain avens populations (e.g. MW23), generally showed higher and more stable water levels than the monitoring wells located within the basin bog along Transect 1. The position and extent of the transitional lagg has not been rigorously defined for Big Meadow Bog, although the inferred location is along the peripheral eastern and western streams. The lagg has an important role in maintaining high water levels in raised bogs (Schouwenaars, 1995), and it is not known how past drainage activities have affected this regulatory function.

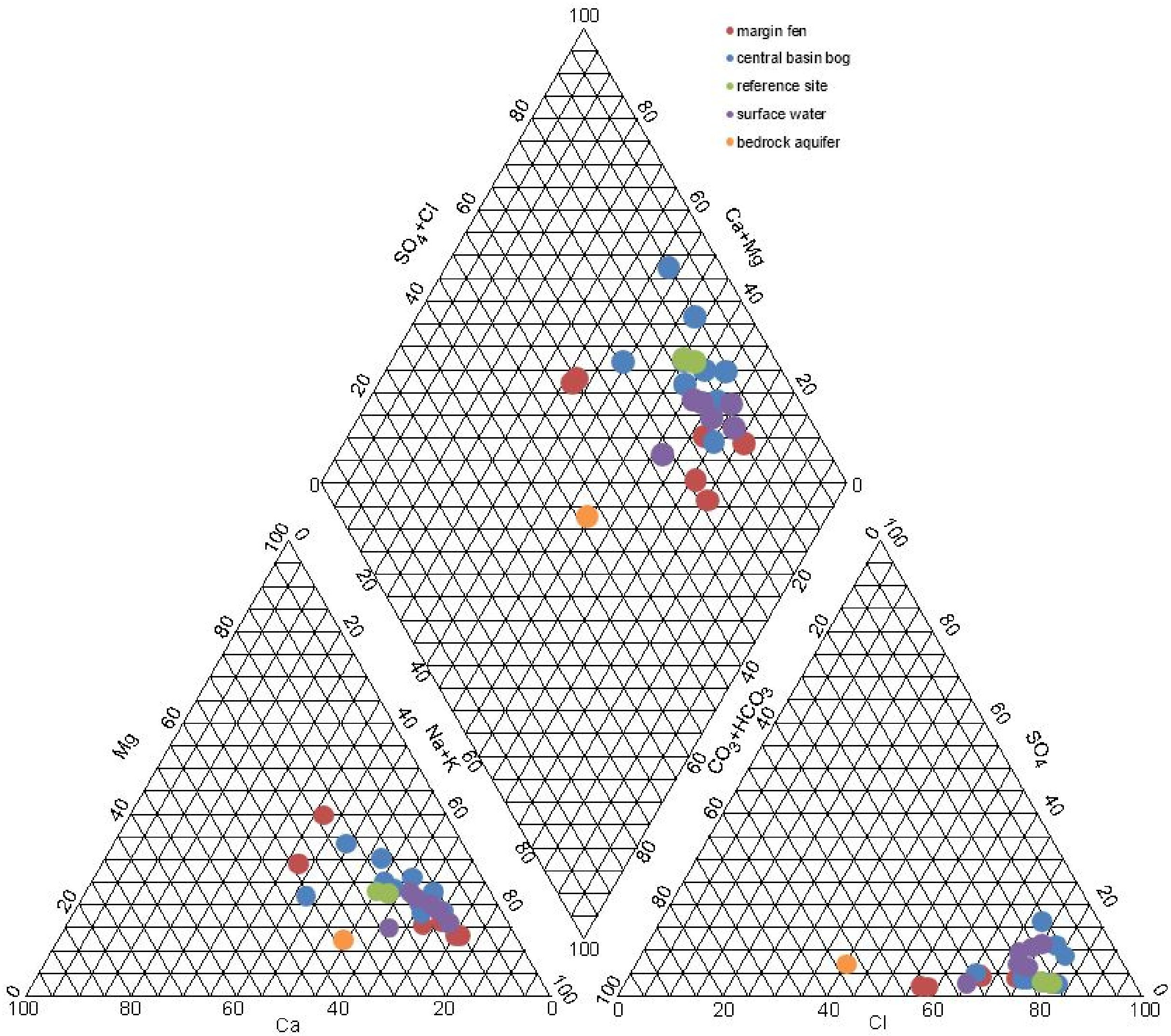

Figure 8. Piper diagram of major ion concentrations for groupings of samples.

The greatest horizontal groundwater flow gradients were interpreted near the northeast and southeast peripheral streams (within 100 m of the streams), especially at the northeastern end of the bog, suggesting that groundwater discharges to surface water from the central bog are also greatest in these areas (Figure 9). Based on a limited survey, the saturated horizontal hydraulic conductivity, representative of deeper peat layers (0.2 to 1.2 m depth) of the bog, was heterogenous, but typical of peats. Vertical hydraulic gradients using multi-level piezometers were not measured during the current baseline program, although Brown (2003) previously reported that the central ditch caused a small upward vertical hydraulic gradient immediately adjacent to the ditch and downward vertical gradients at distances ranging from 10 to 40 m from the central ditch based on measurements in four piezometer nests installed along Transect 3. A greater understanding is needed with respect to vertical hydraulic gradients, spatial variability of hydraulic conductivity (vertical and horizontal), groundwater flow connectivity between the peat and underlying sediment and bedrock, and the role of the basal sand layer interpreted in the peat core, which may redistribute pore pressures across the bog.

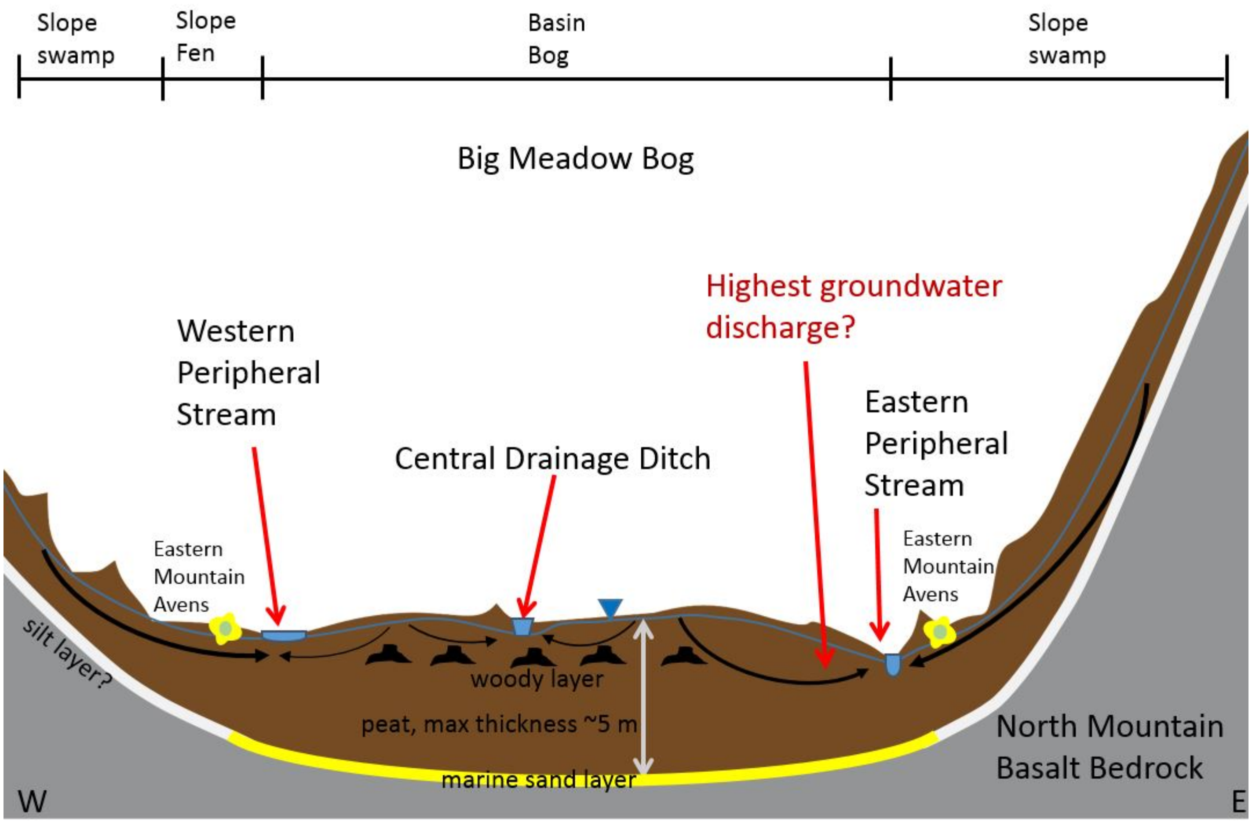

Figure 9. Conceptual illustration of Big Meadow Bog system along Transect 1.

The observed horizontal hydraulic gradients suggest that the central basin bog is not hydrologically isolated from the western upland, with ingress of minerotrophic water near Transect 2. The pH and major ion chemistry across the peatland, however, is generally consistent with an ombrotrophic bog, indicating that the majority of the basin bog does not receive significant water inputs from underlying bedrock or upslope minerotrophic areas. The major ion chemistry (e.g water type) is similar among surface water, the central bog, the fen margins and the reference site, but some of the monitoring wells installed in the fen margin near eastern mountain avens populations show higher relative contributions of bicarbonate alkalinity.

Organic nitrogen accounted for the majority of total nitrogen in the groundwater and surface water samples. In comparison to previously reported values for bogs (e.g. Wind-Mulder *et al*., 1996), much higher nutrient levels were detected in Big Meadow Bog, which maybe due to nutrient enrichment from gulls. The highest nutrient concentrations in groundwater and surface water were associated with the northern part of the bog (Transect 1 and the northern surface water outlets) where the most intense gull nesting activity was observed. Similarly, analysis of available flow data indicates that the greatest export of dissolved inorganic nitrogen and phosphorus corresponds to the northern outlets and occurs during the fall season, coinciding with higher runoff rates and plant senescence. Additional characterization of nutrient loading to receiving waters, especially during fall and early spring, is warranted. Undisturbed ombrotrophic bogs derive the majority of their nutrients from atmospheric deposition and are especially sensitive to nitrogen enrichment. Over longer terms, high nitrogen deposition is associated with increased phosphorus availability, increased vascular plant biomass and leaf area index, and a decrease in coverage of *Sphagnum* species (Thormann and Bayley, 1997; Bubier *et al*. 2007). The availability of these nutrients, therefore, may have a long-term effect on the bog's vegetation-community dynamics and impede restoration efforts. More study is also needed on potential contaminants of concern that may be present in the wetland complex, such as methyl mercury.

The coring work (Spooner, pers. comm., January 24, 2014) did not intercept bedrock, and therefore the complete surficial stratigraphic profile of the peat system is not known. As expected, the interpreted peat thickness was greatest towards the centre of the basin bog, although the raised bog character noted in historical descriptions of Big Meadow Bog is no longer evident in some areas, especially near the central drainage ditch (MacDonald and Webster, 2014). These areas are likely experiencing higher rates of subsidence due to greater water level drawdowns and concomitant oxidation, shrinkage and secondary compression processes (e.g. Kennedy and Price, 2005). Along the northeast-southwest axis, a domed profile can still be readily observed (MacDonald and Webster, 2014). In order to assess the degree of structural change and impairment due to drainage, more study would be needed on the physical structure and properties of the peatland (e.g. decomposition and bulk density).

The components of the site's water balance have not been quantified, and seepage losses or groundwater interaction with underlying sediments is not known. However, it is expected that the principal mechanisms for water losses from the central basin bog include evapotranspiration and groundwater discharge to the central ditch and peripheral streams. Surface water discharge was found to be greatest in 2014 during late fall when a series of large rain events occurred and evapotranspiration losses were low (Webster *et al*. 2015). Total discharge during this period, however, may have been lower relative to an undisturbed system due to the low antecedent water levels and the greater available water storage capacity associated with the disturbed peatland system. Surface water discharge in early spring was not captured by the flow monitoring program, although it is expected that water losses to drainage ditches and peripheral streams during this period would represent a significant portion of total annual water losses from the peatland. Due to the site's coastal setting and more moderate winters, however, snowmelt is less likely to be an important contributor to spring discharge compared to inland wetland sites.

Discharges from the central basin bog to the northern and southern outflows of the central ditch are estimated to be of similar magnitude. The central drainage ditch does not convey much water during the growing season, displaying a muted discharge response to rain events compared to the peripheral streams. It does, however, appear to sustain continuous baseflow through groundwater discharge to the ditch (Webster *et al*. 2015). The stream modifications (e.g. dredging) along the eastern side of the basin bog have also likely resulted in higher horizontal hydraulic gradients and enhanced groundwater discharge to the NE and SE streams relative to pre-disturbance conditions. The observed surface water discharge dynamics suggest that drainage modifications have redistributed discharge patterns both spatially and temporally resulting in lower peak flows in the peripheral streams following large rain events (especially when water levels are low) but higher water losses sustained through groundwater discharge to the peripheral streams and central ditch between rain events (i.e. baseflow component).

Evapotranspiration patterns have also been affected by the drainage modifications. Higher rates of evapotranspiration are inferred in the central part of the basin bog due to the presence of the ditch and the change to woody vegetation. The overall shift in vegetation across the bog has likely resulted in increased rates of interception and evapotranspiration, which may be partially offset by lower water levels that limit the availability of water for evapotranspiration. Water balance components such as evapotranspiration, groundwater discharge to peripheral streams and streamflow at all six outlets, should be monitored to better understand the site water balance.

The Big Meadow Bog is not a stable system: water levels are lowered and more variable as a result of the changes to interception, evapotranspiration and runoff patterns. These conditions are not conducive to the survival or colonization of peat-forming vegetation, such as non-vascular *Sphagnum* species. The combined effect of hydrological modifications to the wetland complex and nutrient enrichment from herring gull populations favours afforestation and displacement of native or pre-disturbance species. An analysis of the site's existing plant communities and historical vegetation change patterns is being conducted under companion research (e.g. MacDonald and Webster, 2015). More study is needed to improve our understanding of the effect of site disturbances on populations of eastern mountain avens, although given that this rare species is associated with moist, cool habitats (Hill, 2014), the observed changes to a drier, more terrestrial system could threaten their long-term survivability. Preliminary findings with respect to horizontal hydraulic gradients and surface water flow dynamics suggest that interventions to reduce water losses from the peatland should be concentrated on the central drainage ditch and eastern peripheral streams.

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