HYDROLOGICAL RESTORATION OF A DRAINED PEATLAND

by

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ABSTRACT

The historical drainage activities in Big Meadow Bog on Brier Island, Nova Scotia have altered the hydrologic regime and physical characteristics of the wetland complex. The high ecological value of BMB, due to populations of Eastern Mountain Avens, was the initial motivation for the wetland to be restored. The effect of the restoration activities on water levels throughout the wetland complex was investigated on two different spatial scales: sitewide and within a focused study plot. The spatial variability of water level recovery was investigated and comparisons were made to a reference wetland.

Growing season water levels were closer to ground surface for longer periods post-restoration, indicating that the restoration was successful at raising water levels across BMB. However, some areas of the bog showed poorer water level recovery when comparing the pre- and post-restoration predicted minimum water levels over the growing season. The prolonged drying and decomposition of the peat could be affecting its ability to retain water. Future research should include monitoring other comparable peat wetland systems as references, characterizing the health of the peat material, and monitoring the community of vegetation in the bog and potential recolonization of bog moss species.

LIST OF ABBREVIATIONS USED

ºC	Degrees Celsius
ρ	Density
%	Percent
ANOVA	Analysis of Variance
BMB	Big Meadow Bog
cm	Centimetre
CSRS	Canadian Spatial Reference System
CWCS	Canadian Wetland Classification System
EMA	Eastern Mountain Avens
g	Gravity
GPS	Global Positioning Systems
h	Head
HSD	Honestly Significant Different
ID	Identification
km	Kilometre
m	Metre
M	Mean
mm	Millimetre

MW	Monitoring Well
NAD83	North American Datum 1983
NS	Nova Scotia
NSDNR	Nova Scotia Department of Natural Resources
NSE	Nova Scotia Environment
NWWG	National Wetlands Working Group
P	Pressure
PVC	Polyvinyl Chloride
RTK	Real-Time Kinematic
SD	Standard Deviation
US	United States

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CHAPTER 1 INTRODUCTION

1.1 Project Context

The Big Meadow Bog (BMB) wetland complex on Brier Island, Nova Scotia (NS) has been impacted by drainage activities since the late 1950s. Many peatlands across Nova Scotia have historically been altered, subsequently lowering their water table, in order to increase the quality of land for agricultural purposes. In the case of BMB, drainage ditches were dug and modifications to the natural drainage channels were made in order to create desirable lands for farming. These ditching activities have altered the hydrology of the system; since then water levels have decreased and the upper layers of peat have become unsaturated. This has facilitated the increased presence of woody vegetation within BMB over the years, which has accelerated drying of the peat material due to increased evapotranspiration. The woody vegetation has also created competition within the vegetation community and made it more difficult for bog vegetation to be dominant.

The peatland has also been impacted by the emergence of herring and great black-backed gulls. Since the 1970s, the gulls have taken over many portions of the bog to use it as a nesting habitat. The presence of gulls has increased nutrients in the bog, impacting the survival of native bog vegetation. The combined effects of the historical drainage and the gulls has threatened the habitat of the Eastern Mountain Avens (EMA), *Geum peckii*, a globally rare plant that gives the bog its high ecological value. The species is listed as endangered both federally and provincially (Nature Conservancy Canada, 2020).

The disturbances in BMB from the artificial drainage and gull nesting, along with the decrease in EMA habitat, motivated the restoration of the wetland complex. In 2015, a Request for Proposals was issued for the design of a restoration plan for BMB. East Coast Aquatics Inc. (ECA) was chosen to complete the restoration. ECA's restoration plan focused on the hydrologic restoration of BMB and aimed to restore ombrotrophic state in the domed portion of the bog and reestablishment of the lagg zone. This lagg zone is the principal habitat of the EMAs and therefore an important component of the BMB wetland complex. The restoration objectives identified by ECA included (East Coast Aquatics Inc., 2018):

- *Restoring summer low flow period shallow groundwater elevation to within 0 – 20 cm of the ground surface in lagg areas,*
- *Re-create natural ground saturation conditions unsuitable for nesting gulls,*
- *Re-create natural rate of discharge on the site, and*
- *Re-establish bog/fen hydrology with little to no future maintenance.*

The restoration of BMB involved the two primary activities of (i) constructing ditch blocks and reprofiling the ditches, and (ii) the additional activity of removing woody vegetation. Ditch blocks were constructed to block any flow of water in the existing ditches and redirect surface water to natural channels. The ditch blocks were built using saturated, catotelmic peat from nearby borrow pits. A total of 123 ditch blocks were installed throughout the BMB site, with spacing determined by the slope of the ground surface. The lengths of the drainage ditch between ditch blocks were re-profiled to create a more gradual slope and allow for native vegetation re-colonization. Lastly, the removal of woody vegetation in the central raised portion of the bog was completed to reduce evapotranspiration and promote recovery of water levels and native vegetation. The restoration of the southern end of BMB commenced in the spring of 2016 and carried into the spring of 2017. The northern portion of the bog underwent restoration during the fall of 2017. Figure 1 illustrates the sequence of restoration activities completed by ECA (East Coast Aquatics Inc., 2018).

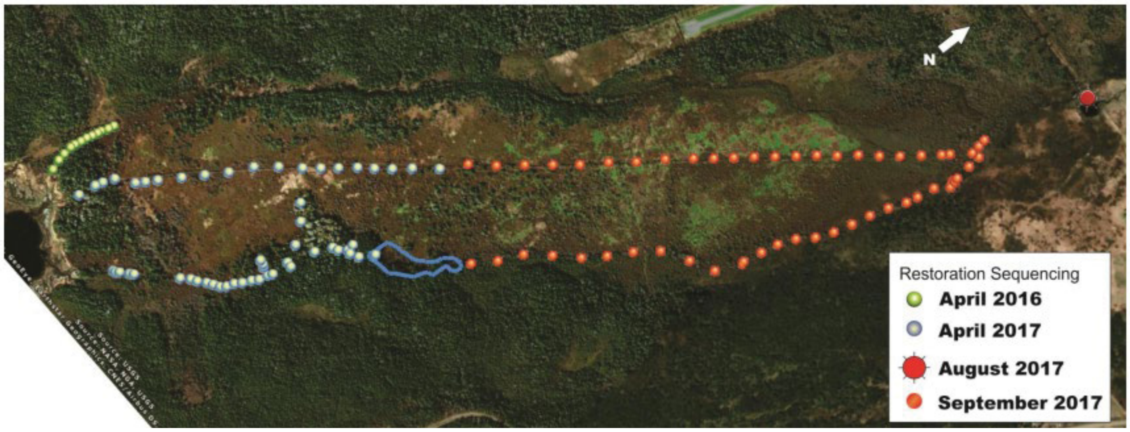


Figure 1. Sequence of restoration activities completed by East Coast Aquatics in Big Meadow Bog, illustrating ditch block installation locations (East Coast Aquatics Inc., 2018)

1.2 Scope and Objectives

The purpose of this research is to understand the effect of restoration activities on the hydrology of Big Meadow Bog on Brier Island, Nova Scotia. The specific objectives of the study are:

- Determine the effect the restoration activities had on water levels in Big Meadow Bog, and
- Determine the spatial variability in terms of water level recovery

CHAPTER 2 LITERATURE REVIEW

2.1 Wetland Definition

Wetlands are abundant landscape features across Canada, as well as across Nova Scotia. According to the 2004 inventory of Nova Scotia lands, freshwater wetlands accounted for 6.6 % of the total land area and salt marshes another 0.3 % (Nova Scotia Environment, 2011). A large majority of these wetlands are peatlands, specifically bogs and fens (NSE, 2011). Wetlands are environments typically inundated or saturated for long enough periods that allow wetland processes to occur. These processes are a product of poorly drained soils and a prevalence of vegetation that is adapted to saturated conditions (NWWG, 1997). Wetland environments are not always flooded but the water table can commonly be at or near the surface for the majority of the growing season (NWWG, 1997). The term 'wetland' often refers to wet habitats like swamps, marshes, bogs, and fens. In Nova Scotia, a large majority of our wetlands are classified as bogs and fens (NSE, 2011).

Wetland development is a function of the interaction of numerous environmental factors. These factors can include climate, geomorphology, hydrology, chemistry, and biology (NWWG, 1997). The availability of water is essential to wetland development and, in many cases, is determined by climate. Landform and soil parent material are both major factors in the land's ability to capture and retain water to create the characteristic saturated conditions of a wetland (Tiner, 2017). The regional differences of these factors have produced vast biodiversity in wetland plant communities and numerous hydric soil types (Tiner, 2017). These differences also create a great deal of variation when it comes to the definition of a wetland.

Wetlands are valuable habitats due to their biodiversity and because they are often very productive environments. They can provide many benefits to people, some of which include purifying water by removing pollutants, buffering water flows, and capturing and storing atmospheric carbon (Environment and Climate Change Canada, 2016). Therefore, wetland identification and delineation are also valuable. Wetland identification is the simple recognition of a wetland area while wetland delineation is the more complex and detailed determination of the boundaries of a specific wetland (Tiner, 2017). When delineating a wetland, there are three main diagnostic environmental characteristics that allow one to determine if an area is considered a wetland; hydric soils, hydrophytic vegetation, and wetland hydrology.

2.1.1 Hydric Soils

Wetland soils are classified as hydric soils, which develop as a result of prolonged saturation or inundation cycles. Hydric soils can be organic or mineral, depending on the amount of organic matter in the matrix. Organic soils are composed mostly of plant tissues remains (leaves, stems, and roots) while mineral soils are a combination of sand, silt, and clay (Tiner, 2017). Organic hydric soils develop under almost continuous inundation or saturation. These types of soils are commonly known as peat or muck. Mineral hydric soils are more often periodically saturated for sufficient duration to produce soil properties indicating a reducing environment. As soils become saturated, oxygen becomes limited, and reducing soil conditions become more prominent (US

Army Corps of Engineers, 2012). This anerobic environment lowers the soils redox potential and results in the chemical reduction of some soil components, like iron and manganese oxides. The reduction of these elements can change the physical characteristics of the soil, including the development of different soil colours (US Army Corps of Engineers, 2012). Gleyed soils have a characteristic bluish-gray or greenish-gray colour that develops in an area where iron is reduced, this is a common indicator of hydric soils (US Army Corps of Engineers, 2012). Another hydric soil indicator, for soils that are low in iron or manganese, is the accumulation of organic matter. Microbes in the soil use carbon found in organic matter as an energy source. Under wet conditions, aerobic bacteria are replaced with facultative and obligate anaerobes and the rate at which organic carbon is utilized by these microbes is much lower than that of an aerobic soil environment (Tiner, 2017; US Army Corps of Engineers, 2012). In these systems partially decomposed organic matter can accumulate and in wetlands can be identified as thick organic layers of peat or organic-rich mineral material (US Army Corps of Engineers, 2012).

2.1.2 Hydrophytic Vegetation

Hydrophytic vegetation are plants that have adapted to environments where soil saturation or inundation is frequent enough to have a controlling influence on the plant community (US Army Corps of Engineers, 2012). Hydrophytes are the community of plants that grow in or near water and have the ability to also grow in anerobic soil conditions (Tiner, 2017). Using vegetation to indicate wetland areas takes into consideration the ‘prevalence of vegetation’, which is characterized by the dominant species in the plant community. This is usually estimated by either basal area or percent areal cover (US Army Corps of Engineers, 2012). Hydrophytic vegetation is prevalent when the dominate species of the plant community are adapted for anaerobic soil conditions. Plant indicator status categories are used to determine if a plant is adapted for anerobic soil conditions. There are five indicator categories: obligate wetland plants, facultative wetland plants, facultative plants, facultative upland plants, and obligate upland plants. There is a relative probability for each of these to occur in a wetland environment (US Army Corps of Engineers, 2012). Identification of plants and their indicator category can provide a basis for determining the point at which the wetland begins and the upland ends (Tiner, 2017).

2.1.3 Hydrology

Wetland hydrology can be characterized by water depth or periods of saturation and inundation. The US Army Corps of Engineers states that an area can be considered a wetland if that area is inundated (permanently or periodically) or surface saturation occurs during the growing season to support vegetation adapted for saturated soil conditions (US Army Corps of Engineers, 2012). As previously stated, the presence of water has an influence on the soil and vegetation of a wetland area due to anaerobic conditions. For wetland delineation, it is necessary to establish that a wetland area is periodically inundated or has saturated soils during the growing season. Evidence of recent flooding can also be used as an indicator of wetland hydrology (Tiner, 2017). However, it is considered the least precise parameter because indicators of wetland hydrology are sometimes difficult to recognize in the field (US Army Corps of Engineers, 2012). Considering this, wetland hydrology indicators should be used in combination with hydric soil and hydrophytic vegetation indicators. This is also true for the opposite case where wetland areas have undergone alteration in the form of drainage ditches or channelization because hydric soils and hydrophytic vegetation can still be present for periods of time where conditions for wetland hydrology have not been met (Tiner, 2017).

2.2 Wetland Classification

The diversity of wetland systems across the globe is a result of the interaction of various environmental factors, which creates both characteristic similarities and differences between wetland systems (NWWG, 1997). These characteristics can be used to group them into classes. The source of water, how much is delivered to the wetland, and by what mechanism it is delivered to the system combine to be able to classify wetlands (Money et al., 2009). There were numerous wetland classification systems developed in Canada by different intended users. Due to the variety of wetland definitions from different fields of study, there was much variability between classification systems. This had limited collaboration between users of different study areas (Zoltai, 1995). The Canadian Wetland Classification System (CWCS) was first developed in 1987 as a part of the *Ecological Land Classification* Report Series by Environment Canada but later revised by the National Wetlands Working Group (NWWG) to include expertise from wetland scientists across Canada. The CWCS standardized the classification of wetland areas in Canada and facilitates communication between various potential users (NWWG, 1997). Proper classification of wetlands, through understanding the interactions between hydrological, chemical, and biotics factors, will allow for appropriate management of them (Zoltai, 1995).

The CWCS takes into account hydrologic regime, carbon budget, and water chemistry. The classification system has a hierarchical structure with increasing complexity. Wetlands are most broadly grouped into classes, which is based on the genetic origin of the wetland area. There are five main classes of wetlands in the CWCS: bogs, fens, swamps, marshes, and shallow water. These classes are then subdivided into wetland forms. The form of a wetland describes its surface morphology and patterns, relationship to open water, and the underlying soil material. Wetland form is further broken down into wetland types, which is based on the physiognomic characteristics of the vegetation.

2.2.1 Bog

Bogs are S*phagnum* dominated peatlands. They are ombrotrophic, indicating that they are unaffected by groundwater and runoff. The only sources of water into a bog system are precipitation, fog and snowmelt (NWWG, 1997). The water table is usually at or slightly below the surface, which can be raised or level with the surrounding terrain. Bogs are acidic due to humic acids produced from the decomposition of the *Sphagnum* mosses (Zoltai, 1995). There are two main soil layers in a bog; surface layer and deep layer. The surface layer is the living, aerobic layer that has plants and roots undergoing decomposition at the bog surface. The deep layer is a poorly oxygenated layer composed of decomposed peat material. Levels of decomposition can vary based on depth but bogs usually have poorly to moderately decomposed peat. Water flow through the deep layer is much slower than that in the surface layer (NWWG, 1997).

2.2.1.1 Bog Forms and Subforms

The classification of bog wetland forms is based on surface form, relief, and proximity to water bodies. Some bog forms, like basin and blanket, are level with the surrounding area while other forms have a convex surface like mound or domed bogs. In the case of domed bogs, the convex surface can be several meters higher at the centre than the edges of the bog (NWWG, 1997). The margins of a raised, domed bog are referred to as the lagg (Holden, 2006). The lagg is a transition, usually wet, zone where water from the surrounding upland area is routed around the main raised portion of the peat bog (Howie & van Meerveld, 2011). The chemistry of the water within the lagg can also be more similar to a fen than a bog because of the nutrient input from the upland areas (Bragg & Tallis, 2001). A high water table in the lagg will support the raising of the water table across a raised bog site and therefore is an important consideration in bog restoration (Howie & van Meerveld, 2011).

The CWCS also classifies bogs forms and subforms by whether the surface is level or not. Slope bogs usually occur in areas of high rainfall on sloping terrain (NWWG, 1997). Bogs that are adjacent to lakes or slow flowing rivers are classified as riparian bogs, some of which can have a floating mat of peat material (NWWG, 1997). One of the other main criteria that bogs area categorized by is whether or not the bog is perennially frozen, which mostly applies to bogs located in Northern regions of Canada where permafrost is present (NWWG, 1997).

2.2.2 Fen

Fens are peatlands that have both groundwater and surface water influence, classifying them as minerotrophic (NWWG, 1997). The water chemistry in these wetlands is highly influenced by the chemistry of the surrounding mineral deposits (Zoltai, 1995). The relative abundance of those dissolved minerals will determine if a fen is classified as rich or poor. Rich fens are alkaline, usually having bicarbonate and calcium as dominant dissolved species. They are dominated by moderately decomposed brown mosses and sedges (NWWG, 1995). Poor fens are acidic wetlands dominated by *Sphagnum* vegetation, restricting water flow and nutrient availability, making them more similar to bogs (Zoltai, 1995). Both rich and poor fens can accumulate peat (NWWG, 1997).

2.2.3 Swamp

A swamp wetland can exist in mineral or peat soils, with higher rates of organic decomposition than bogs and fens (NWWG, 1997). The water table is influenced by minerotrophic groundwater and surface water and has strong seasonal fluctuations (Zoltai, 1995). On average, the water table sits at or below the ground surface, which in some swamps can be below the hummock ground surface, making them drier than marshes, fens, and open bogs. Hummocks also create an aerated soil environment suitable for root growth of trees and shrubs. Swamp vegetation is dominated by trees and tall shrubs, usually covering around 30 % of the wetland area (NWWG, 1997). Wood-rich peat ground cover is highly decomposed but peat accumulation is limited due to rapid decomposition (Zoltai, 1995).

2.2.4 Marsh

Marshes are mineral wetlands with water influence from surrounding catchment, stream inflows, precipitation, groundwater discharge, and tidal action. Water levels can fluctuate daily, seasonally, or even annually due to tidal influences, groundwater recharge, or seepage losses (NWWG, 1997). These wetlands are nutrient rich due to groundwater and surface water flow. Eutrophic conditions are sometimes present, which creates an environment where bryophytes cannot compete with the vascular plant production (Zoltai, 1995). Dominant vegetation consists of rushes, reeds, grasses, sedges, and some floating vegetation (NWWG, 1997). Rapid decomposition of vascular plants prevents any significant peat accumulation (Zoltai, 1995).

2.2.5 Shallow Water

Shallow water wetlands are those that have seasonally stable water levels that sustain aquatic life and floating vegetation (Zoltai, 1995). These wetlands can be permanently flooded and open water must occupy at least 75 % of the surface area of the wetland area (NWWG, 1997). Nutrients and dissolved minerals present in a shallow water wetland are dependent on the underlying geological material, hydrology and plant community. These wetland forms are the transitional class between all other wetland classes (bog, fen. marsh, and swamp) and permanent, deep water bodies (NWWG, 1997).

2.3 Peatlands

Peatlands are characteristically distinct from other non peat forming wetlands due to the interaction of the hydrology and biotic factors that produce an environment with decreased plant production and decomposition (Zoltai, 1995). The development of a peatland relies heavily on sustained, stable water levels, which creates an imbalance in the system. The hydrological conditions of a peatland can affect nutrient availability, gas diffusion rates, and species diversity (Holden, 2005). Prolonged stability of the water table restricts total water flow within the peatland. The production of biomass, in this case peat, exceeds the rate of decomposition and this gradually increases the depth of the peat layer (Zoltai, 1997).

2.3.1 Characteristics of Peat

Peat is an accumulation of dead, and decaying, organic material. *Sphagnum* mosses are the primary peat-forming plant in most northern peatlands (Clymo, 1970). A *Sphagnum* plant has long strands of leaves and stems, which gives the peat its matted-like network of decaying material (Landva & Pheeney, 1980). These types of mosses thrive in environments where there are low concentrations of inorganic solutes, like nitrogen and phosphorus. Nutrients are fixed within the peat during decay, but the low nutrient requirement is also reflected in a peatland environment. The optimal habitat for a *Sphagnum* moss is also one that is acidic. In a peatland, pH values can range from below 4 – 7 (Schumann & Joosten, 2008). Peat can be a very amorphous material, depending on decomposition, with a poorly defined structural arrangement (Mesri & Ailouni, 2007). It is a very porous material with pore volume accounting for between 80-98% of its volume (Delicato, 1996).

2.3.2 *Formation of Peat*

Peat soils have properties distinctly different from those of mineral soils (Ingram, 1978). This is due to the content of organic matter but also largely due to their formation. Peatlands are a hydromorphic landscape feature, indicating that they are formed during conditions where there is an excess of water (Price, 2003). The formation of peat occurs at small scale of an individual hummock or hollow, more generally defined as mounds and depressions (Belyea & Clymo, 2001). Plant litter deposited at the surface, and in the rooting zone, forms a porous mass. Air circulates and surplus water drains readily through the porous structure. The litter undergoes aerobic decay and is buried under the weight of younger material. Once buried, the main plant structure of the litter will lose their integrity and eventually collapse (Clymo, 1984). This collapse will cause a decrease in the size of the pore space within the structure of the soil and consequently reduces the hydraulic conductivity of the peat. Incident water supply is dispersed laterally through the thin, porous layer near the surface, where the hydraulic conductivity is much higher (Belyea et al., 2001). The seepage though the lower layer is hindered. This waterlogging of lower layers is the forcing progression of peat accumulation. An anaerobic environment is created in the waterlogged layer, which promotes further decay of the organic material (Belyea & Clymo, 2001).

2.3.3 Acrotelm and Catotelm Division

This peat accumulation process creates a division between the upper and lower layer of peat. The upper layer, termed acrotelm, is directly affected by the oscillating water table within the system. This oscillation, usually seasonal, makes this layer subject to dewatering when the water table lowers and as a result, air re-enters the pore space (Ingram, 1978). Due to the aeration of the layer there is an abundance of peat-forming bacteria. The acrotelm has a greater range and is more susceptible to sudden variation in its properties, like hydraulic conductivity and water content (Ingram, 1978). In contrast the lower layer, referred to as the catotelm, is much less variable. The hydraulic conductivity is almost negligible. Since the conditions are saturated, its water content stays constant. There is no air entry within this system and therefore there are no aerobic peat-forming microorganisms. Decay of the organic material within this layer is present. However, this decay occurs at a much slower rate than the aerobic decay within the upper layer above the water table (Belyea & Clymo., 2001).

2.3.4 Bog Growth Models

Clymo's bog growth model is one of the highly influential models for peatland formation (Beylea & Baird, 2006). In Clymo's model the peat structure is made up of two layers, the acrotem and the catotelm. Litter addition on the surface of the peat is constant through time. A proportion of the acrotelm and the catotelm are lost through aerobic and anaerobic decay, respectively. The decay within the catotelm is much smaller than that in the acrotelm. In the bog growth model, the water table rises at exactly the same rate as bog growth (Beylea & Baird, 2006). During early development of the bog, the litter production exceeds the decay losses and the height of the bog increases. In the later stages of development, litter production equals decay losses and the bog height remains constant (Beylea & Baird, 2006). This repetitive process of litter production and decay can produce a horizontally banded pattern within the peat fabric. Landva and Pheeney (1980) claim that the horizontal matting within the peat fabric is common due to the iterative expansion and compression from water table fluctuations and snow loads.

Another model of bog growth is the groundwater mound hypothesis developed by Ingram (1982). Ingram’s model proposes that raised bogs are formed due to a mound of subsurface water, or waterlogged peat, that lies above the level of a surrounding stream system (Ingram, 1982). This mound of groundwater is said to be under greater pressure than that of the atmosphere and its upper bounds are the water table near the bog surface. The groundwater mound governs the size and shape of the raised bog (Belyea & Baird, 2006). In a fully formed raised bog the decay of peat is controlled by the position of the water table and in the case of a raised bog, the curve of the water table will influence the bog to have the same shape (Belyea & Baird, 2006).

When comparing the two models the bog growth model focuses more on peat accumulation and not on the storage of water, while the groundwater mound hypothesis mainly only considers catotelm water storage and overlooks peat accumulation. In reality, a raised bog is much more dynamic where water flow and storage are interacting with peat-forming processes (Belyea & Baird, 2006).

2.3.5 Peat Decomposition

The physical properties of peat are heavily dependent on the degree of decomposition. There are significant differences between the physical properties of peat and those of inorganic soils (Delicato, 1996). Peats are generally more highly variable in terms of their properties, which is related to the degree of decomposition. This increases the difficulty to develop an accurate understanding of peat behaviour based on laboratory and field measurements (Mersi & Ailouni, 2007).

The von Post humification scale, Table 1, characterizes the degree of decomposition of the peat. It is a widely used system to identify and classify peat materials. However, it is subjective and only provides a qualitative measure of decomposition (Grover & Baldock, 2013). The degree of humification (H) is scaled from 1 to 10. The lower the peat is on the humification scale, the healthier and less decomposed it is. The criteria for the von Post classification of humification of a peat material is shown in Table 1 (Landva et al., 1980).

Table 1. von Post humification scale (adapted from Landva & Pheeny, 1980)

Degree of Humification	**Decomposition**	**Plant Structure**	**Content of amorphous material**	**Material extruded on squeezing**
H_1	None	Easily identified	None	Clear, colourless water
H_2	Insignificant	Easily identified	None	Yellowish water
H_3	Very slight	Still identifiable	Slight	Brown muddy water
H_4	Slight	Not easily identified	Some	Dark brown, muddy water
H_5	Moderate	Recognizable, but vague	Considerable	Muddy water and some peat
H_6	Moderately strong	Indistinct	Considerable	About one third of peat squeezed out; water dark brown
H_7	Strong	Faintly recognizable	High	About one third of peat squeezed out; water very dark brown
H_8	Very strong	Very indistinct	High	About two thirds of peat; some pasty water
H_9	Nearly complete	Almost not recognizable		Nearly all the peat squeezed out as a fairly uniform paste
H_{10}	Complete	Not discernable		All the paste passes through

2.3.6 Peatland Hydrology

Although the high organic content of a peat soil is a defining characteristic, its existence depends on its ability to retain water (Labadz et al, 2010). The nature of a peatland is controlled by hydrological processes, largely water flow and retention (Price, 2003). Therefore, an understanding of those processes and functions is fundamental.

The hydrological balance of most functional wetlands provides conditions where there is an excess of water for a portion of the year (Money et al., 2009). Most peatland bogs are ombrotrophic and reliant on precipitation for their source of water and nutrients (Money et al., 2009). The processes of evapotranspiration (E), groundwater flow (GW), runoff (O), and soil water storage (ΔS) control the water budget of a peatland (McCarter & Price, 2013). The interaction between all of these processes is the basis for the conceptual water balance model. A simple conceptual peatland water balance model is shown below in Equation 1.

$$\Delta S = P - E - GW - O \qquad \text{Equation 1}$$

The most hydrologically significant part of the water balance within a peatland is the change in storage. Storage changes are a function of the compressibility of the peat (Price & Schlotzhauer, 1999). Characteristically, peat is a highly compressible material due to its high water content.

Peat systems can expand and contract, as a function of water content, due to seasonal fluctuations in water levels. The volume of peat will change under the stress encountered from a decrease in the water table. This decrease causes the weight of the overlying peat and water to be transferred to the larger matrix. This decrease in total stress (σ) is offset by the large reduction in pore water pressure (ψ) and causes an increase in the effective stress (σ'). The relationship of these stresses is governed by Equation 2 (Price, Cagampan, & Kellner, 2005):

$$\sigma' = \sigma - \psi \qquad \text{Equation 2}$$

An increase in effective stress is a consequence of the changes in total stress caused by external loads or a reduction in pore water pressure. A loss of water from the soil pores, termed 'normal compression', is usually the most substantial portion of volume changes in peat under normal conditions (Price & Schlotzhauer, 1999). As the pores collapse, water is expelled. This water loss is equal to the volumetric change of the peat. The changes in effective stress can be large enough to alter the peat volume and cause subsidence. The changes in effective stress can cause the peat to 'deform' on a seasonal basis, but this deformation is usually reversible. In an undisturbed peat system, the condition of the peat is restored when there is an increase in pore water pressure from a rise in the water table (Price, 2003). Therefore, water levels and the exchange of water within the peat system are necessary for consideration when evaluating storage changes (Price & Schlotzhauer, 1999).

Storages changes within a peat system are governed by its storativity. This is defined as the volume of water released from an aquifer per unit surface area per unit decline in head. It can be determined using Equation 3 (Van Seters & Price, 2001).

$$\Delta S = dh\left(S_y + bS_s\right) \pm d\theta \qquad \text{Equation 3}$$

Where:

dh = change in the water table

S_y = specific yield

b = aquifer thickness

S_S = specific storage

$d\theta$ = change in moisture content in the unsaturated zone

The specific yield is defined by characteristics of the soil determined by laboratory analysis. Equation 4 defines the relationship for specific storage (Price, 1996).

$$S_y = \frac{\left[\frac{W_s - W_d}{\rho}\right]}{\frac{W_s}{\rho}} \qquad \text{Equation 4}$$

Where:

ρ = density of water

W_s = saturated weight of a sample of peat material

W_d = dry weights of a sample of the peat material

In peat systems, the specific yield can vary dependent on the quality of the peat. A specific yield of 0.09 is indicative of a decomposed peat, while a value of 0.84 can represent an undecomposed, healthy peat (Price & Schlotzhauer, 1999).

The specific storage is defined as the amount of water expelled from the storage due to the compressibility of the soil matrix per unit change in head. The relationship of specific storage, estimated using Equation 5, takes into account the aquifer thickness (db) and change in head (dh) (Van Seters & Price, 2001).

$$S_s = (db/dh)/b \qquad \text{Equation 5}$$

In mineral soils or peat systems that are shallow (<50 cm), well oxidized, or compacted, compressibility of the material is not a main concern. Therefore, the storage can be estimated by only the specific yield (Price & Schlotzhauer, 1999). Due to the compressibility of many peat systems, the effects of the specific storage cannot be omitted when evaluating the overall change in storage (Van Seters & Price, 2001). Therefore, both specific yield and specific storage can have an impact on the storativity of a peat system.

Price & Schlotzhauer (1999) examined the changes in water storage in a disturbed peatland in Quebec. They evaluated the storage changes over a period of approximately five months, using three different estimations. These included cumulative precipitation and evaporation, specific yield, and the combined changes with specific yield and specific storage. The storage estimate that only takes into account the gravitational drainage of water, represented by the specific yield, was significantly less than the cumulative precipitation and evaporation estimate. However, when the effects of specific storage were taken into account, a much better estimate of the storage changes was obtained (Price & Schlotzhauer, 1999).

2.4 Impacts of Peatland Drainage

There are other forms of compression in a peat system that leave it more vulnerable to irreversible deformation. Volume changes due to air entering the soil, termed “residual shrinkage’, typically manifests as smaller changes than normal compression (Price & Schlotzhauer, 1999). However, over extended periods of shrinkage, compression, and oxidation the soil matrix can become affected (Price, 1996). Since every layer of peat within a raised bog started its existence at the surface, every layer in the deposit has undergone weathering. Seasonal patterns of wetting, drying, snow cover and frost all can have an effect on the peat (Landva et al., 1980). Compression could result in a number of ways. Snow cover could exert considerable pressure onto the unsaturated layer or dying could produce a compression by means of capillary stresses or groundwater drawdown could produce negative pore pressures and increased effective stresses (Landva et al., 1980).

Many human-induced activities are the drivers of change in the hydrology of peatlands, leading to dewatering and subsequent deformation of the upper portion of the peat. Activities that can alter a peatland include drainage, burning, grazing, peat cutting, and construction (Labadz et al., 2010). Artificial drainage includes the creation of drainage ditches in a peatland for the purpose of lowering the water levels (Mallory & Price, 2014). This can be done for many reasons but most commonly for agriculture, forestation, and commercial peat extraction. Artificial drainage is one practice that often leads to an increased chance of irreversible deformation of the peat. The drastic decrease in water level alters the surface conditions and groundwater flow, both of which govern the peatland's relationship with the surrounding area (Price, 1996). The pore structure of the peat matrix is also altered by significant water table drawdown. This compresses the deeper peat and over time causes the surface of the peatland to settle (Mallory & Price, 2014). The smaller pores, in the oxidized peat, create a decrease in the plant available water within the system and subsequently an increased variability in the water level (Price, 1996). In some cases, prolonged desiccation of the surface may lead to the development of a hydrophobic layer. This could reduce the infiltration capacity and increase the occurrence of infiltration-excess overland flow (Labadz et al., 2010).

The hydraulic properties of the peat and subsequent lowering of the water table are connected to the continual deformation of the peatland's condition. Schumann & Joosten (2008) explore the feedback mechanisms between a lower water table and the hydraulic properties of the peat. They explain that when the water table is drastically lowered in a peatland, there is an increase availability of oxygen entering the soil pores. Fissuring and cracking of the peat material can occur through the continuous shrinkage and swelling, which progresses the addition of air and causes considerable shrinkage of the matrix and decreases the overall pore space within the peat (Schumann & Joosten, 2008). Smaller pore sizes within the peat matrix will cause the hydraulic conductivity and storage coefficient to decrease. A decrease in the storage coefficient results in an increase of runoff and a flashier response to rainfall events, promoting a continual increased lowering of the water table (Schumann & Joosten, 2008).

2.5 Examples of Disturbed Peatlands

In 1996, Price investigated the hydrology of a partly restored cutover bog. The upper layers of peat within this bog were harvested. This lead to a disturbed bog site with altered hydrological conditions, unsuitable for *Sphagnum* regrowth (Price, 1996). The peat matrix exhibited shrinkage, oxdidation, and compression, which decreased the plant available water within the pores. Soil cores were taken in the disturbed portion and also an undrained portion of the site to determine the specific yield of the peat. The results of the testing showed that the two sites had greatly different water storage characteristics.

The depth profiles for both sites showed that the specific yield of the undisturbed portion of the bog was more depth dependent than the harvested bog. It ranged from 0.55 near the surface and dropped to about 0.25 at 3 meters below surface. Since the harvested bog had the upper layers removed, the leftover peat had a very low specific storage, averaging at about 0.05. The specific storage of the harvested site was not dependent on depth like the undisturbed site (Price, 1996).

In a study done by Van Seters and Price (2001), the hydrological function of a harvested and abandoned peat bog was investigated. The bog was harvested using a ‘block-cut’ method for approximately 30 years and the bog was then abandoned and expected to return to its origin function. Van Seters and Price evaluated the water balance of the ‘regenerated’ bog and compared it to that of a reference bog. From their water balance, they determined that the harvested bog did not regain previous water table levels. The mean water table levels in the harvested peatland were on average 20 cm lower than that of the undisturbed system. Van Seters and Price also investigated the runoff and streamflow in both systems. The pattern of shallow subsurface runoff characteristic of natural raised peatlands was not exhibited in the harvested site. Instead, a network of deep drains withdrew water from deep within the peat matrix and conveyed it by various routes to the two major outlets (Van Seters & Price, 2001). Runoff ratios for the harvested site were controlled mainly by storm size and only slightly by the antecedent water table during dry conditions. Differences in the structure of the peat matrix and the effect that has on the conveyance of runoff to the margins of the bog was the main difference between the drained and natural peatland. The upper layers of *Sphagnum* in an undisturbed peatland act similar to an overflow system and direct precipitation to the margins of the peatland during wet conditions. When the water table is lowered toward the more decomposed layers of peat, the flow of water dramatically decreases. This causes all subsequent rainfall to be stored by the upper layers of peat. On the other hand, the disturbed peatland discharged water from a deep zone of dense peat near ditches, where the hydraulic conductivity and the storage capacity are much lower. After precipitation, the peat saturates quickly and runoff is conveyed over a longer period of time to the outlet. This indicates that the water table has less of an influence on discharge volumes in disturbed or drained peatlands (Van Seters & Price, 2001).

2.6 Restoration of Peatlands

Measures can be taken to attempt to restore peatlands that have been impacted by artificial drainage. Determining how the hydrologic regime and conditions of a peatland have been altered is a crucial step in beginning restoration (Zedler, 2000). As mentioned previously, the hydrology of a peatland is the fundamental forcing function of its behavior and health. Therefore, restoring the hydrology of a peatland is the initial step to attempting to regain its natural functions (Mallory & Price, 2014). Restoration most commonly begins by rewetting the peatland by blocking active drainage ditches, re-profiling the peat surface, and constructing bunds along elevation contour lines to contain snowmelt during the spring (Howie et al., 2009). These measures can improve the hydrology, and more specifically stabilize the water table, within a disturbed bog system. However, this brings into question how much the natural hydrologic regime has to be restored to regain original function of the peatland. Not only is it important to restore the frequency and magnitude of high water, but also the duration, timing and temporal sequences of high and low water levels (Zedler, 2000). Understanding how water controls the composition and function of peatland is imperative for restoration success. Stabilizing water levels is an important achievement in any restoration project but obtaining hydrologic equivalence should be the end goal. The fact that water levels have been stabilized in a system does not mean that the peatland will regain its normal functions. Mimicking other aspects of the natural hydrologic regime, single flood events or particular sequences of flood events, might be necessary to successfully restore the peatland (Zedler, 2000).

Restoration success can have different meaning in different situations. The task of defining success, in terms of restoring a wetland, can be a challenging and not as definitive as expected (Kentula, 2000). Kentula (2000) mentions three different types of success that are pertinent to wetland restoration; compliance success, functional success, and landscape success. Compliance success is determined by assessing if a project fulfills terms of a contract related to restoration; functional success refers to the evaluation of the ecological functions of the system and if they have been restored; and landscape success is a measure of how restoration maintained or improved the ecological integrity of the region or landscape (Kentula, 2000). It is important to understand what type of success is relevant to a restoration project and be specific as to what measures will be evaluated to determine if success has been achieved. These measures could include species diversity and abundance, soil conditions, nutrient cycling, storage capacity, etc (Ruiz-Jean & Aide, 2005). Multiple performance measures should be used and they should be appropriately linked to project objectives and monitored often to detect the status of the wetland's performance.

Characterization of the pre-disturbed and natural regime of a peatland makes it easier to set these performance measures. However, complete characterization is not always possible because sometimes deformation of a wetland is not planned or assumed. For this reason, reference wetlands are often used as a standard for comparison (Ruiz-Jean & Aide, 2005; Van Seters & Price, 2001). Post-disturbance however, a baseline water balance of the peatland is imperative to measuring the change in the site conditions as restoration takes place.

CHAPTER 3 METHODOLOGY

This study aims to understand the effect of restoration activities on water levels and the spatial variability of water level recovery in Big Meadow Bog.

3.1 Site Description

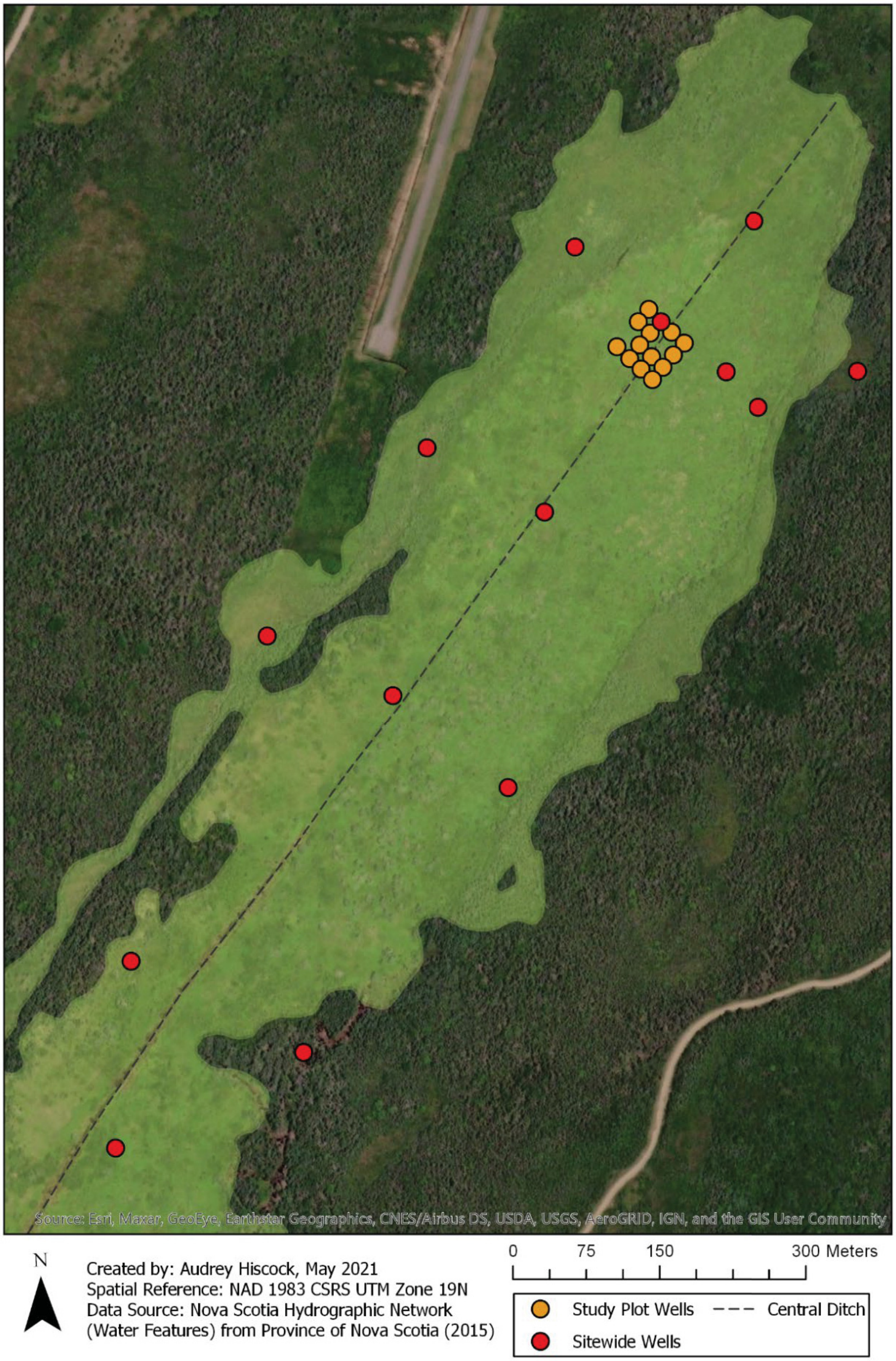
3.1.1 Big Meadow Bog

The study area of Big Meadow Bog is on Brier Island, which is located on the western tip of Nova Scotia at a latitude of 44º 15’ 11” N and a longitude of 66º 21’ 29” W. Big Meadow Bog is a large wetland complex, over 40 hectares, made up of varying wetland types. The central raised bog is bordered by lagg-fen, which is surrounded by slope swamps. The BMB wetland complex has an elongated shape, averaging a width of 350 – 450 m and about 1.8 km in length. The northern portion of the bog is near the community of Westport, NS. The bog drains both to Grand Passage in the northeast and to Big Pond, and subsequently, the Gulf of Maine in the southwest.

Water levels across the Big Meadow Bog site were studied from June 2017 to September 2019. Fourteen loggers were installed in monitoring wells located throughout the wetland complex to provide an overview of the sitewide water level response and level of spatial variability. The BMB study site and locations of the monitoring wells are shown in Figure 2.

3.1.2 Focused Study Plot

A more focused study plot was established and instrumented to investigate water levels and spatial patterns at a smaller scale in BMB. This study site is a 50 m x 50 m plot in the northern portion of the bog, with the existing central ditch running through the middle of the plot. This area of the bog was chosen because of the level of decomposition; increased drying from lower water levels had occurred in this area, which was accelerated by the presence of gulls. The study plot was instrumented in June 2017 with four well transects. The focused study plot monitoring well locations are shown in Figure 2. Soil moisture and temperature probes were also installed at two locations, with various depths, within the study plot. The monitoring equipment in the study plot was installed prior to the restoration of the northern portion of BMB in the Fall of 2017.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Created by: Audrey Hiscock, May 2021
Spatial Reference: NAD 1983 CSRS UTM Zone 19N
Data Source: Nova Scotia Hydrographic Network (Water Features) from Province of Nova Scotia (2015)

Figure 2. Big Meadow Bog with sitewide and focused study plot monitoring well locations.

3.1.3 Reference Wetland

A reference wetland was monitored during the study period to provide a baseline comparison of an unimpacted wetland to the study site of Big Meadow Bog. The reference wetland site was used to compare water level observations throughout the growing season with the changing climate from pre- to post-restoration. The reference wetland is located northwest of BMB at a latitude of 44° 15’ 22” N and a longitude of 66° 22’ 12” W (Figure 3). It is characterized as an undisturbed fen and bog peatland system, similarly sized to BMB. Water levels in the reference wetland were monitored from 2017 – 2019. The three well locations across the reference wetland were chosen to capture hydrologically different regions, which are characteristic in most domed bogs. As shown in Figure 3, the raised center portion of the reference bog is represented by the Dry water level location and the margins, or lagg, of the bog would be represented by the Wet water level location.

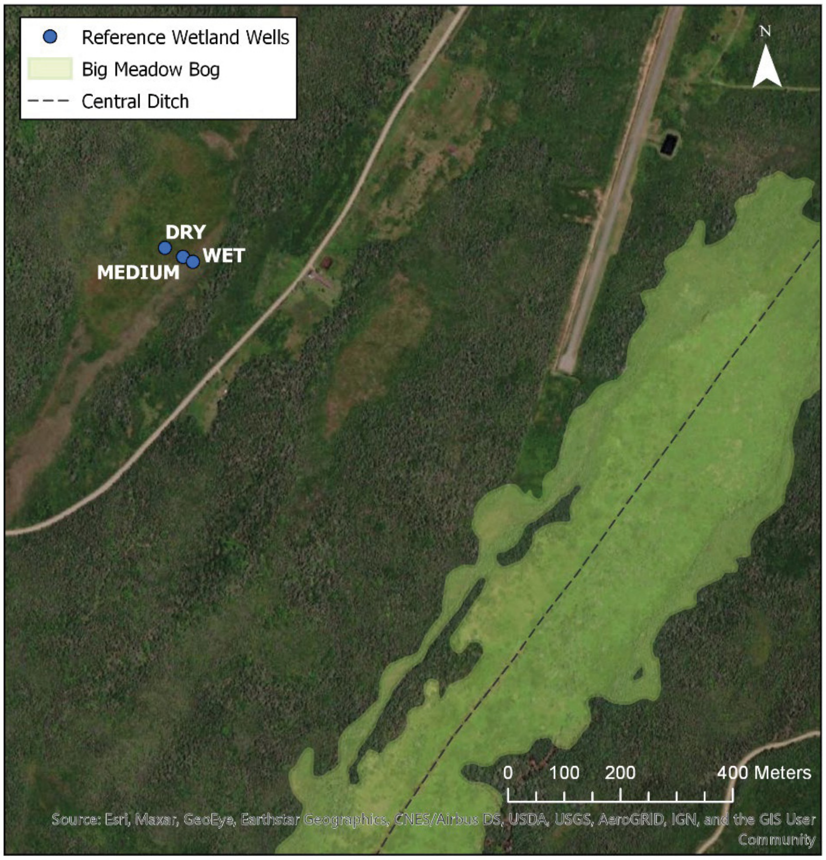


Figure 3. Reference wetland, relative to Big Meadow Bog wetland complex, with monitoring well locations.

3.2 Field Monitoring Program

3.2.1 Topographic Data

Positions of the sitewide wells across were obtained through previous baseline monitoring by the Geological Services Division of the Nova Scotia Department of Natural Resources (NSDNR) (Kennedy, Drage, & Nixon, 2015). The position and elevation of wells in the focused study plot and the reference wetland site were determined with a Real-Time Kinematic (RTK) topographic survey. The survey was conducted using a HiPer Ga (Topcon Positioning System, Inc., Livermore, California, United States) Global Positioning System (GPS) unit. The base station was positioned on the airstrip near BMB at a latitude of 44º 15’ 19” N and 66º 21’ 36” W. The 6-hour survey was coordinated in NAD83 CSRS and processed with the precise Point Positioning service from Natural Resources Canada.

3.2.2 Climate Data

Climate data from Environment Canada was used to provide context for variations in climate between study years. The nearest, most complete data record was the Yarmouth RCS Station (Climate ID: 8206491). Daily precipitation and mean temperature records from this station were gathered for the study period and summarized over an annual period (January – December) and during the growing season (May – September) for 2017 – 2019. Climate normals (1981 – 2010) for the Yarmouth RCS Station were also compared for the study period.

3.2.3 Water Level Monitoring

Continuous water level measurements were taken throughout the BMB site and in a focused study plot. The fourteen sitewide monitoring wells were installed by the Geological Services Division of the NSDNR from previous baseline monitoring (Kennedy et al., 2015). These wells were constructed out of 1-inch diameter PVC pipe and were 1.5 meters in length. The wells were perforated at 5 cm intervals, starting 30 cm from the top of the well casing, and capped at the bottom. The wells in the focused study plot were installed in June 2017. The boreholes for the wells were created using a hand auger. The wells were constructed on-site out of 1-inch diameter PVC slotted screen and casing. The sections were either screwed together using pre-threaded ends or fastened together using 1-inch PVC couplers. The wells were capped at the bottom and covered in well filter sock to prevent in-filling with peat. Each well was 1.25 m in length with 25 cm of casing above the ground surface. After the well was inserted into the boreholes, it was backfilled with silica sand and sealed with hydrated bentonite clay. A locking well plug was fitted in the top of the well to protect the well and to be able to more easily fasten the data logger. Figure 4 shows an example of an installed monitoring well in the focused study plot.

Figure 4. Monitoring well installation in focused study plot

The monitoring wells were instrumented with pressure transducers: HOBO U20 Water Level Data Loggers (Onset® Computer Corporation, Bourne, Massachusetts, United States) and Solinst Levelogger® and Barologger Model 3001 (Solinst Canada Ltd., Georgetown, Ontario, Canada). The data loggers were programmed to record pressure and temperature on a 30-minute time step. Manual water level readings were recorded at regular intervals when downloading and deploying the transducers. A Heron Instruments dipper-T Water Level Meter (Heron Instrument Inc., Dundas, Ontario, Canada) was used to determine depth of water from the top of well casing.

Pressure readings were corrected using barometric pressure data and then converted to a height of water above the logger sensor using Equation 6.

$$P = \rho g h \qquad \text{Equation 6.}$$

Where:

P = pressure (kPa)

ρ = density of water, assumed to be 1000 kg/m^3 in Solinst Levelogger Data Wizard and calculated based on field temperature readings for HOBO data logger compensation.

g = gravity, assumed to be 9.81 m/s^2

h = head of water above the logger (m)

HOBO data logger pressure readings were compensated manually in R Software using hourly pressure data from Environment Canada. Pressure readings were available for the study period from the Brier Island Station (Climate ID: 8200604). Solinst Levelogger pressure readings were compensated with barometric pressure readings from the Solinst Barologger in the Solinst Levelogger. 4.4.0 Software using the Data Wizard Basic: Barometric Compensation. Corrected pressures were adjusted to take into account well measurements and the manual water level measurements from a specific date and time. This correction was done in R Software for all of the sitewide and focused study plot wells (R Core Team, 2013). Continuous water level measurements were summarized as average daily water levels and filtered for the growing season study period (May – September). Reference wetland pressure readings were downloaded and compensated using the same procedure.

3.2.4 Soil Decomposition Classification

Soil samples near eight of the monitoring well locations in the focused study plot were taken pre-restoration in August 2017. Figure 5 shows the locations of the soil samples within the focused study plot. The sample sites included locations near the central ditch on the interior of the plot and then locations on each corner further away from the ditch. The samples were taken at three different depths at each sampling location: 10 cm, 30 cm, and 60 cm below ground surface.

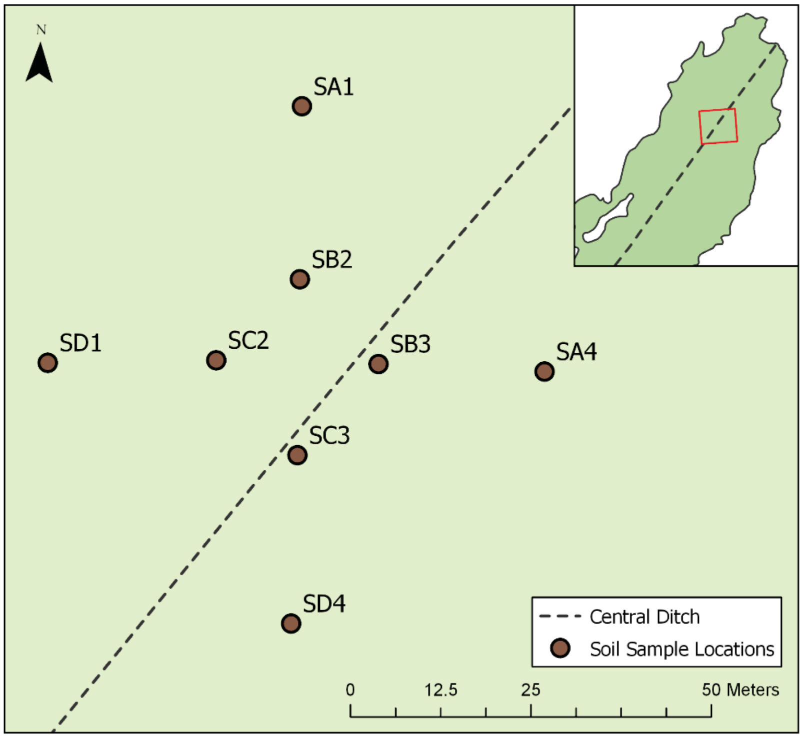


Figure 5. Locations of soil samples for peat characterization within the focused study plot

The degree of humification of the peat at each depth was identified using the von Post Humification scale. The layers of peat were exposed through digging and then a sample of peat was taken at each depth. Figure 6 shows the cross-section of the peat material at a sample location. Peat material was squeezed in a closed hand, observing the liquid and material extruded through the fingers and proportion of peat material that remains in the hand. The degree of humification for each sample location were recorded and comparisons were made between depths at each location and then also the relative location of the sample site within the focused study plot.

Figure 6. Cross-section of peat layers sampled in focused study plot, where the ground surface is at the top.

3.3 Statistical Analysis

Statistical analysis was performed to investigate the differences in water levels between study years and location of wells on a sitewide and focused study plot scale. Boxplots were created in R Software to show the distribution and visually assess the hydrologic characteristics at each monitoring well location (R Core Team, 2013). Descriptive statistics including mean, minimum, and maximum water level for each well were calculated to supplement visual methods of comparison. Time series of water levels, also produced in R Software, were used to visualize trends at specific well locations through the duration of the growing season (R Core Team, 2013).

Two-way analysis of variances (ANOVAs) was completed in IBM SPSS Statistics 27 to compare the mean differences of water levels between study year and well location (IBM Corp., 2020). The levels of each factor tested are summarized in Table 2.

Table 2. Levels of the factors considered in two-way ANOVA analysis

Study Period	**Well Location**	
	Sitewide	**Focused Study Plot**
2017	North of Transect 1	Near central ditch Far from central ditch
2018	Between Transect 1 and 2	
2019	South of Transect 2	

Post-hoc tests were also completed to more closely examine the main effects. Tukey honestly significant different (HSD) post-hoc tests were completed in IMB SPSS Statistics 27 with the two-way ANOVA analysis (IBM Corp., 2020). The data was evaluated for homogeneity of variances prior to completing post-hoc test and this assumption was met. Paired t-tests were also completed in IBM SPSS Statistics 27 to compare the mean differences of the percent of time water levels were within 30 cm of the ground surface for pre- and post-restoration (IBM Corp., 2020). A p-value less than 0.05 was considered significant for all statistical tests.

3.4 Spatial Analysis

The spatial variability of water levels throughout the study period was investigated through interpolation. Interpolation methods can be used to evaluate physical data by generating a continuous surface (Caruso & Quarta, 1998) In ArcGIS Pro, interpolation methods predict values in a cell of a raster based on a number of sampled data points. The method assumes that spatially distributed sample points are spatially correlated; characteristics of sample points that are closer together are more similar than those that are farther away. Kriging was the chosen interpolation method for this analysis, which follows a geostatistical procedure to prepare interpolated surface. Kriging differs from other methods of interpolation like Inverse Distanced Weighting, linear regression, and Gaussian decays, which are categorized as deterministic interpolation methods. Kriging uses the spatial correlation between sampled points to interpolate values rather than depend on a presumed model of spatial distribution. It is the most appropriate method for scenarios where you can assume there is a spatially correlated distance or directional bias in the data, which is why it is commonly used in earth and environmental sciences (Meng et al., 2013). Assumptions within the Kriging model are as follows:

- Stationarity: the joint probability distribution does not change
- Isotropy: uniformity in all orientations

Sitewide and focused study plot water level interpolation was performed in the Geostatistical Analyst toolbox in ArcGIS Pro. Raster inputs into the Kriging model included the well locations with associated average daily water level minimums. Simple kriging (Equation 2) with a spherical semivariogram was the chosen model.

$$Z(s) = \mu + \varepsilon(s) \qquad \text{Equation 7}$$

Where:

Z = variable of interest

μ = unknown constant

ε = autocorrelated error term

s = location

Once the kriging method was chosen and the data was added to the model, the semivariogram was produced to describe the spatial community of the data. The semivariogram is sometimes referred to as a dissimilarity function because it assesses the average decrease in similarity between two variables as the distance between them increases. The semivariogram was fitted through the model processes in the Geostatistical Wizard. One of the default inputs within the semivariogram model that was modified was that the condition of anisotropy was set to 'True'. This indicates that within the data, there may be differences with not only distance but also direction. Weights derived from the semivarigoram model are used to interpolate values for the unsampled points. Data in the neighbourhood of the estimation location is used. A standard neighborhood type was chosen with the number of neighborhood sample points to be five, with at least two used, based on the arrangements of sample locations. The semivariogram model and other inputs were selected through trial and error and inspection of the error of prediction and the interpolated surface. The output cell size was obtained from input raster dataset.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Climate Characterization

Climate data from Yarmouth RCS Station for 2017 – 2019 are summarized in Table 3. Climate normals (1981 – 2010) for the Yarmouth RCS station showed annual precipitation of 1292.9 mm and growing season precipitation and mean temperature of 463.3 mm 14.3 ºC, respectively. The 2017 pre-restoration year was slightly drier than these climate normal values. Comparing 2017 to 2018, it is evident that the 2018 post-restoration year was a particularly dry year. When looking at the growing season precipitation values, 2018 was drier than both 2017 and 2019. The 2019 post-restoration year was the wettest of the study period with annual precipitation exceeding the climate normals. However, even though growing season precipitation for 2019 was slightly below climate normals, it was still considerably more than 2017 or 2018 growing season precipitation.

Table 3. Climate date for Yarmouth RCS Station (Climate ID: 8206491)

Year	**Annual Precipitation* (mm)**	**Growing Season (May – September)**	
		Precipitation (mm)	**Mean Temperature (ºC)**
2017	1097.5	338.4	16.4
2018	996	269.7	16.8
2019	1477.8	434.8	15.7

*Water year taken as October 1st – September 30th

4.2 Reference Wetland Hydrology

Figure 7 illustrates boxplots of the water levels for the three locations during each study year. On an annual basis, water levels were consistent throughout the reference wetland from 2017 – 2019, despite variations in precipitation. Spatial differences in water level between each location in the reference wetland followed expected trends. The Wet, Medium, and Dry locations had average water levels near ground surface, 20 cm, and 40 cm below ground surface, respectively. These water levels are typical of what is expected in an undisturbed bog wetland complex, especially if the main portion of the bog is raised. These results also coincide with findings from MacIntyre (2017), which confirmed that water levels in a relatively unaltered domed bog in this area of the province can range up to 50 cm below the ground surface in the centre of the bog.

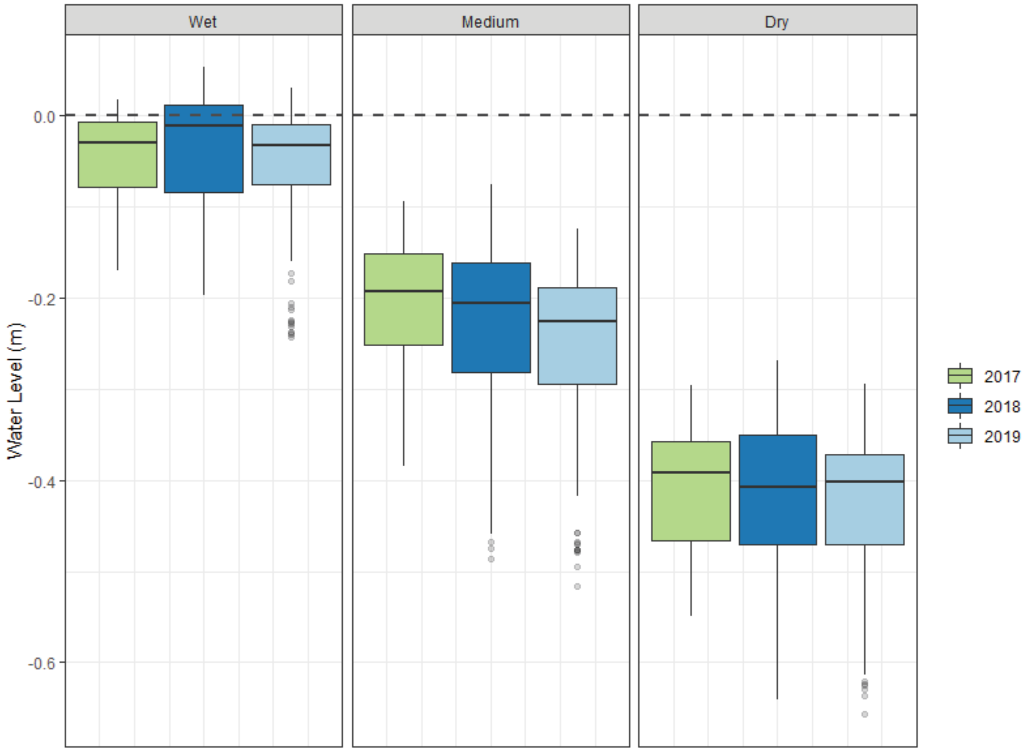


Figure 7. Boxplots of mean daily water levels for wet, medium, and dry sites in reference wetland

4.3 Peat Characteristics

4.3.1 von Post Characterization

Soil samples were taken at eight of the fourteen well sites in the focused study plot. The sample ID corresponds with the well site within the study plot. The degree of humification, or decomposition was identified as per the von Post humification scale (Table 1). The degree of humification at three different depths at each location are summarized in Table 4.

Generally, humification increased with depth from surface and in most cases, the peat was more decomposed at 30 cm below the surface than 10 cm below surface. The humification of the peat at these sample locations varied from H3 at depth 1 to H6 at depth 3. A humification degree of H3 exhibits slight decomposition and indicates a fibric peat. The peat is characterized by visible and identifiable plant structure with only slight amounts of amorphous material. The peat still has structure and is not extruded through fingers when squeezed. Peat with a humification degree of H6 has moderately strong decomposition. Plant structure is indistinct upon initial assessment, becoming more distinct upon squeezing. It contains a considerable amount of amorphous material and about one third of the peat is extruded through fingers when squeezed. A humification degree of H6 indicates that the peat is hemic.

Samples SA1, SC2, SD1 exhibited more decomposition closer to the ground surface. These sample locations were visually impacted by gulls and dominated with woody vegetation, not typical of a bog ecosystem (NWWG, 1997). The amount of decomposition present at these locations is likely a result of prolonged drying as a result of the ditching, instead of waterlogged, anaerobic decomposition that is characteristic in a bog.

Table 4. von Post characterization of soil samples taken at three depths.

Sample ID	**Degree of Decomposition**		
	Depth 1 (10 cm)	**Depth 2 (30 cm)**	**Depth 3 (60 cm)**
SA1	H4	H4	H5
SA4	H3	H5	H6
SB2	H3	H3	H6
SB3	H3	H5	H6
SC2	H5	H4	H6
SC3	H3	H5	H6
SD1	H5	H5	H6
SD4	H3	H4	H5

4.4 Hydrologic Regime of Big Meadow Bog Pre and Post Restoration

4.4.1 Overview of Sitewide Water Level Response

Figure 8 illustrates the locations of the monitoring wells across the Big Meadow Bog site for 2017 – 2019. There are three transects of wells, initially installed by NSDNR, that were also monitored in this study:

- Transect 1: MW38, MW3, MW5, and MW6
- Transect 2: MW19, MW9, and MW12
- Transect 3: MW14 and MW18

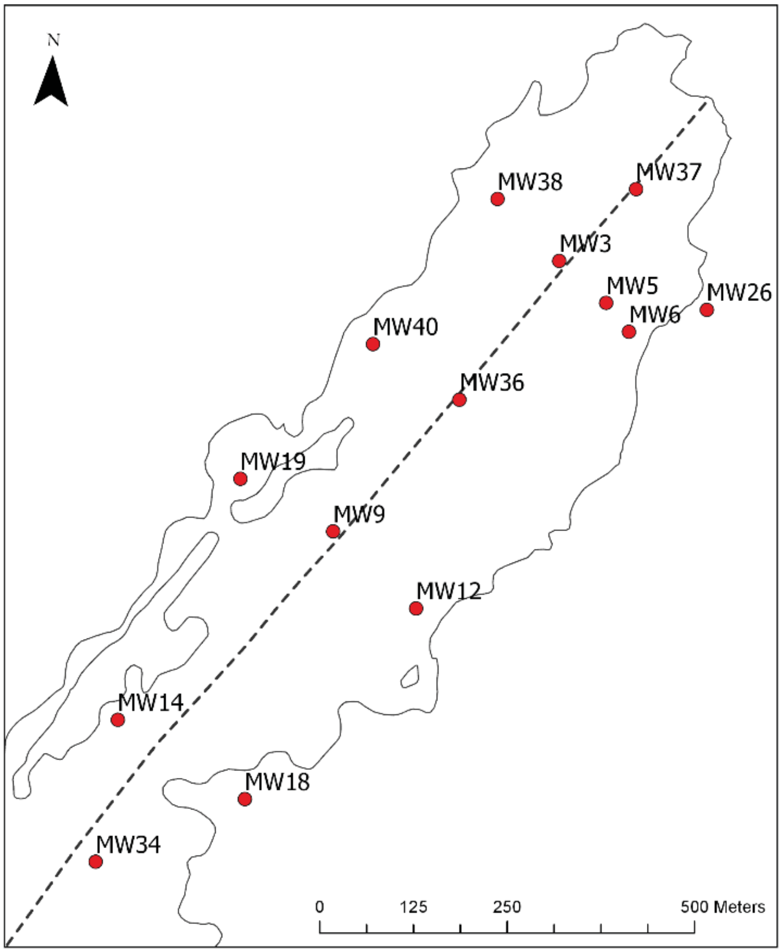


Figure 8. Locations of sitewide monitoring wells in Big Meadow Bog

The variation in mean daily water level for the sitewide monitoring wells during the 2017 – 2019 growing seasons is illustrated in Figure 9. The boxplots are arranged to correspond with locations of the monitoring well as you travel south on the length of Big Meadow Bog. The first well, MW37, is located in the most northernly position of the wetland complex and the last well, MW34, is the most southernly monitoring location. Sitewide water levels showed increasing trends from pre-restoration in 2017 to post-restoration in 2018 – 2019. Larger increases in water level were seen between 2018 – 2019, most likely due to below average amounts of precipitation in 2018. The lack of precipitation in 2018 likely dampened the initial reestablishment of water levels during the first growing season post-restoration. The water level response, however, was not consistent throughout the wetland complex. Overall, the greatest change in water levels was most apparent in the northern portions of the bog. Water levels in several wells located in the central and southern part of the bog did not appear to change. A two-way ANOVA was applied to examine the effect of year (2017, 2018, and 2019) and well location (on or North of Transect 1 (T1), between T1 and Transect 2 (T2), South of T2) on mean daily water levels, with neither the main effects of interaction terms found to be significant.

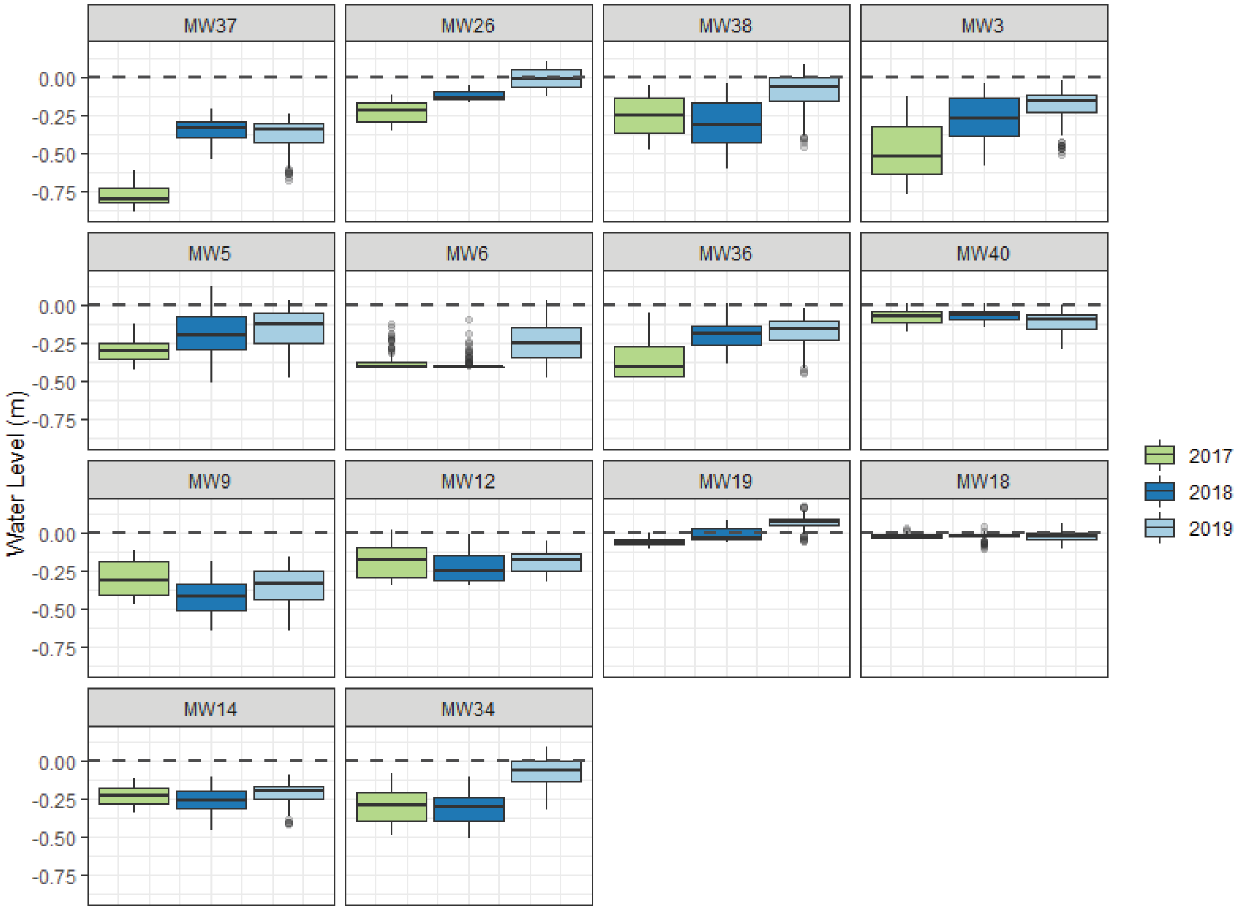


Figure 9. Boxplots of mean daily water levels for sitewide wells relative to ground surface during the growing season (May - September)

Many of the wells on or near the central ditch (MW37, MW3, MW36, MW34) experienced the greatest increase in water levels. These increases were expected as the central ditch was the source of substantial drawdown, between 0.5 – 0.7 m, for prolonged periods pre-restoration. The installation of the ditch blocks appears to have allowed water levels to return to the upper 0.5 m of the peat for a large portion of the growing season. The level of variation in growing season water levels in these wells also increased post-restoration, indicating a flashier hydrologic response. This could be partly attributable to the physical state of the impacted peat, which has been subjected to excessive drying and decomposition. Figure 10 illustrates the growing season water levels in MW3 for 2017 – 2019. It is evident that average water levels have increased post restoration, despite 2018 being drier. In 2019, we can see water levels re-established near surface due to precipitation events in late August – early September.

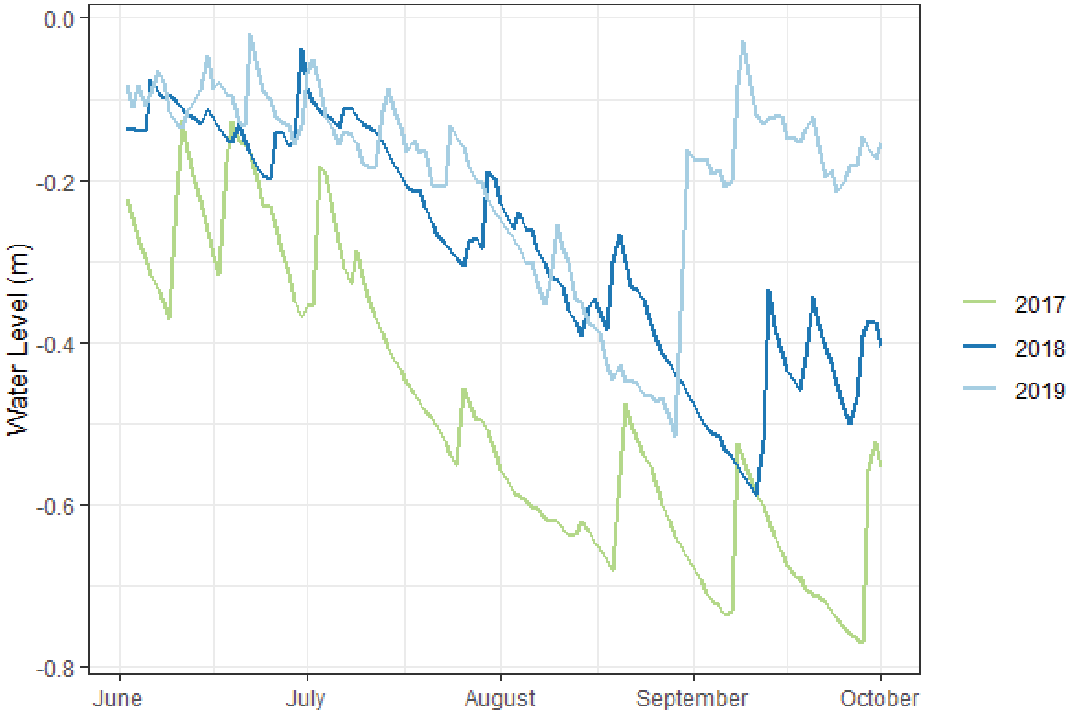


Figure 10. Growing season water levels for MW3 from 2017 - 2019.

In general, wells on the outer boundaries of BMB (MW14, MW18, MW19, and MW40) demonstrated smaller increases in water level, if any. Figure 11 illustrates growing season water levels with similar trends for MW14 from 2017 – 2019. Variation in growing season levels only increased slightly in the two years post-restoration. However, MW26 and MW6, which are in the lagg area on the northeast boundary of the wetland complex, showed a marked increase in water level. These lagg areas are the preferred habitat of the *Geum peckii* and the re-establishment of near surface water levels in the lagg will hopefully limit vegetation competition for the *Geum peckii*.

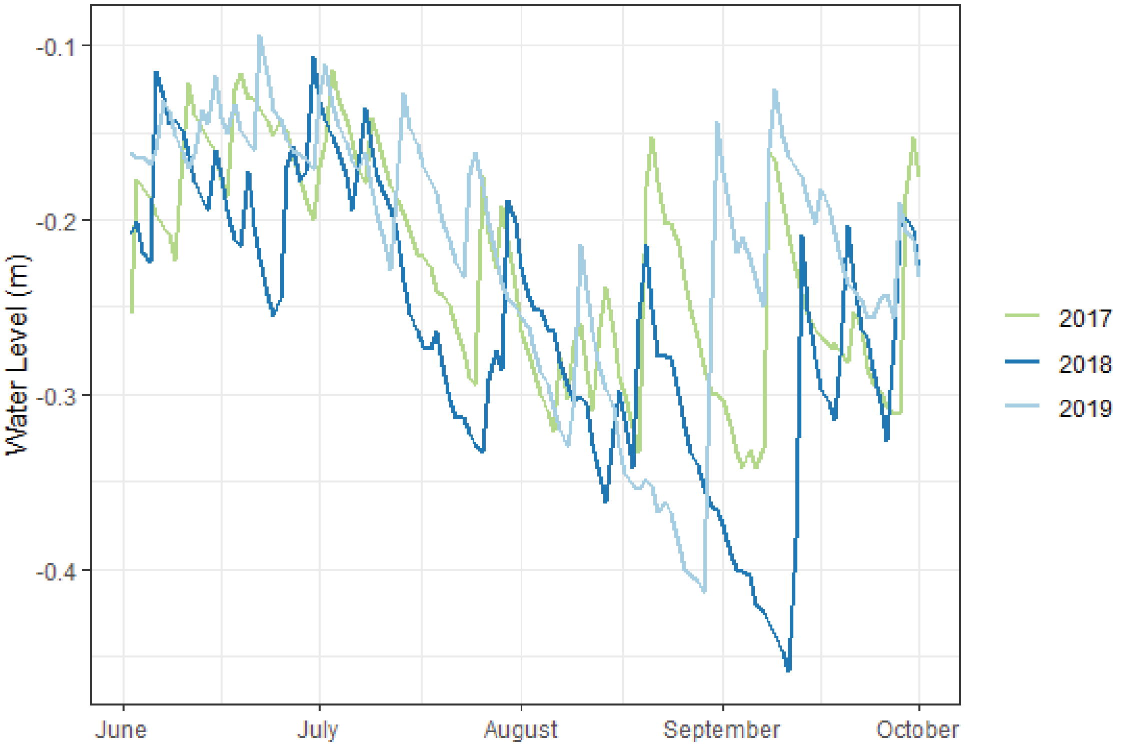


Figure 11. Growing season water levels for MW14 from 2017 - 2019.

Bog hydrology is characterized by a water table that is at or near the surface. A high water table is essential for peatland plants, specifically *Sphagnum* moss, to increase the soil water pressure within the moss to promote re-colonization and to resume the peat-forming process (McCarter & Price, 2013). Figure 12 shows the percent increase in time, from pre- (2017) to post-restoration (2018 and 2019), that the sitewide water levels were within 30 cm of the ground surface during the growing season (May – September). Overall, post-restoration water levels were within 30 cm of the ground surface for longer periods of time as compared to pre-restoration. Wells closer to the ditch (MW36, MW3, MW37, MW34, and MW5), saw an increase in the time the water level was within 30 cm of the ground surface greater than 20%. A number of wells further away from the ditch did not show as great an increase. Pre-restoration water levels in several of these wells (MW18, MW19, and MW40) were already at or very near the ground surface and these levels were maintained post-restoration. When comparing means of all sitewide wells, there was no significant difference in this percentage pre- ($M = 60.29$, $SD = 33.2$) and post- ($M = 70.79$, $SD = 26.12$) restoration ($p = 0.065$).

There does appear to be a relationship between percent increase and distance from the ditch, with a few exceptions. Wells closer to the ditch experienced a larger percent increase in the amount of time water levels were within 30 cm of the ground surface from pre- to post-restoration. Even so, it should also be noted that MW9 had the lowest percent increase (-24%) in time water level was within 30 cm of the ground surface. Trends for MW9 mean daily water levels (Figure 9) indicate that some of the hydrologic interventions have diverted water away from this area of the bog in the two years post-restoration, which is also evident in Figure 12. In 2018, MW9 daily water levels decreased compared to 2017, but 2019 water levels did recover somewhat and were more comparable to levels in 2017.

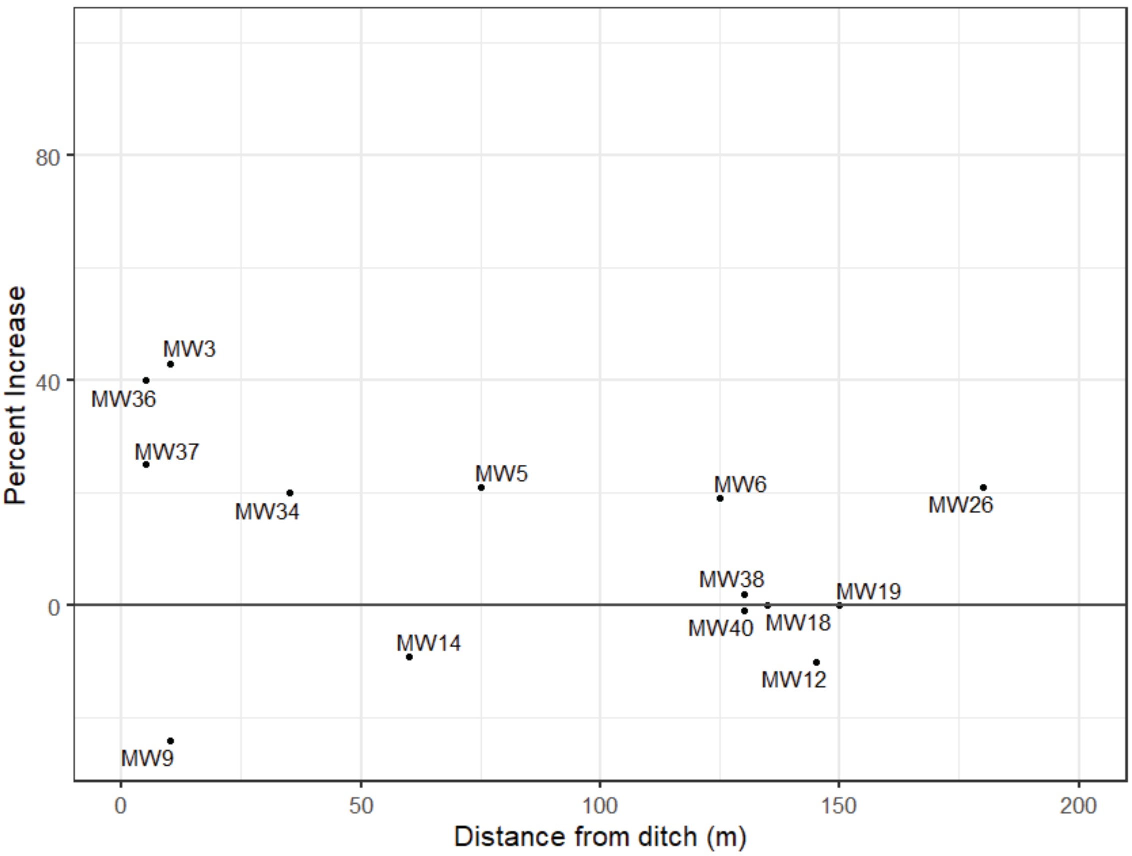


Figure 12. Percent increase in time growing season (May – September) water levels were within 30 cm of the ground surface for sitewide wells, pre- and post-restoration

4.4.2 Spatial Variation in Sitewide Minimum Water Levels

Interpolated contour plots of water levels were constructed to visualize the spatial variation of water levels throughout the site. Figure 13 illustrates the spatial variation in predicted average daily minimum water levels from 2017 – 2019. Overall, there were increases in average minimum daily water levels around the perimeter of the wetland. Ditch blocking the east and west ditches appeared to promote water retention in the lagg regions of the bog. A two-way ANOVA was conducted that examined the effect of year (2017, 2018, and 2019) and well locations (on or North of T1, between T1 – T2, South of T2) on minimum daily water levels. There was a statistically significant effect of well location on minimum daily water level [F(2,33) = 3.965, p = 0.029] but no significant effect of year on minimum daily level. Closer examination of the main effects using a Tukey HSD post-hoc test showed no significant differences were found between the interactions of well locations. The p-values for each interaction are as follows: North of T1 and wells between T1 – T2 (p = 0.056), wells on or North of T1 and wells South of T2 (p = 0.072), or wells between T1 – T2 and wells South of T2 (p = 0.974).

The minimum water level visualizations provide a somewhat different understanding in the hydrology of the system as compared to previous analysis of the mean water levels (Figure 9), which indicated an increase in water level across the site pre- and post-restoration. In Figure 13, we see similar levels, and spatial trends, in minimum water levels across the bog in 2017 and 2018. However, 2019 minimum water levels produced a dominant gradient from the margins of the bog towards the longitudinal middle of the bog. This could be attributed to the physical state of the peat in the middle of the bog, as it was most affected by ditching and gull presence. The gradient could indicate that the disturbed peat near the central ditch of the bog does not have the ability to retain water consistently throughout the growing season. At this point in the restoration, it is expected that the capacity of the peat to hold water during the growing season would be limited. This might improve as the bog stays rewetted for a longer period of time.

Studies have shown that ditch blocking can have an immediate effect on the water table in peat bog systems (McCarter & Price, 2013; Howie et al., 2009; Price, 1996). However, even with this immediate re-establishment of water levels, disturbed peat systems can take many years to re-start the peat forming process. The reversal of the impacts of ditch drainage will not immediately be achieved through raising the water table, although it is the first step. This is due to the continued impairment of the peat in the vicinity of the ditch due to compression and shrinkage from drying (Price & Schlotzhauer, 1999). The lack of pore water pressure within the peat structure causes the peat matrix to shrink, which in turn alters the storage capacity of the peat. Howie et al. (2009) explains that there are differences in the zone of influence of a drainage ditch when compared to that of ditch blocking (restoration). We would expect to see a larger zone of influence in the case of a drainage ditch and the disparity between these two would increase with the amount of time the peat was subjected to drying (Howie et al., 2009). It would be expected that it will take several years for the peat to recover and for the water level regime to stabilize, which is likely the case for Big Meadow Bog.

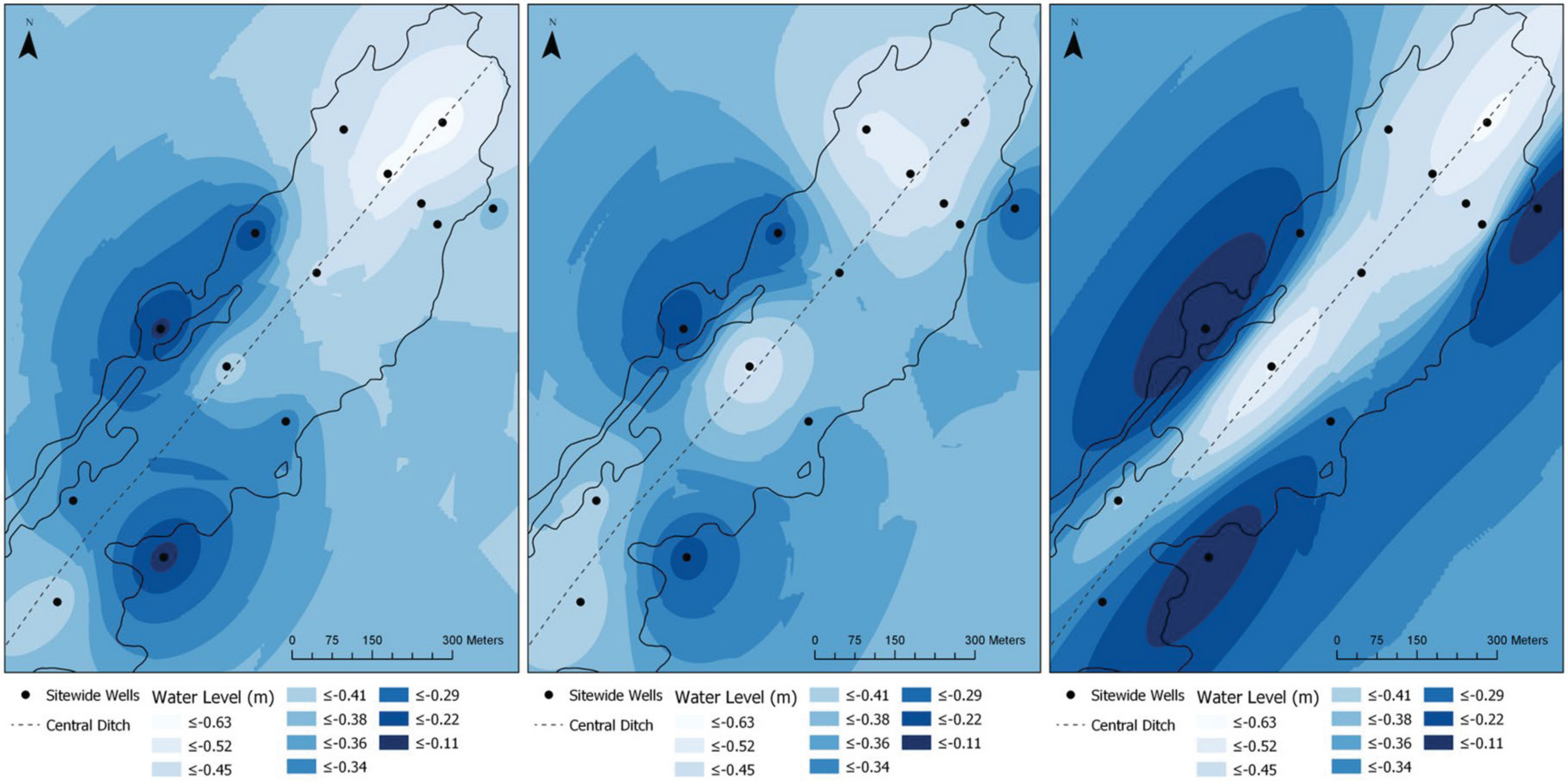


Figure 13. Interpolated minimum daily average water levels for sitewide wells during the 2017 (left), 2018 (middle), and 2019 (right) growing seasons (May – September)

4.4.3 Overview of Study Plot Water Level response

Figure 14 illustrates the locations of the focused study plot wells, in the northern portion of BMB, relative to the central ditch.

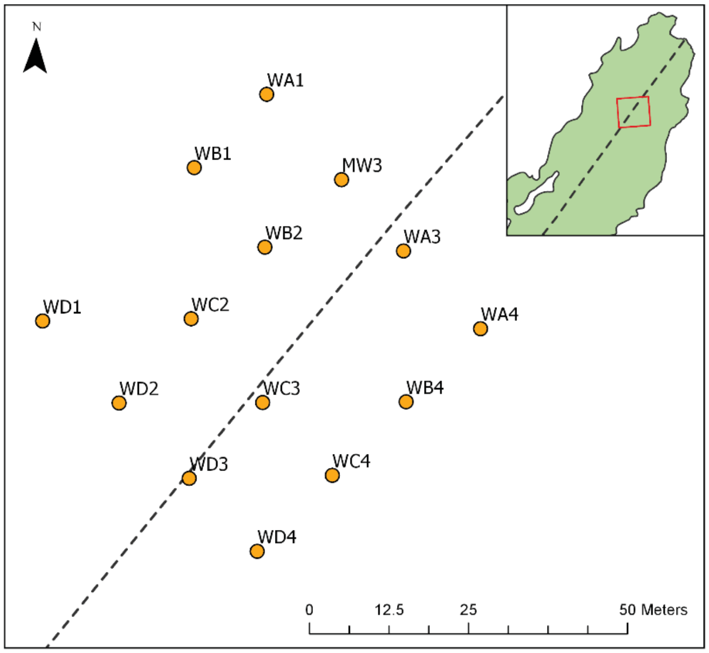


Figure 14. Locations of focused study plot wells in Big Meadow bog relative to the central ditch

The variation in mean daily water levels in the focused study plot for the growing seasons from 2017 – 2019 are shown in Figure 15. The well locations are organized by transects, starting with the most northernly transect of wells, moving southwest (well name A to D), with the wells left to right (well number 1 to 4). The majority of the study plot wells demonstrated increases in mean daily water level from 2017 to 2019. Water levels were also closer to ground surface more often during the growing season. Most water levels increased to be within 30 cm of the ground surface by 2019. As expected, well locations closest to the ditch (WA3, WC3, and WD3) had greater increases between 2017 and 2018 (post-restoration) due to the immediate rewetting from the central ditch blocking. This increase was present even though 2018 was a comparatively dry year. A two-way ANOVA was applied to examine the effect of year (2017, 2018, and 2019) and position (near or far from the ditch) on mean daily water levels. There was a statistically significant effect of year on mean daily water level [F(2,36) = 19.835, p = < 0.001]. Closer examination of the main effects using a Tukey HSD post-hoc test showed that mean water levels in 2017 were lower than 2018 (p = 0.001) and 2019 (p = 0.000), while no significant differences were found between 2018 and 2019 (p = 0.085).

Well locations further away from the ditch (WA1, WB1, WC4, and WD4) continued to see increases in water levels through 2019. However, most wells near the ditch had mean water levels similar to 2018. On the study plot scale, water levels appeared to be more variable during the 2017 pre-restoration growing season compared to 2018 and even more so compared to 2019. This could be an indication that on a smaller scale, water levels are more consistent near the ditch throughout the growing season post-restoration.

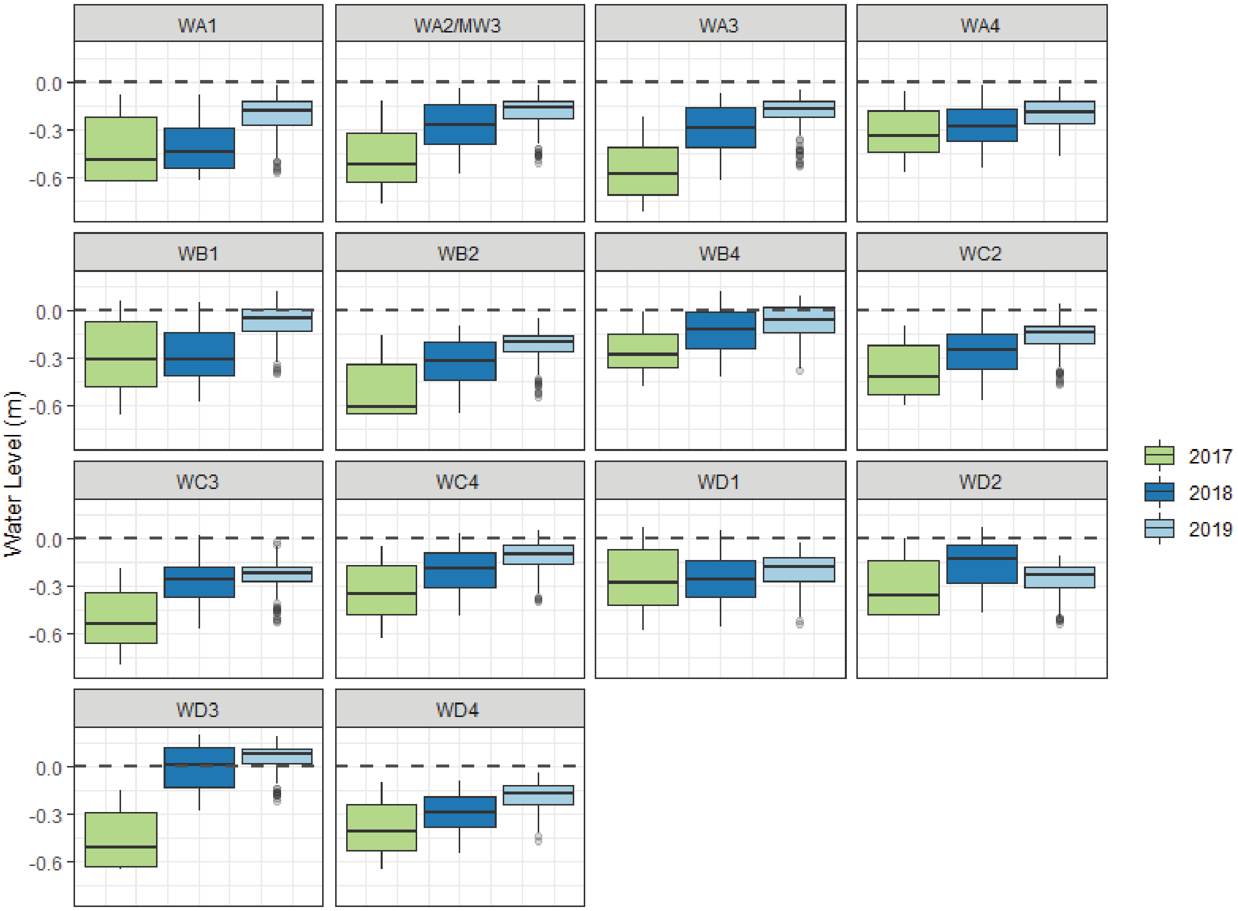


Figure 15. Boxplots of mean daily water levels for focused study plot relative to ground surface during the growing season (May - September)

4.4.4 Spatial Variation in Study Plot Minimum Water Levels

Minimum average daily water levels were interpolated and contour plots produced to show the spatial variation in the study plot between 2017 – 2019 (Figure 16). In 2017, predicted average daily minimum water levels were quite low near the central ditch, approximately 0.65 m - 0.7 m below ground surface. This was expected as the central ditch was 0.7 m – 1 m deep in the northern portion of the bog where the study plot was installed. Daily minimums increased throughout the study plot between each of the study years. Minimum water levels in 2017 ranged from 0.55 m below ground surface around the perimeter on the East and West edges to 0.7 m below ground surface in the center of the study plot. In 2018, minimum water levels ranged from 0.58 m – 0.4 m below ground surface with the wetter area focused around the southern half of the study plot. There was an area that was notably drier in the northern half of the plot in 2018 but water levels had still increased from 2017. In 2019, minimum water levels ranged from 0.5 m – 0.4 m below ground surface. The steep gradient of minimum water levels is much less prominent in 2019 compared to 2017. The less variable pattern across the study plot indicates more spatially even water level minimums during the growing season.

A two-way ANOVA was conducted to examine the effect of year (2017, 2018, and 2019) and position (near or far from the ditch) on minimum daily water levels. There was a statistically significant effect of year on minimum daily average water level [F(2,36) = 10.035, p = < 0.001]. When applying a Tukey HSD post-hoc test it showed that mean water levels in 2017 were statistically lower than 2018 (p = 0.025) and 2019 (p = 0.000), while no significant differences were found between 2018 and 2019 (p = 0.217).

4.4.5 Reference Wetland Comparison

In Nova Scotia there are challenges with finding appropriate reference wetlands due to the limited historical datasets of undisturbed peatlands. Pre-disturbance datasets are typically unavailable and finding a wetland that compares appropriately to a disturbed site can be difficult. Comparisons of wetland types across Nova Scotia, in terms of hydrologic conditions, have been completed in recent years (Bell, 2021 & MacIntyre, 2017). These studies aimed to establish hydrologic baselines that pertain to wetland management, to ultimately aid in the development of restoration targets of disturbed sites.

MacIntyre (2017) showed that domed bogs have differing hydrologic patterns (lower water tables) when compared to basin bogs, where water tables were in the shallow root zone (0 – 20 cm). Bell (2021) had similar findings for wooded peatlands in Nova Scotia, which showed that these sites remained saturated year-long and mean water levels were between 0.04 – 0.17 m below ground surface during the summer months.

Sitewide water level trends in Big Meadow Bog, post restoration, followed similar spatial trends to the Reference wetland. Water levels were near ground surface in the peripheral lagg area of the wetland, getting increasingly drier moving towards the middle of the bog. In the Reference wetland, mean daily water levels in the middle, domed portion of the bog averaged around 0.4 m below ground surface. Comparatively, mean daily water levels in the raised middle of BMB averaged within 0.3 m of the ground surface, with some fluctuations.

The settling of the peat matrix in BMB from prolonged drying has altered the once domed character of the wetland. The Reference wetland also exhibits a hummocky peat surface, which due to drying and impacts from the gulls, is not visible in many areas of BMB. MacIntyre (2017) suggested that perhaps basin bogs would be a more suitable target for mean water table. The findings from this study suggest that the restoration activities in BMB have raised the mean water table to levels slightly higher than those recorded in the Reference wetland. This could indicate that although the Reference wetland hydrology seems to be the ideal end target for BMB, in terms of hydrologic patterns and peat structure, it might not be the most appropriate in these early years post-restoration.

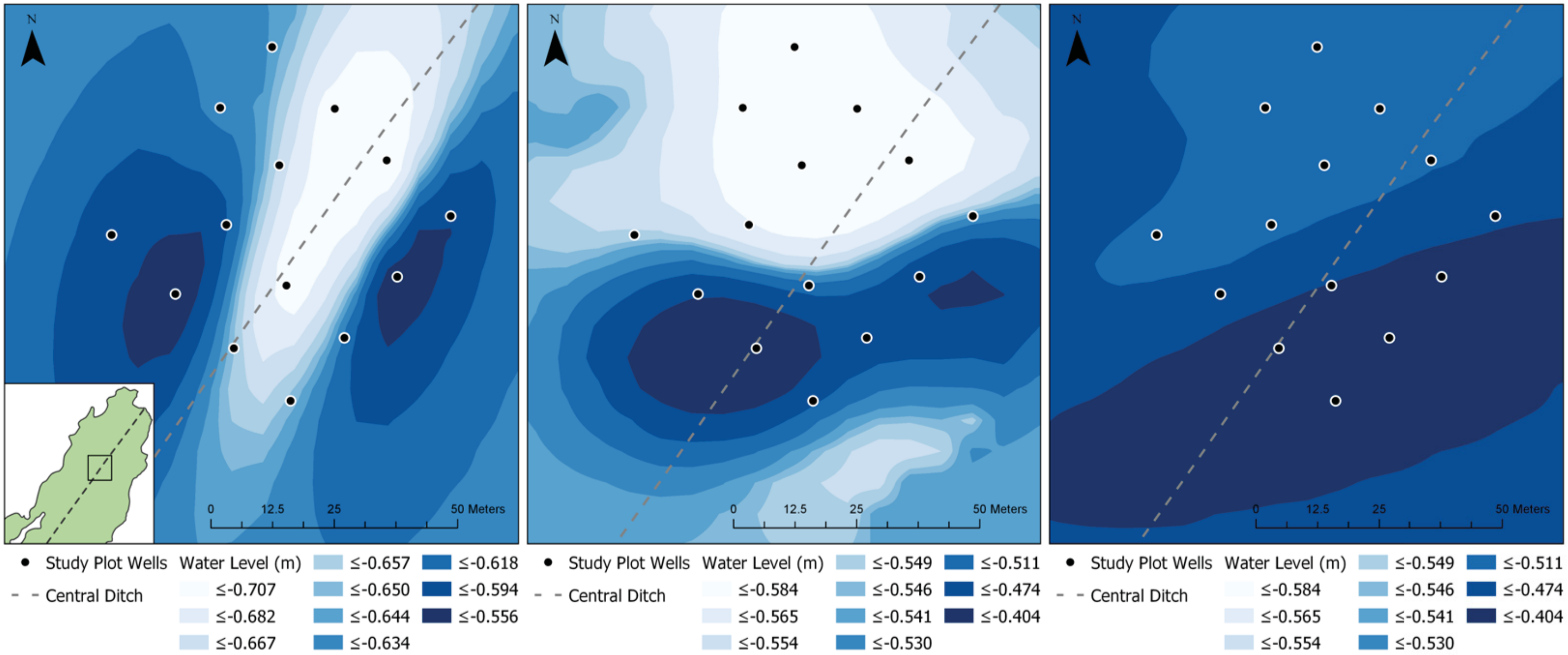


Figure 16. Interpolated minimum daily average water levels for focused study plot wells during the 2017 (left), 2018 (middle), and 2019 (right) growing seasons.

CHAPTER 5 CONCLUSIONS

This study aimed to determine the effect the restoration activities had on water levels in the Big Meadow Bog wetland complex and to investigate the spatial variability in terms of water level recovery. The characterization of post-restoration hydrology will help to direct subsequent monitoring activities.

The findings of the study showed that the restoration activities were successful in raising water levels on both a sitewide and focused study plot scale. Many of the sitewide wells close to the ditch saw an increase, greater than 20%, in the amount of time mean daily water levels were within 30 cm of the ground surface throughout the growing season. These percent increases showed an inverse relationship with the distance the well is located from central ditch.

Minimum daily water levels in the peripheral, lagg areas of the wetland did increase to be within 20 cm of the ground surface in a few focused areas across the site. This was evident in the areas of MW19, MW26, and MW38, which have known populations of Eastern Mountain Avens.

However, the effects of the restoration activities were variable across the wetland complex. Some of the impacted portions of the bog, mainly along the longitudinal middle, appear to have issues with water retention in the summer. This is most likely due to the disturbed nature of the peat, which will need much more time post-restoration to allow the bog to retain water and hopefully regain its former raised bog character. Trends of mean daily water levels at the MW9 monitoring location did indicate that some of the hydrologic interventions have diverted water away from this area of the bog in the two years post-restoration.

At this time, the hydrology of Big Meadow Bog is now considered more comparable to other types of bogs in this region of Nova Scotia. However, there is uncertainty as to what a true ‘reference’ wetland should look like and behave, especially when considering on-going restoration targets for the BMB site.

Overall, the findings from the study have shown that the bog is initially responding well to the restoration activities completed. The hydrology of a peatland is crucial to its health and behaviour and therefore, the establishment of a higher, more consistent water table is an important first step for the bog to regain its natural functions.

5.1 Recommendations for Future Work

The findings of this study have highlighted that there are still areas where further investigation is required to properly measure the success of restoring the BMB wetland complex. First, continued monitoring of water levels on sitewide and focused study plot scale to evaluate the sustained rewetting of the bog. Investigating other aspects of the hydro patterns (year-long water level patterns and responses to rain or flooding events) of BMB might be necessary to fully understand the interaction of the varying wetland features in the wetland complex post-restoration. This would also be helpful to create a better understanding of the most appropriate ‘reference’ wetland site. Additional continuous monitoring of other comparable peatland systems in the region is encouraged.

It is also recommended that future work investigates the status of the peat material at various locations in the bog. Prolonged draining of a peatland can drastically alter its ability to regain storage properties that are imperative to supporting vegetation communities and regulating the water table. The health of the peat has not yet been characterized. Future assessment of the peat could include taking soil samples to determine the specific yield of the peat at varying depths or tracking the movement of the peat surface. This could give insight into the potential disparity of decomposition within the peat profile and whether or not the storativity within the peat is increasing with the more stable water levels.

Finally, future monitoring of BMB should include characterization of the vegetation community. As a part of the restoration, ECA completed the removal of woody vegetation in the raised portion of BMB. This was the first step to limiting habitat competition for vegetative species indicative of a bog, *Sphagnum* mosses. Continued high water table will hopefully limit the regrowth of the woody vegetation and allow the recolonization of the moss. Monitoring of the community of vegetation throughout the bog would be valuable in understanding if peat forming processes have returned.

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