Initial Surface Hydrology Characteristics of Icelandic, Drained, Patchy Wetlands

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Northern wetlands with a high organic content comprise a large portion of Earth's wetlands (Arnalds et al. 2016). Icelandic inland wetlands are mostly fens (Figure 1) that contain varying amounts of inorganic and organic material (Arnalds et al. 2016). The distinctive geology in Iceland affects wetland soils. It is populated with several glaciers and about 30 active volcanoes, fed by a mantle plume under the island, erupting on average every 4-5 years (Bird and Gísladóttir 2014). Aeolian and tephra distribution from these volcanoes is deposited throughout the island, creating variable soil conditions with lower organic content nearer to volcanoes and major dust sources, such as large sandar (Arnalds et al. 2016). The primary region for this study is within the lowlands in southern and western Iceland, the largest area of topogenous fens here. Combining these geographic characteristics creates three wetland soil types, as defined by the Icelandic classification system: histosols, histic andisols, and gleyic andisols (Arnalds et al. 2016).

Permafrost makes up about 22% of the land surface in the Northern Hemisphere, defined as frozen soil found at a temperature at or below 0°C for a minimum of two years (Woo 2012). Infiltration can occur into frozen soil as meltwater from the snow reaches the ground surface (Woo 2012). Permafrost has a tendency of being thinner in maritime climates due to their proximity to the oceans rather than further inland. Thus, interior wetlands in Iceland may contain sporadic permafrost but it likely does not occur along the coastline of the island (Arnalds and Kimble 2001; Woo 2012; Arnalds et al. 2016). If the surface soil has a high water content that freezes, concrete frost can develop (Dingman 2015). This is affected by the amount of vegetation in the soil (Orradottir et al. 2008; Dingman 2015). Good conditions for concrete frost formation are rainfall or snowmelt in warmer weather followed by below zero temperatures. Based on prior research concrete frost tends to develop in open soils which have high soil water content under such conditions (Orradottir et al. 2008). The hydraulic conductivity of permafrost or concrete frost is significantly lower than that of unfrozen soils, an important factor in controlling soil draining and the extent and distribution of wetlands (Eugster et al. 2000). Infiltration is highly variable, and is affected by rainfall amounts and intensity, antecedent soil moisture conditions, and varying soil properties (Dingman 2015). Infiltration capacity is described by Horton's equation as:

$$f_p = f_c + (f_0 - f_c)e^{-kt} \qquad (1)$$

where f_p is the infiltration capacity at time t; k is a constant representing the rate of decrease in f capacity; f_c is a final or equilibrium capacity, and f_0 is the initial infiltration capacity

FIGURE 1. Icelandic fen at the Agricultural University of Iceland, Hvanneyri, Iceland (Source: E. Perera, taken 4 July 2018; permission granted).

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(Viessman and Lewis 2003). Soil factors affect infiltration based on the presence of organic matter in soils, soil compaction, or human modification (Dingman 2015).

Soil moisture exhibits a high spatiotemporal variability (Loew et al. 2013). It can differ spatially within an ecosystem, decreasing downslope and vertically above the water table, or locally due to small scale changes in microtopography (Petrone et al. 2004; Woo 2012). At daily to interannual timescales, variation can also be high, making soil moisture difficult to measure (Loew et al. 2013). Soil moisture has a long-term memory, storing interannual precipitation anomalies in cold, arid climates with frozen soils, making it an important factor for seasonal climate forecasts (Shinoda and Nandintsetseg 2011; Loew et al. 2013). Icelandic soils have high organic and mineral content, with high water retention and porosity characteristic of both peatlands and volcanic soils (Neris et al. 2012; Arnalds et al. 2016).

These soil properties provide an important control on surface vegetation and, to some extent, climate (Rouse 2002). Wetland patches with higher water contents can lead to a greater net solar energy input, so their microclimates will vary depending on surface water content (Sumner et al. 2011). The albedo of a bare soil tends to increase with lower water content, however, soil texture and vegetation cover affect surface radiation, adding complexity to this relationship (Graser and Van Bavel 1982; Jensen 2007). The presence of surface water and dark surfaces can lower ground albedo, enhancing radiation absorption in those areas, and aiding in wetland evaporation losses (Sumner et al. 2011). Surface soil moisture is also affected in Icelandic soil cover under vegetated surfaces by the hummocky ground (thufur) (Jones et al. 2009). This feature, along with the root structure of grasslands here, allows for porous concrete soil frost and patchy ice cover in winter (Orradottir et al. 2008; Jones et al. 2009). The presence of permafrost in Iceland is restricted to higher elevations (Jones et al. 2009) and interior wetlands as mentioned above. Good water conductivity and large water retention capacity allow for seasonal frost in Icelandic andisols, which can reach down to 0.5 m depth, while the hummocky surface features can be seen 0.1-0.5 m into the soil profile (Jones et al. 2009).

PATCHY WETLANDS IN ICELAND

Wetland ecosystems are vulnerable to changes in hydrology on a global scale – modeled and observed precipitation trends have shown that precipitation in the Arctic has continuously exceeded the global average increase in precipitation (Erwin 2009; Bintanja and Selten 2014). Responses to changes in climate could include differences in the distribution and vegetation types in high-latitude regions (Beringer et al. 2005). Circumpolar Arctic regions experience conditions favorable to patchy wetlands, including the wetlands found in Iceland. Patchy wetlands locally contain tundra vegetation, form niches for the wildlife in those areas, and as ecosystems they are distinctly sensitive to land use disturbance and changes in climate (Woo and Young 2003). The climate in Iceland is influenced by the island's location between warm and cold ocean currents - between the warm North Atlantic Drift and the cold East Greenland Current (Einarsson 1984). Iceland's climate is maritime with mild winters and cool summers, where southern temperatures are between 4-5°C and annual precipitation along the coastline (1,000-1,600 mm) is higher than farther inland (700-1,000 mm) (Einarsson 1984).

In total, Icelandic government subsidies facilitated drainage of approximately 47% of these wetlands after the Second World War, mainly for agricultural production to keep up with the rising population, as well as to help adjust with domestic rural-to-urban migrations (Arnalds et al. 2016). Drainage ditches cover 29,700 km of the area, significantly altering the landscape (Gunnarsson et al. 2006). The efficacy of drainage is relative to the distance between ditches, depth of ditching, and hydraulic conductivity of the peat (Price et al. 2003). The majority of the area impacted in Iceland

TABLE 1. Breeding waders in Iceland of international importance (Gunnarsson et al. 2006).

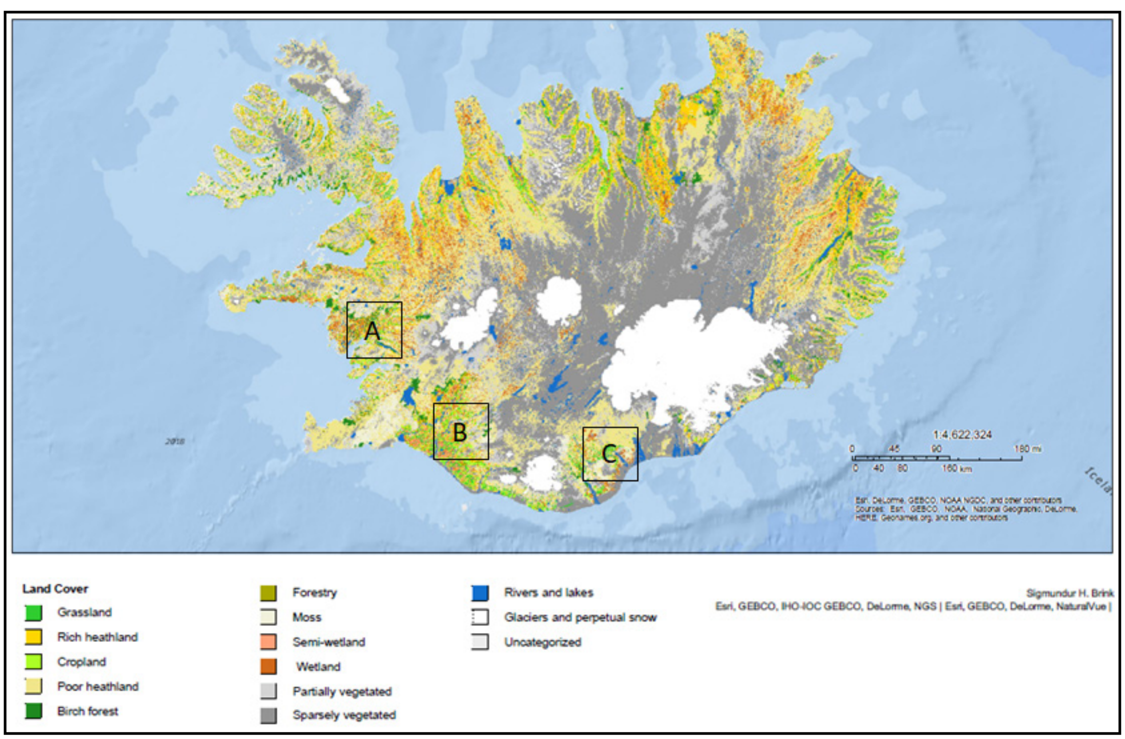
Species	Scientific Name	World population in Iceland (%)	Icelandic population below 200 m a.s.l. (%)
Oystercatcher	*Haematopus ostralegus*	4	100
Golden Plover	*Pluvialis apricaria*	52	32
Ringed Plover	*Charadrius hiaticula*	32	33
Whimbrel	*Numenius phaeopus*	40	75
Dunlin	*Calidris alpina*	16	49
Purple Sandpiper	*Calidris maritima*	46	19
Snipe	*Gallinago gallinago*	6	62
Redshank	*Tringa totanus*	19	97
Black-tailed Godwit	*Limosa limosa*	10	97
Red-necked Phalarope	*Phalaropus lobatus*	6	55

has low ditch density, with about 67% of ditched area at a density of 0.1-0.5 km km^{-2}, and 25% of the ditched areas at a density of 5-10 km km^{-2} (Arnalds et al. 2016). Landscape characteristics such as slope and bedrock hydrology affect the impacts of low ditch densities (Arnalds et al. 2016). Effects from drainage in peatland soils (histosols) are increases in runoff, peak flows, and baseflow relative to natural conditions, although decreases in peak flow have also been observed due to greater available storage capacity in drained soils between storms (Price et al. 2003). With the exception of studying infiltration characteristics in Icelandic lowland andisols, which took place within 15-35 km of the study area in this project (Orradottir et al. 2008), not much else is known about the hydrological characteristics of these wetlands or the impacts from drainage (Arnalds et al. 2016). Most previous studies have covered the soil characteristics, such as the physical properties, and nutrient content of these wetlands and other Icelandic land covers (Arnalds and Kimble 2001; Gudmundsson et al. 2004; Arnalds 2008). Many of the wetland patches were drained for hay making or grazing purposes, however, some were not set aside for specific use, leaving them without a functional purpose (Biological Diversity in Iceland, 2001; Arnalds et al. 2016).

Icelandic coastal inland fens are an important ecosystem providing habitats for about 20 migratory bird species which use these wetlands for food, resting, and nesting. Ten of these are breeding waders, some of which comprise most of the world's population of their species – as such, changes to these fens directly impact the well-being of these birds (Table 1; Gunnarsson et al. 2006). Thusly, afforestation efforts, livestock grazing from sheep and horses, and the prevalence of hydropower in Iceland present continued threats to these populations, which tend to prefer the open spaces of wetlands and grasslands (Gunnarsson et al. 2006; Arnalds et al. 2016). While wetland patches smaller than 3 ha should not be disturbed under current law, this reference size should likely be smaller (e.g., 0.5 ha) due to the importance of small wetland patches to the overall ecosystem (Arnalds et al. 2016). Currently over 40% of wetland areas in the 1-5 ha patch size fall between 1-2 ha, with about 55% of remaining wetlands unprotected by Icelandic government policy (Arnalds et al. 2016). Though wetland drainage is no longer a concern, as with elsewhere in the Arctic, little is known of climate warming impacts on these drained wetland patches (Erwin 2009; Young and Abnizova 2011).

Varying degrees of carbon in Icelandic inland wetland soils lead to their soil classification into three main groups: histosols (>20% C), histic andisols (12-20% C), and gleyic andisols (<12% C) (Arnalds et al. 2016). In particular, the majority of the active volcanic zone is dominated by gleyic andisols, with a gradient of carbon content gradually increasing with further distance from volcanoes and active dust sources (Arnalds et al. 2016). Both the organic and mineral soils in gleyic andisols have higher water retention than expected as a result of their andic soil properties (Arnalds 2008). Andisols are highly vulnerable to aeolian and water erosion due to a lack of particle cohesion and high soil water retention, leading to further erosion of the soil (Orradottir et al. 2008; Anderson 2013).

FIGURE 2. Land cover classifications delineated across Iceland. Sites are marked by black boxes: to the west is the histosols site at Hvanneyri (A), to the south are histic andisols at Þúfa (B), and in the southeast are gleyic andisols at Prestbakki (C). (Map layers provided by S. Brink, with further edits by M. Chase and E. Perera.)



STUDY OBJECTIVES

This study had three main objectives: 1) to assess the hydrology of these drained, patchy wetlands, through infiltration tests and soil moisture, 2) to evaluate spatial variation throughout these wetlands in soil moisture and albedo measurements, and 3) to improve understanding of the hydrology of these patchy wetlands, so that future impacts from human modification and climate warming may be understood, thusly addressed by policy makers. The research questions are: 1) does infiltration vary between soil type? and 2) how does near surface soil moisture content vary by wetland soil type, along with proximity to drainage ditches?

STUDY AREA AND METHODS

This study took place from 26th June until 5th July, 2018, for a total of 8 days of data collection. For each soil type (histosol, histic andisol, and gleyic andisol) one patch was sampled, for a total of 3 sites. The first site, Þúfa, was in the south (63°58'51.6" N, 20°17'06.4" W), the second, Prestbakki, in the southeast (63°49'51.20" N, 18° 1'59.02" W) and the third site was at the Agricultural University grounds at Hvanneyri, in the west (64°33'37.1" N, 21°45'23.0" W) (Figures 2 and 3). Near each drained patch an intact wetland was also sampled to serve as a "control," based on the proximity of the intact wetlands (Figures 2d and 1). In each site, 4-6 transects were sampled. At Þúfa, 4 transects in the drained patch and 1 transect in the intact wetland were sampled for a total of 5 transects; at Prestbakki, 3 transects in both the drained wetland patch and intact wetland were sampled, for a total of 6 transects; and at Hvanneyri, 3 transects in the drained patch and 1 transect in the wetland were sampled, for a total of 4 transects.

In each drained patch, 2-4 infiltration tests were taken using a double ring infiltrometer, placed within 3

FIGURE 3. Site locations (Photos courtesy of E. Perera):

a - Hvanneyri drained patch (in front of ditch)

b - Þúfa drained patch (facing southeast)

c - Prestbakki drained patch (adjacent to ditch)

d - an intact wetland at Hvanneyri site

meters of the ditch, and about 20 m apart from the previous test (Figure 4). This produced a total of 10 infiltration rates representing the 3 soils. Volumetric soil moisture content (%) was taken with a Theta soil moisture probe, measuring near surface soil moisture at a depth of 0.0-0.06 m. Leading into the patch from the infiltration test, near-surface soil moisture measurements were taken along 50 m transects, every 5 meters, where an average of 3 readings represented a sample. This scheme was also used for albedo measurements read around solar noon. Albedo was taken using a Li-Cor pyranometer to measure incoming and outgoing solar radiation. In total at each drained and wetland patch, 2-4 transects were sampled, except for the intact wetland at Þúfa (1 transect). Hvanneyri was more limited in scope, being smaller in size compared to the other sites. In drained patches, along each transect at the 10 m mark and at the 25 m mark, a soil pit was dug down to 0.60 m (Figure 5). For each soil pit, the soil was described for each visible horizon and a sample collected for laboratory analysis. Temperature and soil moisture were recorded by using a soil thermometer for vertical temperature profiles, a Theta soil moisture probe for vertical soil moisture profiles, and a Hobo SmartSensor 10HS for recording both temperature and moisture as a comparison.

Lastly, at the beginning (0 m), middle (25 m), and end (50 m) of each transect, 2-4 vegetation quadrats (0.25 x 0.25 m) were sampled for an overview of the surrounding vegetation at the different sites. Meteorological data, including wind speed, relative humidity, and temperature, were recorded daily using a Kestrel, and supplemented with Hobo temperature and relative humidity data loggers, and nearby weather station data when available.

RESULTS AND DISCUSSION

Preliminary results indicate elevated soil moisture conditions from the preceding May, which had a recorded precipitation of over 125 mm for the month (Iceland Monitor 2018). These antecedent moisture conditions contributed a greater distribution of soil moisture frequency in the southeast at Prestbakki (Figure 6) compared to the south at Þúfa and the west at Hvanneyri. More variation in soil moisture content may possibly be attributed to greater amounts of observed tephra and lower organic content in gleyed andisols vs. histic andisols and histisols.

Analysis of variance indicated that near surface soil moisture was significantly different between drained sites: t-test results revealed values of $p < 0.001$ between Prestbakki in the southeast and Hvanneyri out west, $p < 0.005$ between Þúfa in the south and Hvanneyri, and $p < 0.05$ for Þúfa and Prestbakki. Also, soil moisture content was statis-

FIGURE 4. Infiltration tests were conducted using a double ring infiltrometer; typically placed between hummocks.

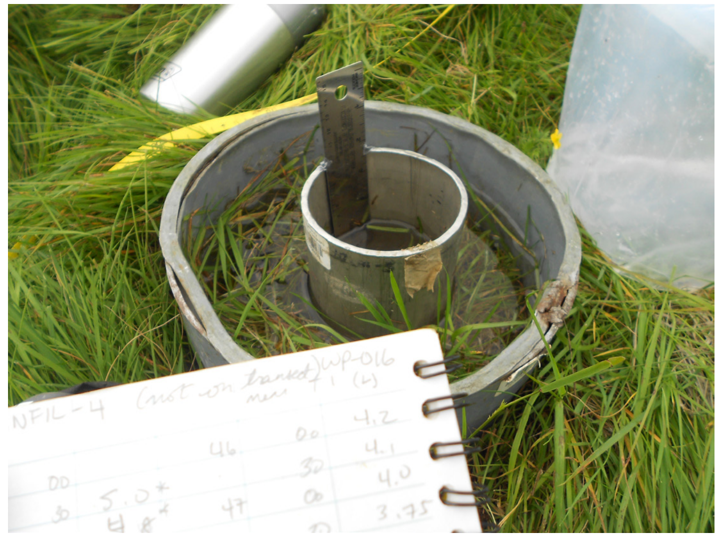


FIGURE 5. Soil pit dug down to 0.60 m depth; tephra layers are black, indicated here by dashed lines. (Photo courtesy of A. Aggarwal, taken 1 July, 2018.)

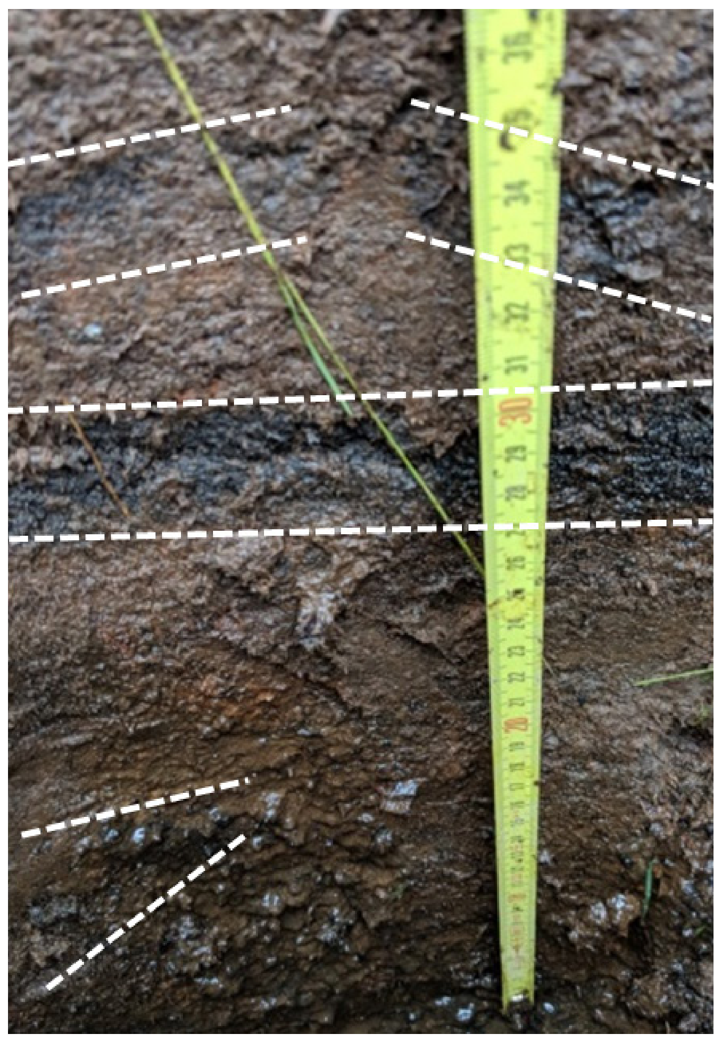


FIGURE 6. Frequency histograms show the number of times a volumetric soil moisture content sample within a given percentage range occurred at a) Hvanneyri, b) Þúfa, and c) Prestbakki drained patches (e.g., SMC (%) fell into the 90-100 percent range a total of 7 times at Þúfa). Greater variation in soil moisture is seen at Prestbakki in the southeast, an area located near volcanoes and highly influenced by tephra and aeolian deposition.

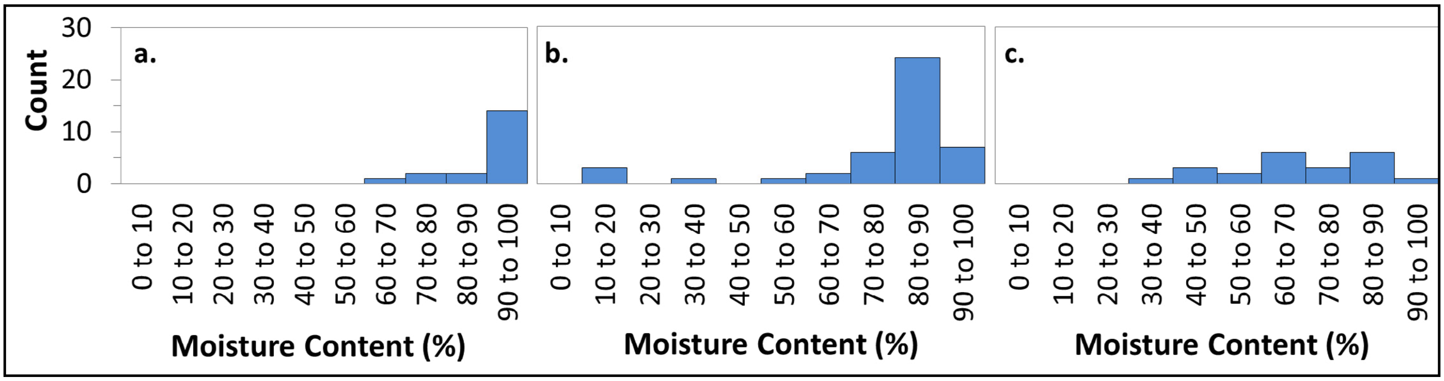


FIGURE 7. Ditch drawdown at study sites: a) Hvanneyri, b) Þúfa, and c) Prestbakki. A step function of near surface soil moisture (%) indicates that soil moisture levels off at 5 m to 10 m distance from drainage ditches. The ditch is indicated by an arrow at 0 meters. Darkened lines represent an average of the total soil moisture values from transects; the lighter lines indicate the original measured soil moisture transects.

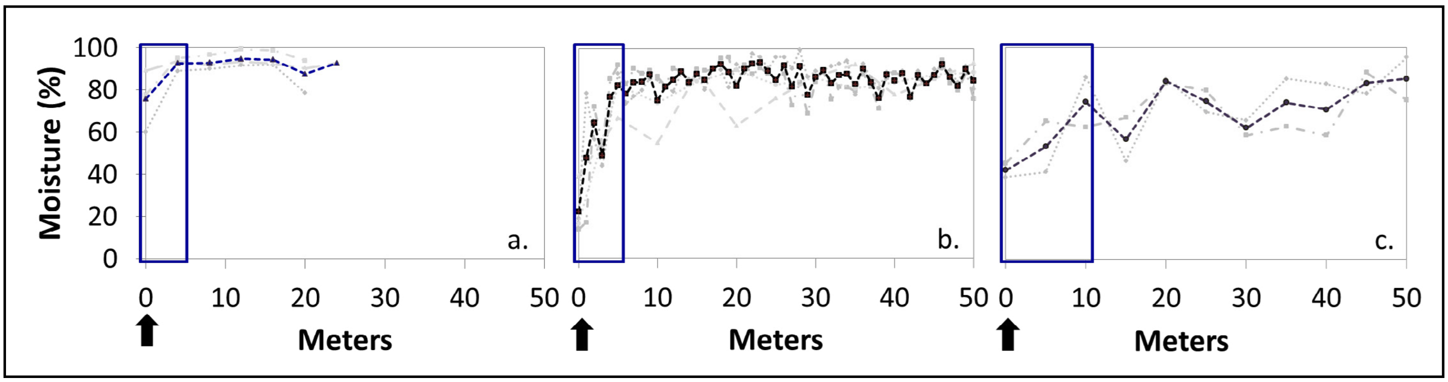
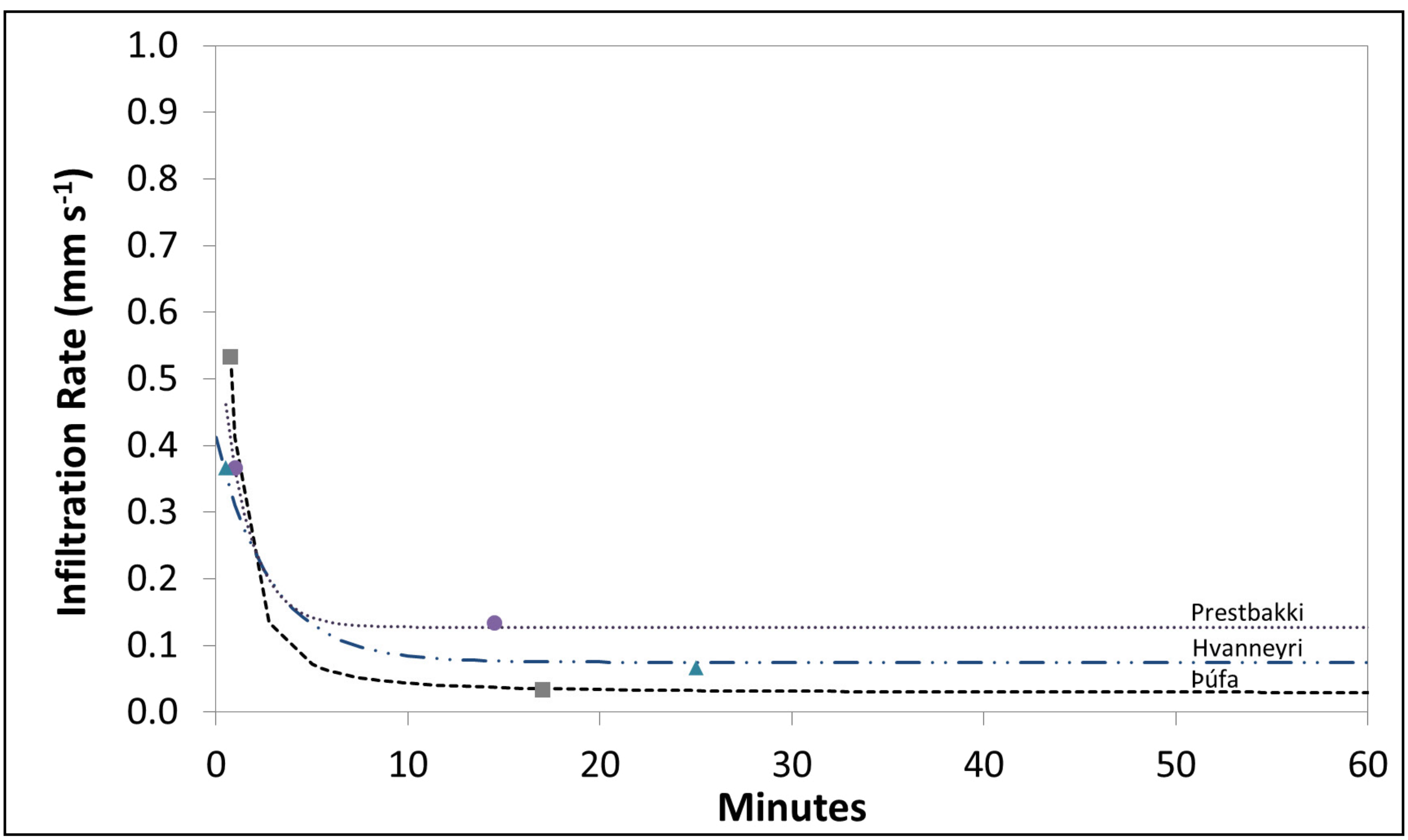


FIGURE 8. Infiltration curves for the three soil types in this study: histosols (Hvanneyri), gleyic andisols (Prestbakki), and histic andisols (Þúfa). Initial (f0) and equilibrium (fc) points are marked for each curve.



tically significant ($p < 0.001$) between the intact wetland (wetter) and the drained patch (drier) at Prestbakki, likely as a result of sharply inclined slopes at the intact wetland compared to the hilly but more level drained patch.

Soil moisture content at all three drained patches shows minimal drawdown from the drainage ditches compared to other peatland sites, except for decomposed fen peats at lower latitude in western England (Price et al. 2003). This drawdown is noticeable in Figure 7, where at Hvanneyri (a) in the west and Þúfa (b) in the south, respectively, ditch drawdown is 5 m, and ditch drawdown at Prestbakki (c) is up to 10 m. Although the study period here did not cover the entire summer growing season (May to September), this indicates the possibility that drainage ditches here lose their efficacy faster than peatland at other sites where drawdown is within 15-50 m of ditches (Price et al. 2003), at least resulting from the antecedent soil moisture conditions for this year. If this study had continued through September, the lateral drainage of the ditch could possibly remain the same in these areas due to the high water retention of gleyic andisols, with similar results in histosols because of poorly decomposed organic matter and limited shrinkage (Arnalds et al. 2016.)

Many of the infiltration curves (7) produced highly saturated results; however, one curve per drainage patch offers an idea of their differing infiltration variables (Figure 8). Results here are similar to previous High Arctic and Low Arctic wetland studies (Woo and Young 1997; Orradottir et al. 2008). Southern Icelandic lowland summer final rates ranged from 28 to 369 mm h^{-1}, while maximum capacity rates here are slightly higher than other arctic silts (except for those with large cracks), at 0.13 mm s^{-1} versus ~0.10 mm s^{-1} (Woo 2012; Orradottir et al. 2008). These soils are silty wetland soils with infiltration rates ranging between 2-22 mm min^{-1}. The data for total test runs with *in-situ* measured infiltration rates for Figure 8 show that Þúfa has a higher initial infiltration rate (f_0 = 0.53 mm s^{-1}) than Prestbakki and Hvanneyri (f_0 = 0.37 mm s^{-1}), while the latter two had higher final infiltration capacities ($f_{c(pr)}$ = 0.13 and $f_{c(hv)}$ = 0.07 mm s^{-1}) than Þúfa (f_c = 0.03 mm s^{-1}).

Cumulative infiltration displayed the most water infiltrated was first at Prestbakki, which infiltrated 789 mm of water, next at Hvanneyri, which infiltrated 744 mm of water, and lastly at Þúfa, where 172 mm of water entered the soil. Ground surface ponding was observed at 50 m at Prestbakki, and pooling was observed in soil pits at 10 m and 25 m from the drainage ditch at both Þúfa and Prestbakki.

SUMMARY

Excessive precipitation in May yielded high volumetric soil moisture contents in drained patches, with several low infiltration capacity rates due to saturation. Infiltration rates are comparable to prior studies of patchy wetlands and andisols in the Arctic (Woo and Young 1997; Orradottir et al. 2008). More variation is seen in the southeast at Prestbakki, possibly due to the influence of tephra in the soil. This variation in near surface moisture also led to pooling observed in soil pits at drained patches Þúfa and Prestbakki, and surface ponding seen at Prestbakki. In previous years, the varying infiltration and soil moisture contents would likely be lower from drier antecedent conditions.

Next steps for this study will begin with comparisons of soil properties to previous studies (Gudmundsson et al. 2004; Arnalds et al. 2016) as soil testing has been completed for soil texture, bulk density, soil organic carbon, and pH. Attempts will be made to analyze these data using Principal Components Analysis where factor 1 is based on soil textural properties and factor 2 is composed of properties relating to porosity (modifying the approach used by Neris et al. 2012). Albedo measurements and meteorological data will be compared between and within both intact wetland patches and drained patches to assess differences, if any. *In-situ* pH of ditch and pooled water, and electrical conductivity measurements of ditch water will be compared between intact wetlands to the drained patches. Vegetation and landscape characteristics such as slope and hummock filled ground will also be examined amongst drained patches for an understanding of how micro-topography affects infiltration and soil moisture content. Afterwards, these wetlands can be understood on a case-by-case basis for each site, to help better inform policy makers about the characteristics of these drained, patchy wetlands. ■

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