Surface Hydrology Characteristics of Inland Patchy Wetlands in Southern and Western Iceland

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Abstract

Icelandic inland wetlands were drained after World War II for agricultural production. These wetlands provide the habitat for migratory birds and act as carbon sinks. There is little information on the local hydrology of patchy wetlands or effects from ditching. Infiltration trials, transects of near-surface soil moisture and surface albedo, and soil stratigraphy for volcanic and organic soils were collected for comparison across wetland soils in southern and western Iceland. Wet antecedent moisture conditions led to total saturation for the majority of samples. Final infiltration capacities (0.006-0.09 mm s^{-1}) were comparable to previous infiltration rates from other Arctic studies, while tephra had limited impacts on infiltration. Soil moisture and albedo comparisons (most p-values < 0.05, 0.001) between regional drained and undisturbed locations revealed drainage has impacted the surface hydrology characteristics of disturbed wetlands, suggesting this could be the case for other drained wetlands across Iceland.

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Units and Notation

Energy

α albedo (dimensionless)

K* net shortwave solar radiation (W m^{-2})

K↓ incoming shortwave solar radiation (W m^{-2})

K↑ outgoing longwave solar radiation (W m^{-2})

L* net longwave solar radiation (W m^{-2})

L↓ incoming longwave solar radiation (W m^{-2})

L↑ outgoing longwave solar radiation (W m^{-2})

Q* net radiation (W m^{-2})

Hydrology

Θ degree of saturation, or, degree of wetness (%) = (Φ / θ)

θ volumetric water content (%)

θ_g gravimetric water content (g H2O g^{-1} dry soil)

Φ porosity (dimensionless)

Ψ matric potential (in mm—height of water column under pressure, or in kPa)

f_0 initial, or, maximum infiltration capacity (mm s^{-1}, mm min^{-1}, mm h^{-1})

D_b bulk density (g cm^3, g ml^3)

f_c infiltration constant, or, final infiltration capacity (mm s^{-1}, mm min^{-1}, mm h^{-1})

f_t infiltration capacity at time t (mm s^{-1}, mm min^{-1}, mm h^{-1})

G_s specific gravity (dimensionless)

i infiltration rate (mm s^{-1}, mm min^{-1}, mm h^{-1})

I_p depth of ponding (mm)

k_{sat} hydraulic conductivity (mm s^{-1})

SIR steady-state infiltration rate (mm s^{-1}, mm min^{-1}, mm h^{-1})

L effective reading depth of hydrometer (cm)

P percentage (%) of particles suspended at time t

R hydrometer reading (g L^{-1})

W weight (g) of hydrometer sample

w(t) water-input rate (L t^{-1})

z depth (mm) of wetting front

Measurement

μm micron, micrometer

μS micro-siemens (μS)

ρ density (g cm^{-3} or kg m^{-3})

ρ_w density of water (g cm^{-3} or kg m^{-3})

σ standard deviation

$\bar{\chi}$ mean

D diameter (cm, m)

e Euler's number = 2.7182…

ha hectare = 10,000 m^2

n sample size

T/t time (s, min, h, d)

V volume (cm, ml, L)

CHAPTER ONE: INTRODUCTION

1.1 Introduction

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 that contain varying amounts of inorganic and organic material (Figure 1.1) (Arnalds et al. 2016). The distinctive geology in Iceland affects wetland soils. Iceland is populated with several glaciers and about 30 active volcanoes, which erupt on average every 4-5 years (Bird and Gísladóttir 2014). This elevated volcanic activity results from the construction of Iceland: a combination of sea floor spreading and the superposition of this boundary over the underlying Iceland mantle plume, which provides magma to the volcanoes as parts of the plume rise (Thordarson and Larsen 2007). High winds deposit aeolian and tephra materials from volcanoes throughout the island creating variable soil conditions with lower organic content nearer to volcanoes and major dust sources, such as large sandar (outwash plains formed of glacial sediments, found at the terminus of a glacier) (Arnalds et al. 2016). The primary regions for this study are the lowlands in southern and western Iceland, where the largest extent of topogenous (i.e. valley) fens are found (Arnalds et al. 2016).

Figure 1.1: Undisturbed wetland patch at the Agricultural University of Iceland (AUI), Hvanneyri, western Iceland. Photograph was taken 4th July, 2018.

Fens are wetlands (which include peatlands) that receive water and nutrients from the surrounding surface environment, such as soil, rocks, and groundwater, and also from rainwater and snowmelt ("minerotrophic"). Closer to drainage ditches, this changes to only rain/snowmelt-fed from drainage ("ombrotrophic") (UK Biodiversity Action Plan 2011; Arnalds et al. 2016). In Iceland, water movement is primarily vertical in the peat or soils of inland fens, rather than horizontal. Wetlands are found in patches in these areas, owing to the dissected landscape as well as the climate (Woo and Young 2003).

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). These soil types are found regionally; Histosols in the West and Andisols in the South, and a combination of the two can be found in areas between (see Ch. 2, Fig. 2.1). For this study, we wanted to discover how differences in soil types and ditching affect surface hydrological characteristics of wetland patches, primarily infiltration rates and soil moisture regimes. Government subsidies after World War II facilitated drainage of wetlands all around the country, which likely altered their surface hydrology. As a result of this widespread initiative, many of these wetland patches are not in use and the majority of the wetlands once present in southern Iceland have been disturbed (hereafter referred to as “drained”). They are also under limited protections, and much of the remaining undrained wetlands (“undisturbed”) that are larger in size, >3 ha, are at risk from development (construction, afforestation) and/or natural landscape changes (aeolian erosion) (Arnalds et al. 2016).

Elsewhere, comparable wetland patches can also be found in the Canadian High Arctic (Woo and Young 2003), and in the southern Andes (Polk et al. 2017), though these are typically underlain by permafrost. Northern wetlands are especially sensitive to changes like the 50-60% increase in precipitation in the Arctic anticipated to occur this century, and are locally affected by changes in evaporation and temperature (Bintanja 2018). In 2018, the year of this study, Iceland experienced a surprisingly wet May—traditionally the driest month of the year—with Reykjavík receiving 129 mm of rain (Climatological Data 2012; Icelandic Meteorological Office (IMO) 2019, Figure 1.2). In fact, the majority of the country received above average precipitation, with higher than normal counts of precipitation days in the South (Iceland Meteorological Office 2019). The climate in Iceland is affected by volcanoes and glaciers in the interior of the country, and can be affected by its distance of only ~400 km from the Greenland Ice Sheet (GrIS), since sea ice sometimes extends to the northern coast lowering regional temperatures (Hanna et al. 2004). Mainly, however, the climates of both countries are influenced by synoptic patterns such as the North Atlantic Oscillation. Atlantic Ocean currents modify the climate through frequent low-pressure cyclones in the southern area, bringing much rain and wind (Einarsson 1984, Hanna et al. 2004). The southern coast typically receives up to 1000 mm of annual precipitation, with a relationship of warm periods being wetter in the 20th century overall (Hanna et al. 2004).

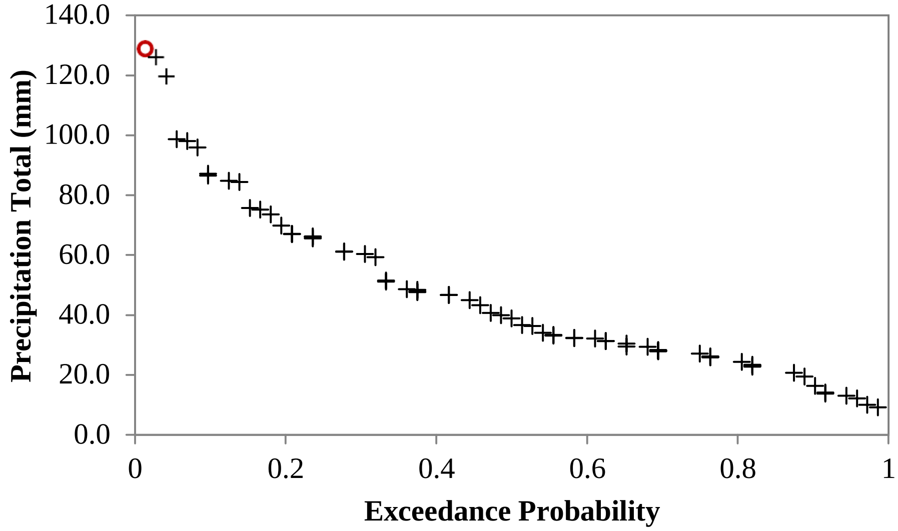


Figure 1.2: Data for exceedance probability of May precipitation for Reykjavík (1949 – 2018). May of 2018 is at the top (red circle). Data retrieved from the Icelandic Meteorological Office (en.vedur.is/climatology/data/ - monthly averages for selected stations).

Prior studies in Iceland include some information on soil infiltration (Orradottir et al. 2008, Scheffel 2018), and studies related to soil characteristics such as organic content and bulk density (Arnalds and Kimble 2001, Guðmundsson et al. 2004, Arnalds 2008), but up until the time of this study, virtually none of this was specific to inland wetland soils.

The primary goal of this thesis was to investigate surface features (infiltration, soil moisture, surface albedo) for an initial understanding of the hydrology of small, drained wetland patches. From this study it might be possible to evaluate how they might change in the future due to climate warming and guide government policies to protect wetlands from future disturbance.

CHAPTER TWO: LITERATURE REVIEW

2.1 Geology and Soils of Iceland

The geologic history of Iceland is quite new in its timeline and is unique compared to other parts of the world. Iceland lies between two tectonic plates: the North American plate and the Eurasian plate. Large-scale eruptions from numerous volcanoes add new material to the surface once tephra is released. The oldest rocks in this region are from the late Tertiary period, but many of the superficial rocks are <3 million years old with Holocene lava and tephra deposits (Arnalds et al. 2016). Aeolian deposition and redistribution of volcanic ash provides the parent materials for soil formation, which develop into Andisols, and can weather into clay, termed allophane (Brady and Weil 2010, Arnalds et al. 2016). Outside of volcanic regions there are mainly Tertiary basalt rocks whose porosity has been lessened through chemical weathering by secondary minerals (e.g. calcite, silica, zeolites and clays) (Arnalds et al. 2016). This adds to the higher frequency of wetlands within the Tertiary formation than in active volcanic regions (Arnalds et al. 2016). The Andisols that have lower organic content are typically gleyed, or, mottled blue-green-grey coloring indicative of reduced aeration (Dingman 2015).

Organic deposits that accumulate in wet areas where plant growth exceeds decomposition rates lead to residue. The residue then sinks into the water becoming anoxic, forming peat (Brady and Weil 2010). West Icelandic soil is full of mainly herbaceous peat, meaning the land contains residue of sedges, reeds, and cattails: these Histosols are classified specifically as Fibrists (Arnalds et al. 2016), such that the residues are intact for identification (Brady and Weil 2010). Iceland's combination of volcanoes, glaciers, and aeolian dispersal combine all of these traits, forming the soil type of Histic Andisols (Arnalds et al. 2016). Histic Andisols have a combination of soil characteristics from each type Histosol and Andisol, and contain an intermediate amount of carbon between Andisols and Histosols. It is worth noting that Histosols also show signs of influence by tephra distribution (Arnalds et al. 2016).

2.2 Hydrology and Properties of Soils

2.2.1 Peatland Hydrology

Hydric soils are termed thusly because they exhibit morphologies based on saturation or inundation repeatedly over more than a few days at a time (Anderson and Davis 2013). This water logging, along with microbial activity in the soil leads to oxygen poor soils; promoting organic matter accumulation, and the accumulation/reduction/translocation of iron (Fe) and other reducible elements (Anderson and Davis 2013). These characteristics are noticeable and distinguishable whether the soils are in wet or dry periods (Anderson and Davis 2013). Peatlands are controlled by hydrological processes, where peats exist based on water retention characteristics, water supply, and organic content. The surface of the peat ("acrotelm") is generally the most permeable, while, below this, in the "catotelm," oxygen is unavailable due to saturation of the peat, and compaction occurs here (Labadz et al. 2010).

Subsurface flow in peatlands is quite variable, so this diplotelmic model can be relatively simplistic and does not account for all spatial variability unless measurements are carefully obtained (Labadz et al. 2010). One site in Cumbria found hydraulic conductivity at 0.003 m d^{-1} at 1 m depth. However, in some locations within this bog, measurements were close to 1 m d^{-1} (Labadz et al. 2010). Typical values for peatlands are likely cm or mm per day but in some cases the acrotelm layers can go as high as hundreds of meters per day (Labadz et al. 2010). Elsewhere, in northern Canada, high conductivity values (10-1,000 m d^{-1}) in the top 0.1 m of the lightly decomposed peat (acrotelm) decrease with depth below the zone of 0.2 m, to a rate of 0.5 – 5 m d^{-1} (catotelm) (Quinton et al. 2008).

2.2.2 Hydrology of Volcanic Soils

Volcanic soils, termed "Andisols" in soil taxonomy ("Andosols" in the Icelandic classification system), are rich in aluminum and/or iron-humus compounds, as well as clay minerals including allophone (Jones et al. 2009). These soils are moderately weathered in arctic regions due to low temperatures. Andisols typically have high infiltration rates under natural conditions. In Tenerife, steady-state infiltration rates (SIR) of Vitric Andisol quartiles ranged from 0.08 – 0.12 mm s^{-1} and Nonvitric Andisol quartiles ranged from 0.03 – 0.14 mm s^{-1} (Neris et. al 2013). Icelandic Brown Andisols/Vitricryands ranged from 0.03 – 0.1 mm s^{-1} (Orradottir et al. 2008). This is because of their aggregate stability, high organic matter content, and mineralogical properties (Neris et al. 2012). Changes in land use such as cropping or changes in dominant vegetation lead to the degradation in the structural properties of Andisols, as well as a decrease in infiltration capacity, where structure is dependent upon organic matter (Neris et al. 2012).

2.3 Soil Moisture in the Cryosphere

Soil moisture in the cryosphere adds to the intensity of cryogenic processes within frozen soils and modifies soil temperature (Jones et al. 2009). Needle ice is a phenomenon that can occur when soil moisture is brought to the surface due to changes in temperature between the surface and the soil below (Jones et al. 2009). Through the movement of soil materials from frost action (cryoturbation), soil moisture can influence carbon content in soils. When cryoturbation is dormant or inactive, soil can be a source of carbon depending on the present amount of soil moisture, while in active cryoturbation, soil acts as a carbon sink by incorporating organic matter (Jones et al. 2009).

Soil moisture exhibits a high spatiotemporal variability (Loew et al. 2013). It can differ spatially within an ecosystem, decreasing upslope and vertically above the water table, or locally vary due to small scale changes in micro-topography (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). Long-term, soil moisture persistence is where the soil can "remember" wet or dry conditions causing an anomaly, such as atypically heavy rainfall which takes weeks or months to dissipate (Koster and Suarez 2001). This memory, for example, stores interannual precipitation anomalies in cold, arid climates of Eurasia with frozen soils, and such information is useful in evaluating long-term seasonal forecasts relying on soil moisture data (Koster and Suarez 2001; Shinoda and Nandintsetseg 2011). Icelandic soils have both high organic and mineral content, with high water retention and porosity which are characteristic of both peatlands and volcanic soils (Neris et al. 2012; Arnalds et al. 2016). Soil organic matter increases the infiltration of water in soils and decreases runoff. Additionally, humus improves soil water retention and humic acids release essential nutrients (Brady and Weil 2010). Minerals affect composition in a soil through texture (sand, silt, and clay sizes), and can indicate what a soil is made of (Anderson and Davis 2013). For example, manganese oxides produce black colors, while gleying is a result of a reduction in iron (Fe) and often has a blue-grey or greenish-grey color (Anderson and Davis 2013).

2.4 Infiltration in Frozen and Non-frozen Soils

Infiltration is the process of water entering the soil, when water moves from the surface of the soil and into it (Brady and Weil 2010). This is distinguished from percolation, which is the movement of water through the soil (Linsley et al. 1982). Hydraulic properties modifying infiltration rates include the hydraulic conductivity (k_{sat}) of an unsaturated soil, matric potential (Ψ), and elevation. Hydraulic conductivity is how easily a liquid, such as water, moves through a porous medium. Matric potential is the attraction of water to solid surfaces, influencing the retention and movement of water in soils (Brady and Weil 2010). The k_{sat} increases when soil moisture increases. In the unsaturated zone, water flows from high matric potential (wetter) to lower matric potential (drier) (Brady and Weil 2010). Taking these properties into account, the equation for infiltration from Darcy's law (i, mm s^{-1}) is then written as:

$$i = -K_{sat}\left(\frac{-\psi_{sat} + z_{sat}}{z_{sat}}\right) \tag{1}$$

where K_{sat} is the hydraulic conductivity at saturation (mm s^{-1}) and z_{sat} is the depth (mm) of the wetting front (a boundary between the dry underlying soil and soil already wetted). The surface is assumed at saturation while the wetting front is saturated with a matric potential equal to ψ_{sat} (– mm) (Brady and Weil 2010, Bonan 2016).

Infiltration continues under the influence of gravity once water has entered the soil and moves from larger soil spaces, or pores, to smaller ones (Linsley et al. 1982). Rainfall infiltration is usually down to several centimeters below the surface, and the infiltrated water overall is found within the upper meter of soil (Linsley et al. 1982). This meter of soil usually holds about 10-45 cm of water (Brady and Weil 2010). The maximum amount of water a near surface soil can hold is called the infiltration capacity, measured by recording the drop in water level during infiltration. This is described by Horton's equation (eq. 2, Viessman and Lewis 2003) as:

$$f_t = f_c + (f_0 - f_c)e^{-kt} \tag{2}$$

where f_t 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.

Rates of infiltration generally enter dry soil rapidly, afterwards decreasing over time during rainfall or irrigation (Brady and Weil 2010). Infiltration is important as a key factor in determining runoff, an influential factor in the solute concentration of runoff, and as the way for solutes to enter into the soil profile (Assouline 2013; Bonan 2016). Solutes are often nutrients responsible for plant health, or pollutants which lower soil and water quality along with those available resources.

There are also several situations in relation to infiltration and depth of ponding (I_p, the depth of water standing on the surface): no ponding, saturation from above, and saturation from below (Dingman 2015). No ponding (eq. 3.1.1) is where the infiltration rate (i) equals the input of water (w(t)) and is less than or equal to its infiltration capacity (f_t);

$$I_p = 0, i = w(t) \leq f_t \quad (3.1.1)$$

saturation from above (eq. 3.1.2) means that ponding is present because the input rate is greater than infiltration capacity, and the infiltration rate is equal to capacity;

$$I_t > 0, i = f_t \leq w(t) \quad (3.1.2)$$

lastly, saturation from below (eq. 3.1.3) is where ponding occurs because the water table is at or above the surface and the soil is entirely saturated, making the infiltration rate and infiltration capacity at zero:

$$I_t \geq 0, i = f_t = 0 \quad (3.1.3).$$

Saturation from below is perhaps the most relevant in the case of wetlands compared to the other two ponding conditions (Dingman 2015).

Permafrost makes up about 22% of the land surface in the Northern Hemisphere, and is defined as frozen soil found at a temperature at or below 0°C for a minimum of two years (Woo 2012). Permafrost has a tendency of being thinner in maritime climates due to their proximity to the oceans (warmth) rather than further inland. Thus, interior wetlands in Iceland may contain sporadic permafrost but it likely does not occur along the coast 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 seasonal frost can develop (Dingman 2015). Concrete frost 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 in Iceland, 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 drainage and the extent and distribution of wetlands (Eugster et al. 2000). Infiltration can occur into frozen cracked soil as meltwater from the snow reaches the ground surface (Woo 2012). For unfrozen conditions in northern Canada, infiltration is close to saturated hydraulic conductivity at ~0.0034 mm s^{-1}, and in frozen silt loam of Minnesota infiltration is 0.0063 mm s^{-1}, which includes lateral flow (Kane and Stein 1983).

Table 1: Infiltration rates for various soil types in differing climates.

Soil Type	Rate	Units	Region
Volcanic			
Aridisols[1]	0.009 – 0.02	mm s^{-1}	tropical (Canary Islands)
Vertisols[1]	0.003 – 0.01	mm s^{-1}	
volcanic ash/sediments[2]	0.009 – 0.06	mm s^{-1}	Low Arctic (Iceland)
Andisols[3]	0.007 – 0.10	mm s^{-1}	Low Arctic (Iceland)
Frozen			
permafrost[4]	19	mm d^{-1}	alpine (Swiss Alps)
max[4]	0.003	mm s^{-1}	
inter-hummock peat[5]	197	m d^{-1}	Arctic tundra (Canada)
permafrost[6]	188	m d^{-1}	Arctic tundra (Alaska)
concrete frost (silt loam)[7]	0.0063	mm s^{-1}	Midwestern USA
Unfrozen			
discontinuous permafrost (silt loam)[7]	~0.0034	mm s^{-1}	northern Canada
Chromic Luvisol[8]	0.001 – 0.003	mm s^{-1}	Mediterranean (France)
Gleyic Cambisol[8]	0.003 – 0.009	mm s^{-1}	

[1]Neris et al., 2013
[2]Scheffel, 2018
[3]Orradottir et al., 2011
[4]Rist and Phillips, 2005
[5]Quinton et al., 2000
[6]Dingman, 1973
[7]Kane and Stein, 1983
[8]Leonard and Andrieux, 1998

There are three categories of infiltration under frozen conditions. Unlimited infiltration is the case for coarse-grained and cracked soils and fractured bedrock, because when these are frozen and dry, large pores and fissures allow for water flow (Woo 2012). Once the soil reaches saturation, the next category is restricted infiltration; this is common when rainfall or snowmelt freeze, or in wetlands, because an ice layer near the soil surface impedes water entry (Woo 2012). Infiltration may also be restricted from cryosuction-induced upward migration of water that freezes and blocks downward flow (Walvoord and Kurylyk 2016). Lastly, when frozen, most soils fall between these two categories into limited infiltration (Woo 2012).

2.5 Northern Wetlands and Climate Warming

High latitude ecosystems occupy large areas, with their sensitivity to changes in climate affecting local, regional, and global climates (Beringer et al. 2005). Climate change threatens both the disturbed and the remaining undisturbed wetland soils at both high latitudes and altitudes (Woo and Young 2014). This is due to the global vulnerability of wetland ecosystems to changes in hydrology (Erwin 2009). Climate model predictions have generally agreed upon an expected increase in precipitation due to climate warming, especially over high latitude regions; an expectation regardless of seasonality. Studies of precipitation trends, both modeled and observed, 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 changes in the distribution and type of vegetation found in high latitude areas such as Iceland (Beringer et al. 2005).

2.5.1 Wetland Surface Energy Balance Feedbacks

The surface energy balance helps us understand land-atmospheric interactions by looking at heat and moisture transfer among other biogeophysical interactions, and is determined by varying amounts of incoming and outgoing shortwave ($K^*=K\downarrow-K\uparrow$) and longwave ($L^*=L\downarrow-L\uparrow$) radiation (Bonan 2016). Locally, evaporation in wetlands fluctuates daily from changes in energy supply and moisture. A warm and dry year led to higher evaporation rates in northern Canada, near Resolute (1998=104 mm or 2.6 mm d^{-1}) compared to the year before, which had cool and wet weather (1997=67 mm or 1.7 mm d^{-1}) (Woo 2012). Evaporation is higher in fens than in bogs, and high values are likely because total evaporation exceeds precipitation in summer for many Arctic wetlands (Woo 2012). Water storage is then replenished through rain and inflow by water storage, with interannual variability. The micro-topography of wetlands also encourages evaporation through surface detention/depression storage while reducing flow through surface irregularities (hummocks, cracks, troughs) and vegetation (Woo 2012).

Albedo is a useful term for better understanding climate change factors related to the water budget and water cycle, such as evaporation and infiltration, because radiation absorbed at the ground surface is the driver of many hydrological processes (for example, snowmelt, evaporation, and ground thaw). Albedo is the ratio of the amount of solar radiation reflected by a surface to the amount of incoming radiation (Oke 2002). Water has a lower albedo ($\alpha \approx 0.03$-0.1, except with a large zenith angle it can go to up to 1) than other natural materials such as soil ($\alpha \approx 0.05$-0.4) and vegetation ($\alpha \approx 0.16$-0.26) (Oke 2002). Accordingly, drained patches of wetlands in Iceland will have a higher surface albedo if found with dry ground cover ($\alpha \approx 0.3$ (0.4, in this study)) compared to saturated areas, potentially leading to different radiation receipt and wetland evaporation losses across Iceland (Sumner et al. 2011). Because wetland patches with higher water contents can lead to a greater net solar energy input (Sumner et al. 2011), the microclimates of saturated patches will vary compared to drained patches. Enhanced evaporation rates from wetland patches will lead to greater water loss and lower water inputs from their catchments (Bintanja and Selten 2014). This suggests there will be noticeable changes to Icelandic inland fens in the future.

Evapotranspiration depends on the availability of water, the energy available to enable a change of state, a vapor concentration gradient, and a turbulent atmosphere to carry the vapor away from the surface (Oke 2002). In the morning evapotranspiration of dew, soil water, and plant water adds moisture to the lower atmospheric layers, and humidity increases. In the afternoon, evaporation is at its peak but humidity drops, while into the night, evapotranspiration decreases as energy levels decrease, illustrating the importance of net radiation and soil moisture on evaporative losses (Oke 2002). Note that Arctic regions above 66.5°N see 24 hours of sunlight – most of Iceland sits below 66.5°N but it receives considerable solar energy during the spring/summer season (up to 22 hours of sunshine along the southern coast), though frequent low-lying clouds and rainy periods can diminish incoming solar radiation receipts. Long summers with high heat increase the evaporation of stored moisture in wetlands (Woo 2012), although evaporation can largely vary as a result of climate fluctuations and surface conditions (Bring et al. 2016).

Daily wetland evaporation for high latitudes tends to range from 0 to 4 mm, and up to 6 mm at maximum (Anderson and Davis 2013). Estimates for arctic/polar regions can be seen below in Table 2.

Table 2: Estimates of wetland evaporation in Arctic regions.

Environment or Location	Amount (mm d^{-1})	Study
polar desert wetlands	1.5-2.5	Woo, 2012
sandur-wetland complex, Iceland	2.1-2.3	Scheffel, 2018
max	5.6-6.4	
sedge-moss fen, Polar Bear Pass, Nunavut	0.4-4.0	Young and Labine, 2010
wetland complex, Prudhoe Bay, AK	1.4-1.6	Mendez et al., 1998
tussock tundra, Eagle Creek, AK	0.4-1.2	Stuart et al., 1982
intertussock area	0.6-1.9	
fen site in the Hudson Bay Lowlands	3.1*	Lafleur, 1990
backshore zone within coastal wetland	2.6*	Lafleur, 1990
peat plateau, Scotty Creek, NWT	0.8*-1.3*	N. Wright et al., 2008

*daily mean

2.5.2 Soil Moisture and Vegetation

Surface soil moisture is also affected in Icelandic soil cover under vegetated surfaces by the hummocky ground (thufur) (Jones et al. 2009). Thufur are earth hummocks widespread across Iceland and sub-Antarctic islands. These features are mainly located in southern Iceland, with a sometimes flat-topped morphology (Van Vliet-Lanoë et al. 1998). For the most part, thufur are related to the alteration of Holocene volcanic ashes from loessic cover (Van Vliet-Lanoë et al. 1998). They develop in the absence of permafrost, similar to mountain hummocks ('buttes gazonnées'), but are still characterized as true hummocks with seasonal frost ground patterns relative to the uneven distribution of snow and imperfect drainage (Van Vliet-Lanoë et al. 1998). Thufur are also specific in that they have a high likelihood of recurrence following a disturbance, in contrast to other forms of hummocks (Van Vliet-Lanoë et al. 1998).

Thufur and the root structure of grasslands in Iceland allow 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).

2.6 Patchy Wetlands in Iceland

2.6.1 Global Wetlands and Their Importance

Wetland ecosystems are vulnerable to changes in hydrology on a global scale (Erwin 2009; Bintanja and Selten 2014). Circumpolar Arctic regions experience conditions favorable to patchy wetlands, including the wetlands found in Iceland. Patchy wetlands are found where water supply is largely available locally during the thawed season, causing saturation. These develop as a high water table is maintained (Woo and Young 2003); locally they contain tundra vegetation, and form niches for the wildlife in those areas.

The areal extent of saturated areas tends to fluctuate with changes in water level. In Resolute, Canada, a patchy wetland experiences variations in the extent of surface ponding as its water level changes. This change in storage leads to expansion/shrinkage of surface flow areas due to low topographic gradients and shallow frost tables which underlie most permafrost wetlands (Woo 2012). Large shifts in wetland storage are also seen near Prudhoe Bay, AK, where surface water on the Alaskan Arctic Coastal Plain can vary in area during the thaw season from 65% down to 15% (Woo 2012). Below treeline in the subarctic, herbaceous peatlands can occur in small to large patches, with thin to thick peat (>40 cm), such as the Aleutian wet meadow-peatland complex (Innes 2015, Fire Effects Information System (FEIS –

USDA/USFS)), or wetlands with low, narrow ridges (Tarnocai and Zoltai 1988). In the Andes, wetland changes in the Cordillera Real (Bolivia) depend on the intensity and distribution of precipitation, while wetland increase over a 27-year period coincided with glacier (and snow) reduction (Dangles et al. 2017). Here, alternate wet/dry years led to wetland drying with individual wetlands prone to partial drying, although there was an increasing trend in mean wetland total area and number (Dangles et al. 2017). These habitat patches serve a crucial component for the wild populations and in the connectivity of local pastoralism/irrigation practices (Dangles et al. 2017). Limited drying even in the range of tenths of meters can significantly impact population dispersal of species living in alpine ecosystems (Dangles et al. 2017).

The climate in Iceland is influenced by the island's location between warm and cold ocean currents - 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 area annual mean 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). Over time, the climate trend (1871-2002) suggests warming in Iceland is consistent with global warming trends in the 20th century, while warmer periods seem to correspond with wetter trends (Hanna et al. 2004). Changes in the south-north temperature difference allude to a reduction in sea ice extent on the northern Icelandic coast over this time period, with a clear connection between extreme temperatures in Iceland and southern Greenland (Hanna et al. 2004). In fact, there was an ongoing extreme melt event in Greenland (2019), from the end of July into August, where the Greenland Ice Sheet (GrIS) lost approximately 55 billion tons in meltwater in one week (Freedman 2019, The Washington Post). This summer melt led to bare ice and flooded snow areas along the GrIS. Although the current effects of this melt on Iceland are unclear, when the GrIS experiences melt, Greenland rises as it loses weight, as the area in Iceland Höfn í Hornafjörður, does near Vatnajökull glacier and in East Iceland (Sigmundsson et al. 2018, Ástvaldsson 2019). The material in the mantle then streams towards Greenland, leading to sinking under Southwest Iceland (Sigmundsson et al. 2018, Ástvaldsson 2019). On top of this extreme melt event, many Alaskan glaciers have reduced snow and ice this year, supporting previous predictions about vulnerability in the Arctic (Freedman 2019). These extreme temperatures and melt events are likely going to worsen as the climate continues to warm.

2.6.2 Ditched Regions

Peat drainage is intentionally done to lower the water table, producing a complex hydrological response. The efficacy of drainage is relative to the distance between ditches, depth of ditching, and hydraulic conductivity of the peat (Price et al. 2003). Drawdown is largest adjacent to the ditch, and tends to quickly diminish with distance. In some cases this could be as low as 5-15 m in distance, although fibric peats in Minnesota show drawdown to 50 m (Price et al. 2003). 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).

In Iceland, government subsidies facilitated drainage of approximately 47% of these wetlands after the Second World War. This was mainly for agricultural production to keep up with the rising population, as well as to help adjust with domestic rural-to-urban migration (Arnalds et al. 2016). Many of these wetlands are, as yet, are unprotected from further development, in particular the ones less than 3 ha in size, despite their ecological importance in providing habitats for migratory birds and maintaining the ecosystem balance (Arnalds et al. 2016).

2.6.2.1 Iceland Ditching: Drawdown, Depth, Width, Density

Drainage ditches cover 29,700 km of the country, significantly altering Iceland's landscape (Gunnarsson et al. 2006). The majority of the area impacted in Iceland has low ditch density, with about 67% of ditched area at a density of 0.1 – 0.5 km per km^2, and 25% of the ditched areas at a density of 5 – 10 km per km^2 (Arnalds et al. 2016). Landscape characteristics like slope and bedrock hydrology affect the impacts of low ditch densities (Arnalds et al. 2016).

Previous studies have covered the soil characteristics, such as the physical properties and nutrient content of these wetlands, and other Icelandic land covers (e.g. Arnalds and Kimble 2001; Guðmundsson et al. 2004; Arnalds 2008). Many of the wetland patches were drained for hay making (15%) 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). 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 is known about the hydrological characteristics of these wetlands or the impacts from drainage (Arnalds et al. 2016).

2.6.3 Infiltration in Iceland

An earlier infiltration study in the lowlands of South and West Iceland of Brown Andosols looked at infiltration into five plant communities: birch, woodland, lupine fields, lava fields, and a Sitka spruce woodland and grassland. Orradottir et al. (2008) found that constant infiltration rates were reached in a matter of 10 to 20 minutes. These sites included Gunnarsholt near

Selfoss, excluded from grazing since the early 19th century, which was composed of the plant communities birch, lupine fields, lava fields, spruce, and grassland fields, and Hafnarskogur which is just south of Hvanneyri, with hummocky birch woodland and grassland (see Ch. 4, Fig. 4.2). Summer infiltration rates (calculated as the mean of the last three measurements at 5 min intervals) ranged from 0.008 to 0.1 mm s^{-1} (or 0.47 to 6.25 mm min^{-1}), with the lowest rates in the H-grassland community. They also found that bulk densities of the surface soil horizon in the Hafnarskogur birch and grassland communities (ρ = 0.24±0.02 g cm^{-3}, 0.25±0.013 g cm^{-3}, respectively) significantly correlated with these constant infiltration rates in the July-August 2000 period of their study ($r = -0.85$, $p < 0.001$) (Orradottir et al. 2008). In sandy soils infiltration rates ranged from 0.03 – 0.1 mm s^{-1}, compared to in the fine textured soils, from 0.008 – 0.03 mm s^{-1}. The grassland site in the west resulted in a higher (3x) constant infiltration rate when the area was given a year break from horse grazing, compared to the year prior (Orradottir et al. 2008). This greater infiltration rate, they suggest, means that Andisols are hydrologically resilient where vegetation cover is continuous and the soil contains high organic carbon content.

2.6.4 Wetlands as Habitats

Icelandic coastal inland fens are an important ecosystem and provide 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. Subsequently, any changes to these fens directly impact the well-being of these birds (Table 3, Gunnarsson et al. 2006). Afforestation efforts, livestock grazing from sheep and horses, and the prevalence of hydropower in Iceland present continued threats to these populations, which prefer the open spaces of wetlands and grasslands (Gunnarsson et al. 2006; Arnalds et al. 2016).

Table 3: 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 alpine*	16	49
Purple Sandpiper	*Calidris maritima*	46	19
Snipe	*Gallinago gallinago*	6	62
Redshank	*Tringa tetanus*	19	97
Black-tailed Godwit	*Limosa limosa*	10	97
Red-necked Phalarope	*Phalaropus lobatus*	6	55

While wetland patches >3 ha should not be disturbed under current law, this reference size should likely be made 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 undisturbed (i.e. damp, saturated) wetlands unprotected by Icelandic government policy (Arnalds et al. 2016). Though wetland drainage is no longer a concern in Iceland, as it is for other wetland regions, little is known of climate warming impacts on these drained wetland patches (Erwin 2009; Young and Abnizova 2011).

2.6.5 Soil Properties

Varying degrees of carbon in Icelandic inland wetland soils define three main soil classifications: 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 at further distances from volcanoes and active dust sources (Arnalds et al. 2016). This gradient determines the overall distribution of wetland soils. Figure 2.1 shows an upscaled estimate of coastal wetlands with varying degrees of saturation, including their designated soil types (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 and Davis 2013).

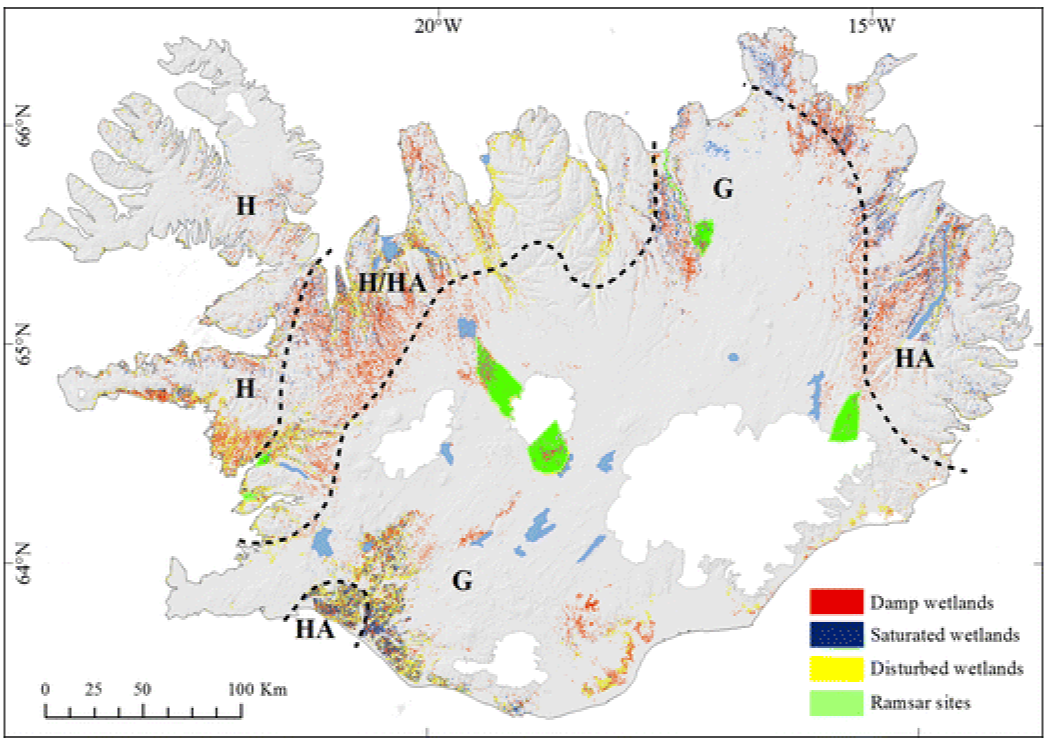


Figure 2.1: General distribution of undisturbed ("damp", "saturated"), disturbed, and Ramsar wetlands shown within the boundaries of each wetland soil type: Histosols (H), Histic Andisols (HA) and Gleyic Andisols (G) (image from Arnalds et al. 2016).

In summary, Iceland's geology leads to the formation of highly volcanic (Andisols) and organic (Histosols) soil, the mixture of which are uncommon elsewhere (Arnalds et al. 2016). Peat has variable subsurface flow rates, and peatlands are controlled by factors such as water retention and the amount of organic content in the soil, usually high. Volcanic soils also have high organic content, and mineral contents. These tend to have high infiltration rates and can even contain macropores from tephra residue, leading to preferential flow (Arnalds et al. 2016). Changes in organic matter content causes structural changes in the soil and affect hydrological processes (for example, higher infiltration, decreased runoff).

Soil moisture influences carbon content in frozen soils, and fluctuates depending on topography, temperature, and precipitation. It can be a useful factor in understanding local climate. Infiltration determines runoff and quickly decreases over time. It is highly variable spatially and is affected by rainfall amounts and intensity, antecedent soil moisture conditions, and varying soil properties like compaction or texture (Dingman 2015). In subarctic and arctic regions infiltration can be much lower than in temperate regions, with lower hydraulic conductivity in frozen soils.

High latitude wetlands are vulnerable to and threatened by climate change and human intervention. Increased evaporation could change the water balance of wetlands by affecting soil moisture regimes. The continued warming of Earth's Arctic regions and previous trends seen in the Arctic suggest that more extreme changes to northern wetlands will occur or are presently occurring. Human disturbances such as afforestation, construction, ditching, and harvesting resources, threaten wetland habitats. Icelandic Andisols, however, may prove resilient in the future, due to their hydrological resilience in areas with continuous vegetation cover and high soil organic carbon content (Orradottir et al. 2008).

CHAPTER THREE: OBJECTIVES

3.1 Objectives and Research Questions

This study had three main objectives: 1) to assess the hydrology, specifically, the soil moisture and infiltration characteristics of small, drained, wetland patches in Iceland; 2) to evaluate the spatial and interlinkages between soil moisture and surface albedo conditions of wetland patches; and 3) to improve understanding of the hydrology of these drained, wetland patches, so that future impacts from human modification and climate warming may be better understood, thusly addressed by policy makers. The research questions were: 1) does infiltration vary between soil type? 2) How do near surface soil moisture content and surface albedo vary by wetland soil type, along with proximity to drainage ditches? And 3) how might current infiltration and moisture content feedbacks change in the future?

3.2 Hypotheses

There are three study hypotheses, as follows:

1) Higher bulk density in mineral soils of the Andisols, in comparison to organic layers and Histosols, with corresponding lower infiltration rates.
2) Higher soil moisture content in saturated wetlands compared to the drained patches; in terms of surface albedo, undisturbed wetland soil will have a low albedo, while drier patches will have higher albedos.
3) Higher infiltration rates will occur in the Andisol soils (sandy) compared to the Histosols (peat).

CHAPTER FOUR: LOCATION AND METHODOLOGY

4.1 Study Sites

Fieldwork took place from 26th June until 5th July, 2018, for a total of eight days of data collection in Iceland (Figure 4.1). For each soil type (Histosol, Histic Andisol, and Gleyic Andisol) one drained and another undisturbed wetland patch were sampled in each type, for a total of three sites. The first site was on a southern farm in the region of Þúfa (63°58'51.6" N, 20°17'06.4" W) off of Landvegur (Rte 26), the second site was in Kirkjubæjarklaustur along the Rte. 202 Prestsbakkavegur/Mörtunga roads in the southeast (63°49'51.20" N, 18° 1'59.02" W), and the third site was on the grounds of the Agricultural University of Iceland (AUI) in Hvanneyri, in the western region (64°33'37.1" N, 21°45'23.0" W) (Figure 4.2). The AUI is also known as Landbúnaðarháskóli Íslands (LBHI).

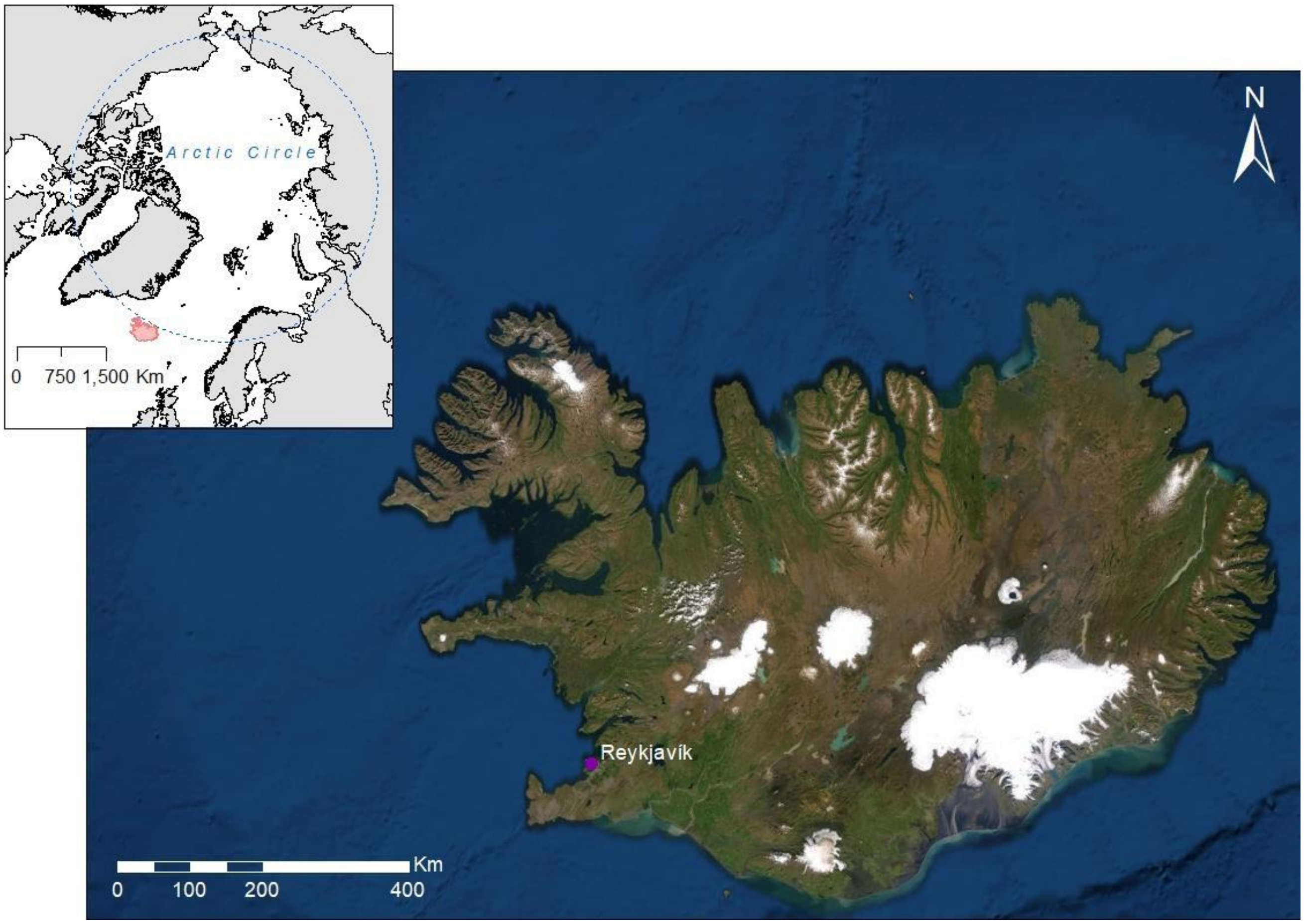


Figure 4.1: Overview map of Iceland. Reykyavík, the capitol, is located in the southwestern region (purple circle) (sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community). Inset: Iceland highlighted (red) just outside the circumpolar North (Arctic Circle is shown with blue dots) (sources: world continents layer from ESRI, Global Mapping International, and the U.S. Central Intelligence Agency (The World Factbook). Projection: Stereographic North Pole. Geographic lines from Natural Earth).

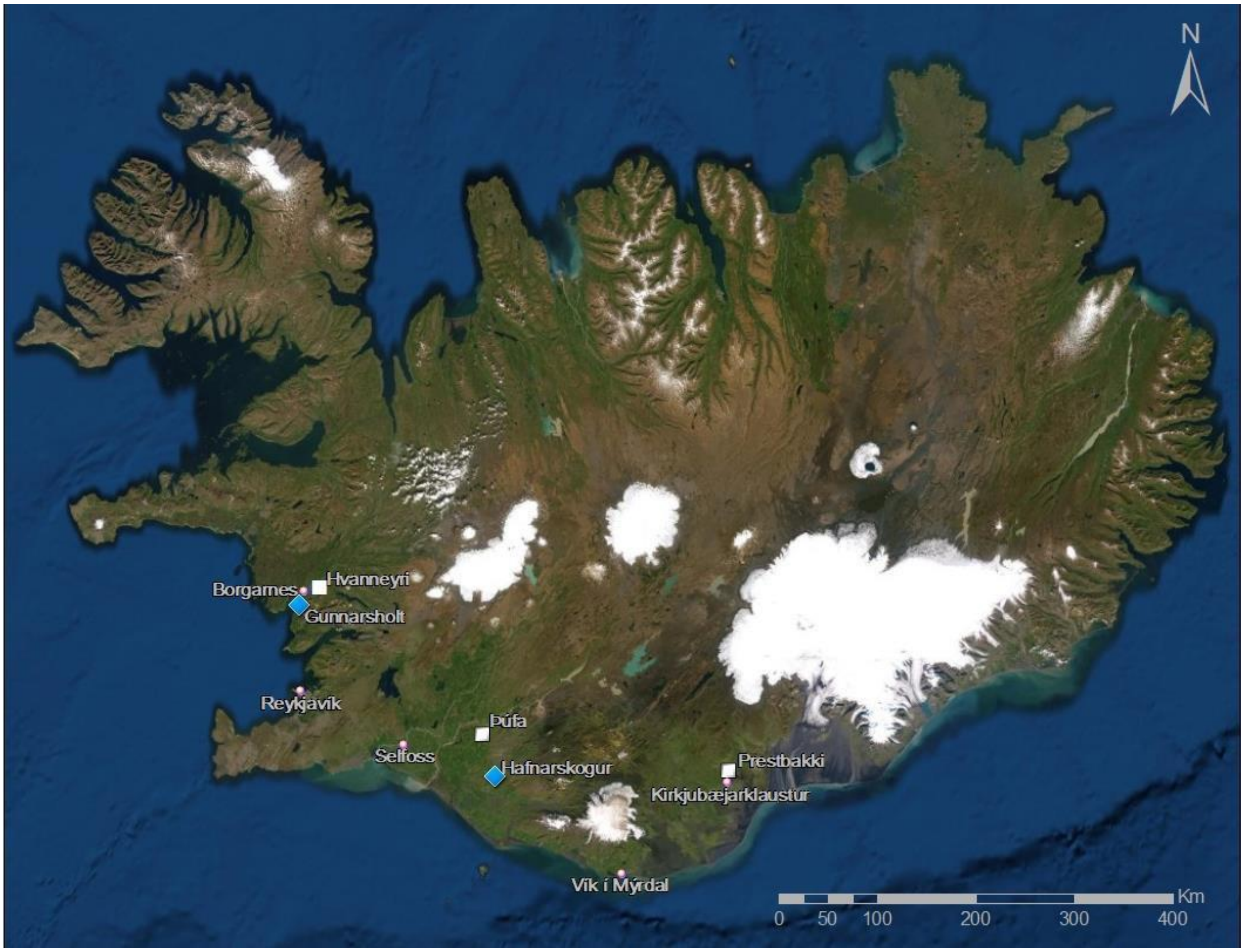


Figure 4.2: Location of study sites for this project (white squares), previous infiltration trials (Orradottir et al. 2008, blue diamonds), and nearby, well known towns in western and southern Iceland. To the west is the Agricultural University of Iceland in Hvanneyri, and in the south are study sites in Þúfa and in Prestbakki, near Kirkjubæjarklaustur (sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community).

4.2 Vegetation and Landscape

4.2.1 Vegetation

Typically, these patchy, drained wetlands are dominated by vascular plants with not many *Sphagnum* moss wetlands (Arnalds et al. 2016). In undisturbed wetlands, there were various *Carex* species and cotton grass (e.g. *Eriophorum angustifolium*) as well as moss species (e.g. *Hypnum, Mnium, Rachometrium* and *Philonotis*) (Arnalds et al. 2016), and more frequently woody species in damp wetlands. In this study, mainly graminoids were found (at certain locations, moss was present on/near thufur) which corresponds with the predominance of vascular plant species especially in the drained wetlands (Arnalds et al. 2016). This is because of the fertile soils directly impacted by aeolian deposition, and since most Icelandic inland wetlands are minerotrophic and change to partially ombrotrophic in nature (Arnalds et al. 2016).

Wetland vegetation are similar at first glance, however, the undisturbed and drained patches could be differentiated in person. Visiting sites in person, one could see changes in the variation and distribution of grasses in the undisturbed patches (no/little signs of grazing and more lush vegetation) compared to the drained wetlands (refer to Figure 4.3). Quadrat data were taken every 0 m, 25 m, and 50 m per transect, with between 2-4 quadrats nearby acting as representative. It was difficult to tell the difference between undisturbed and drained wetlands, both being quite lush. However, difference in color is noticeable in satellite data (Figure 4.4). Shorter vegetation and less diversity are also apparent at Þúfa drained wetland (Fig. 4.3a), while in Hvanneyri color and topography differ between drained and undisturbed wetlands (Fig 4.3e-f).

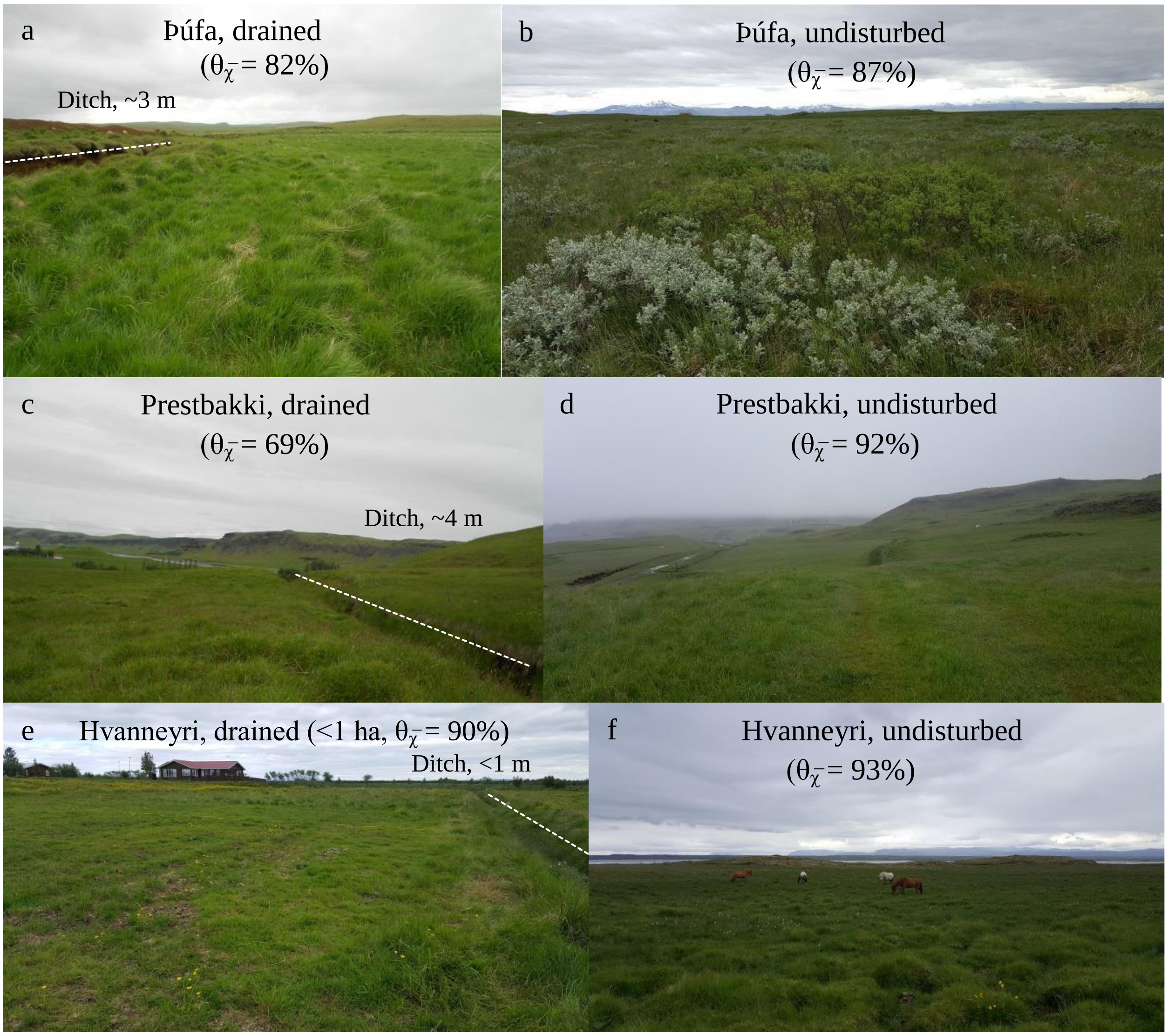


Figure 4.3: Vegetation of the study sites: Þúfa drained patch and undisturbed patchy wetland (a-b), Prestbakki drained patch and undisturbed wetland (c-d), and Hvanneyri drained patch and undisturbed wetland (e-f).White dashed lines are placed at the edge of drainage ditches, and $\theta_{\bar{\chi}}$ shows the volumetric near-surface soil moisture mean.

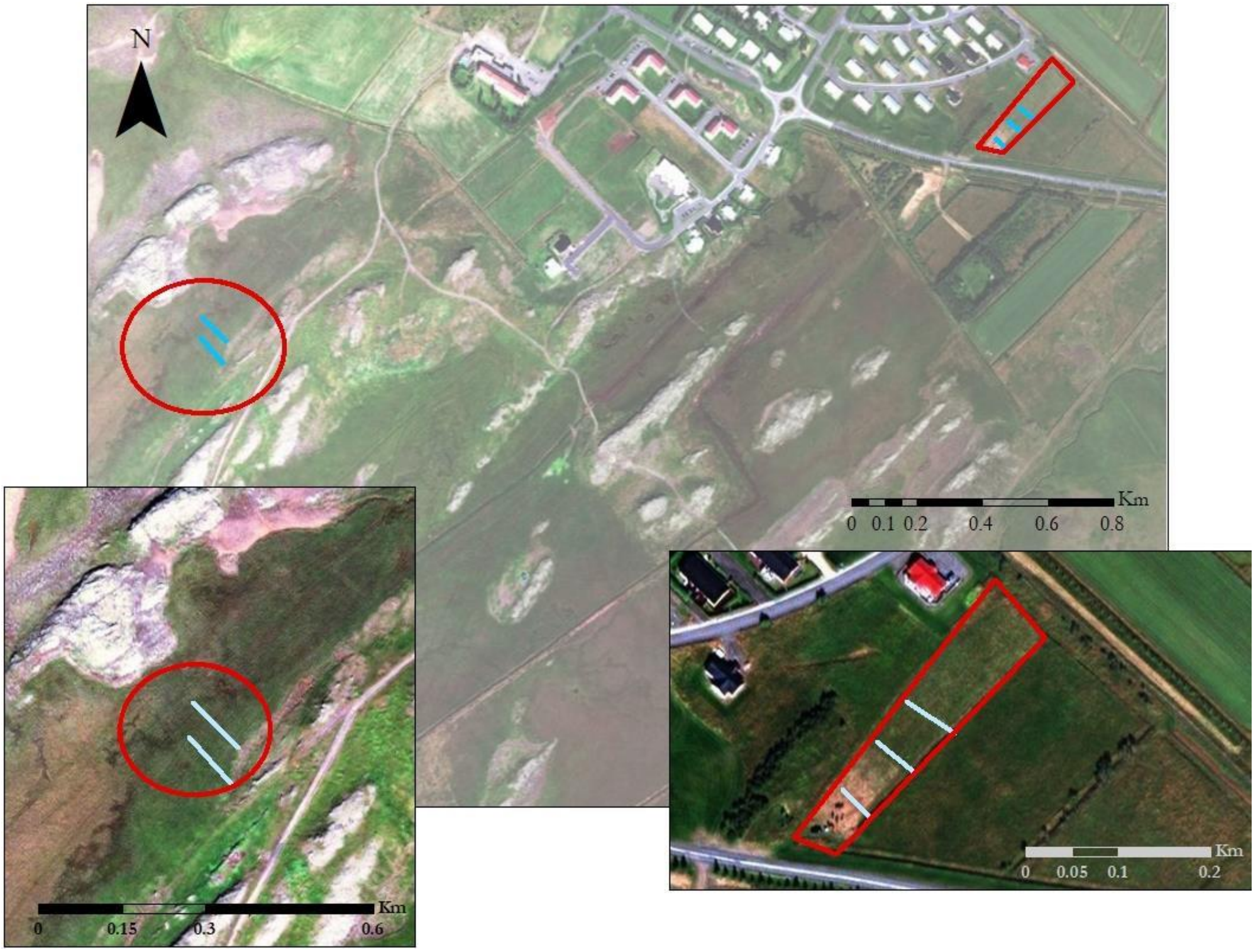


Figure 4.4: Satellite view of Hvanneyri drained and undisturbed wetland patches (sources: Esri, DigitalGlobe, GeoEye, Earthstar Grographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community). Insets: to the left is the undrained wetland (circle), and to the right is the drained wetland (polygon). Blue lines are transects.

4.2.2 ArcticDEM Slope Data

Slope data were derived from the ArcticDEM intiative. ArcticDEM data were generated from the panchromatic bands of the WorldView-1/-2/-3 satellites, creating a Digital Surface Model of the Arctic including slope, aspect, and contour data, for all land area north of 60º. This imagery is processed into elevation models with a 2 meter resolution, with approximately 4 meters accuracy in horizontal and vertical planes.

The slope at Prestbakki was much gentler in the drained patch than at the undisturbed wetland: two infiltration trials facing north were at the top of a hill near a steeper slope angle of 15-17º, while the easternmost infiltration trial was at a slope angle of 7º (Figure 4.3c). These three tests were near the drainage ditch, with the fourth towards the middle of the patch in a slight depression with a slope angle of 5º. At the undisturbed wetland, slopes were steeper by comparison. Soil moisture and albedo surface transects were measured in front of the plateau (not seen) pictured in Figure 4.3d: the transects measured starting from a stream with slope of 14º and 19º up to 5 m, then rising to approximately between 31-35º for another 10 m distance, and after, dropping back down to 17-22º (see Figure 4.5). The drained site was 40 m a.s.l, and the undisturbed site was 80 m a.s.l.

Figure 4.5: Study transect along steeper slopes (gradient approx. 30º) at Prestbakki undisturbed wetland, viewpoint looking westwards upslope (30th June, 2018).

Þúfa was about 100 m a.s.l, with a gentle slope westwards, from 1-2º to 7º. To the north at the end of transects, the slope was between 3-8º; the sampled area was similar in range. At the undisturbed wetland there was a relatively straight drop at the stream, while elsewhere ranged between 6 to about 15º. At Hvanneyri, there was little slope; the majority of the undisturbed site was at or below 6º (transects between 1º and 6º), although higher in spots further. Similarly the drained site was mainly below 10 m a.s.l. although near a slope: adjacent to the ditch at 6-7º, with ~20 m distance from ditch at respectively, probably no more than 10-12º.

4.3 Assessing Soil Moisture, Albedo, and Infiltration Along Transects

Along with each drained wetland patch, an undisturbed wetland (undisturbed by human activity) was sampled to serve as a "control," (and for additional information on local hydrology), since they were located nearby. In each site, 3-6 transects were sampled. At Þúfa, 4 transects in the drained patch and 1 transect in the undisturbed wetland were sampled for a total of 5 transects; at Prestbakki, 2 transects in the drained wetland patch and 1 in the undisturbed wetland were sampled, for a total of 3 transects; and at Hvanneyri, 3 transects in the drained patch and 1 transect in the undisturbed wetland were sampled, for a total of 4 transects.

Upon arrival at each site, we set up HOBO data loggers to record air temperature (°C), light intensity levels (lux), and relative humidity (%). The HOBO loggers took readings every 5 minutes. Also, average and maximum windspeed (m s^{-1}) and dew point (°C) spot measurements were taken with a Kestrel meter held ~2 m above ground. Additional data were obtained from the Icelandic Meteorological Office stations near each study site. At Hvanneyri, the weather station data are from 1963 – 1995, at the Þúfa area station called Hella data are collected from 1958 – 2004, and at Kirkjubæjarklauster the data are from 1931-2012 (Climatological Data 2012).

Prior to conducting the infiltration tests, 4-6 volumetric soil moisture measurements were taken with the Theta probe (±1%) to assess the near surface moisture conditions (0-0.06 m depth). Infiltration tests were run adjacent to ditches (except for one test in the middle of Prestbakki drained wetland). These were up to 3 m distance from the edge of drainage ditches and within 2 m of the transect tape for a total of 4 tests in Þúfa, 4 at Prestbakki, and 2 at the Agricultural University of Iceland. A double ring infiltrometer was hammered 0.15-0.2 m in the ground, leaving it to extend ~0.1 m above ground.

For these tests, the constant head method was applied (Dingman 2015). Both rings were filled with between 50-80 mm of water (Eijkelkamp soil and water 2018), and the inner ring was refilled once the water infiltrated below 50 mm to the starting point of that trial until 1-2 hours passed. Changes in mm were measured every 30 s by a ruler in the inner ring and recorded. The outer ring was always flooded to insure that water in the inner ring moved vertically and not horizontally. Infiltration trials were only run at the drained wetland patches, not the undisturbed. There, surface ponding was observed in several locations along transects at the undisturbed wetlands, indicating saturated conditions.

Near-surface soil moisture (θ) was sampled using a Theta probe along transects. Transects were placed between 15-20 m apart in order to account for spatial variation of moisture conditions, and started from the ditch edge (0 m) to the interior of the wetland (50 m). One sample was represented by an average of 3 replications, which were taken within 0.02 m of each other at the same meter mark. Because Þúfa was the first site sampled, we took soil moisture and albedo measurements every 1 m mark up to 50 m for the first two transects (n=51). For any transect thereafter, sampling occurred at every 5 m up to 50 m (n=11); i.e., soil moisture shown in Figure 5.5 at 0 m is from an average of 3 replications, then measurements were replicated at 5 m, at 10 m, and so on, until reaching 50 m. This scheme was also used for albedo measurements, measured using a LiCor pyranometer attached to a multimeter. The pyranometer was held at approximately the same height and pointed upwards to measure downwelling radition (K↓), then pointed downwards to measure upwelling radiation (K↑). This was for every 5 m after the first two transects (n=11). Readings from the multimeter were then used to calculate the ratio K↓ / K↑. Overhead conditions were usually stable, but three values from the multimeter were recorded for the pyranometer as it was held, to collect an average. Albedo (α) measurements were taken between 13:15 h and 14:20 h, which is around local solar noon (~13:30 h) (Jacob and Olioso 2005). There were two exceptions for measurements taken at the Þúfa sites: one transect at the drained patch (taken 15:00-15:50 h) and one at the undisturbed wetland (taken at 15:20-15:30 h). Solar noon was calculated using the equation of time (min) and the difference in longitude (°) between the Prime Meridian and the longitude (°) of Reykjavik, since the time was similar across all sites (see the low accuracy equations found at ESRL Global Monitoring Division 2020). Surface albedo was calculated as upwelling / downwelling radiation (i.e., α 0.513/1.515 = 0.34) for each replication, and the mean α of the replications represented a sample.

Vertical soil moisture was measured by digging pits at 10 and 25 m at the drained patches of Prestbakki and Þúfa, while at the AUI drained patch these were dug at 10 and 20 m (the opposite edge of the patch). Soil pits were dug down to ~0.6 m below the surface. These moisture contents were measured using a Theta probe (n=1 per horizon) at all sites, and in the southern sites the HOBO SmartSensor 10HS was also used (n=1 per horizon). Soil pit stratigraphy was identified by describing layers (organic, aeolian, tephra, a mix of the three) at their respective depths. Measurements, descriptions, and characteristics are detailed in Appendix B. At the western site, due to elevated moisture contents leading to visibly homogenous peats, soil layers were divided into 15 cm depths from 0 cm to -15 cm as layer 1, -15 cm to -30 cm layer 2, -30 cm to -45 cm as layer 3, and -45 to -60 cm as layer 4, for three of the pits except for transect 2, 25 m. This soil pit on the second transect was separated as 0 to -21 cm, -21 to -41 cm, and -41 to -60 cm, respectively.

4.4 Soil Stratigraphy

4.4.1 Laboratory Testing

Soil samples were kept in Iceland at the Agricultural University of Iceland at 4ºC until they could be brought back to Canada, and in between testing they were stored here at around the same temperature. Lab tests were conducted on soil pit samples to determine their pH, moisture content (g g^{-1}), bulk density (g cm^{-3}), Loss-on-Ignition (LOI), and soil texture. For bulk density, hydrometer, and gradation tests, samples were sieved through a 2 mm mesh sieve, while for LOI, they were run through a 125 µm sieve so that only the fines would be tested (Neris et al. 2013). Hydrometer results were used to gain USDA soil textural classifications (seen in Figs. 5.3, 5.11, 5.21). Moisture content was determined for all tests except for pH, with samples dried at 105ºC for 18-24 h until water loss was stable (0.1 g) (Veres 2002). Soil pH was determined using a Hanna pH meter, with the original soil samples and their original water content, firstly by taking 1:2.5 parts soil:water, which was then later checked by taking 10 g of soil with 40 g water (to ensure the instrument was properly reading pH). A summary of these results can be found in Appendix B for each site. Because of limited sample sizes (many tephra/aeolian samples from Prestbakki drained patch yielded <100 g sample in total), the results are limited to horizons with enough soil for testing. Soil pH was obtained for nearly every layer, while total tests for each site are as follows. At Prestbakki drained wetland, 39 soil samples were collected (θ_g = 36, D_b = 36, LOI = 11, hydrometer = 9, gradation = 17); at Þúfa drained wetland 63 samples were collected (θ_g = 46, D_b = 30, LOI = 19 hydrometer = 13, gradation = 21); and at the Agricultural University of Iceland drained wetland 15 samples were collected (θ_g =14, D_b = 9, LOI = 11, hydrometer = 4, gradation = 12).

LOI was determined using a muffle furnace and crucibles. After removing moisture, crucibles were placed in the muffle oven for 2 hours at 500ºC and placed in a glass dessicator for an hour to equilibrate before weighing to determine organic matter lost. Then, they were placed back in the muffle oven at 900ºC for another 2 hours, to determine carbonates. The time frame used here is supported by the overview given by Hoogsteen et al. (2015), who suggest that at temperatures above 650ºC, noticeable differences are negligible beyond 2 hours. However, there are challenges with measuring highly organic soils, especially at small amounts (Wright et al. 2008). Total C measurements less than this LOI value are valid if assuming 51% C in organic matter, or using acid pretreatment to remove carbonates (A.L. Wright et al. 2008). Since there was no pretreatment in this study, LOI estimates here are likely affected by these challenges. In addition, these are merely estimates since carbon cannot be effectively removed from Andisols as determined from a 1995 study (Orradottir et al. 2008) although this was not known at the time of testing—especially since Neris et al. (2012) did determine soil organic carbon through the 1934 Walkley-Black method.

Bulk density (D_b) is defined as the dry density of soil (g cm^{-3}). D_b estimates were conducted on disturbed samples, between 20-60 g in weight. Samples were placed in a graduated cylinder of 50-100 ml to determine volume (Guðmundsson et al. 2004, Áskelsdóttir 2012). "Compacted" bulk density was simulated by tapping the cylinder on the table (from a height of approximately 5 cm in the air) 30 times.

The following formulas (Brady and Weil 2010, Dingman 2015) were used to obtain the different values needed in relation to a range of soil-water relationships. First, gravimetric water content (θ_g) was measured, then volumetric content was obtained by multiplying θ_g (eq. 4.1.1) by D_b/ρ_w (eq. 4.1.2), and, volumetric water content (eq. 4.1.0) divided by porosity (eq. 4.1.4) gave degree of saturation (eq. 4.1.5). Volumetric water content θ ($cm^3\ cm^{-3}$) is the ratio of water volume (Vw) to soil volume (Vs) (eq. 4.1.0).

$$\theta = Vw / Vs \quad (4.1.0)$$

In the lab, it was determined by first weighing a soil sample of known volume, oven drying it, then reweighing it, and calculating for gravimetric moisture content ($g\ g^{-1}$):

$$\theta_g = M_{wet} – M_{dry} / (\rho_w Vs) \quad (4.1.1)$$

here, M_{wet} and M_{dry} are the weights before and after drying respectively, and ρ_w is the density of water (1 $g\ cm^{-3}$ or 1000 $kg\ m^{-3}$).

Dry bulk density (D_b) ($g\ cm^{-3}$) is determined as

$$D_b = M_{dry} / (Va + Vs) \quad (4.1.2)$$

where Va = volume of air, and Vs = volume of solids.

Porosity (Φ) is the proportion of pore space in a given volume of soil; Vw = volume of water,

$$\Phi = Va + Vw / Vs \quad (4.1.3)$$

which can be further modified to the general equation (4.1.4) using a standard particle density, D_p of 2.65 $g\ cm^{-3}$,

$$\Phi = 1 – (D_b / D_p) \quad (4.1.4)$$

Finally, degree of saturation, or, soil wetness (Θ) is

$$\Theta = \theta / \Phi \quad (4.1.5)$$

Hydrometer tests were used to determine the soil texture of selected soil samples using dried samples of 25 – 50 g (Ontario Department of Highways 1957). This method is based on Stokes' Law, which looks at the rate of settling between materials of different density (Blatt et al. 1980, Brady and Weil 2010). The method gives the percentage of particles in suspension at a certain time (t), L is effective depth (the length from the surface of the suspension to the hydrometer's center of buoyancy), K is a constant determined by specific gravity (G_s) of soils, resulting in grain size D, diameter (eq. 5). The particle size is a given equivalent diameter below that level at time (t) (Blatt et al. 1980).

$$D=K\sqrt{(L / T)} \tag{5}$$

$$P=Ra / W \tag{6}$$

Then, in equation 6, percentage (P) of particles suspended at time (T) is obtained by multiplying (R), the corrected hydrometer reading by (a), a constant depending on specific gravity, which is then divided by (W), the weight of the sample (Blatt et al. 2010). Volcanic soils range in specific gravity, G_s (the ratio of a material's weight density to that of pure water at 3.98 ºC – Dingman 2015) from 2.47 to 2.78 (Kitagawa 1976), and without the instruments to run a specific gravity test, we adopted the standard assumption of 2.65 (D_p of mineral quartz), which made (a) the constant equal to 1.

For the hydrometer test, a 152H model hydrometer was used, which is calibrated for 20ºC. First, sodium hexametaphosphate (SHMP, composition $(NaPO_3)_6$) was added to roughly 350-400 ml water, to which 25-40 g of oven dried and sieved soil was soaked for 10 minutes. Then, the mixture was placed on a shaker for 5 minutes before being transferred to a large glass cylinder, taking care not to lose any sample, and filling the rest of the cylinder with distilled water to the 1000 ml mark. As a reference, for hydrometer calculations a graphical temperature correction to account for several variables in the procedure was applied (see: Siriani 2013, Ontario Department of Highways 1957) by running a blank sample of the combined water and SHMP at two temperatures and extrapolating that line equation (eq.7, where y = composite correction, and x = temperature in ºC). This correction was used for 1.02 L of distilled water at 19 and 20ºC to account for a range from 18 – 20ºC due to extra water added occasionally.

$$y = -0.5x + 15.5 \tag{7}$$

After plunging a brass plunger into the cylinder, and shaking the soil for a minute, time was set to T=0 s once shaking stopped. Hydrometer measurements were obtained thereafter every 30 s, 60 s, 30 min, 7 h, and 24 h per test, with temperature measurements taken to verify the room temperature. Samples were then washed through a No. 200 sieve, oven dried, and sieved to quantify the remaining sand sized particles (Ontario Department of Highways 1957). 26 hydrometer tests were run, and samples that were too small dry sieved. Dry sieving was also run on the other soil samples that were not prepped for hydrometer testing. They were put through a nest of sieves in size of No. 10, No. 18, No. 35, No. 60, No. 125, and for the lower end, either the No. 200, No. 230, or both (in earlier sieve runs, the 200 was left out). These sieve sizes were for the particle sizes (in mm) of 2, 1, 0.5, 0.25, 0.125, 0.075, and 0.0625 (WAQTC Idaho, n.d.). Percentage retained on each sieve was calculated to determine the grain size distribution.

4.5 Statistical Analyses

Soil moisture results for near-surface soil moisture between and within sites were analyzed for any differences. In this case, only normally distributed data within soil moisture and albedo transects were utilized (verified using the Lilliefors Test in MATLAB and/or Shapiro-Wilk in SPSS). In total for drained patches, at Þúfa there were a total of 4 transects (n_θ=124; n_α=122), at Prestbakki 2 transects (n_θ=22; n_α=22), and at the Agricultural University of Iceland 3 (shorter) transects (n_θ=19; n_α=18). For undisturbed wetland patches, we had less to compare based on time constraints. At Þúfa undisturbed wetland we were able to obtain 1 transect (n_θ=11; n_α=11), at Prestbakki 2 soil moisture transects with 1 albedo transect (n_θ=23; n_α=13), and at the AUI, 1 soil moisture transect (n_θ=11) and 2 albedo transects (n_α=22). At Þúfa, undisturbed wetland volumetric measurements were obtained in soils testing. At Prestbakki, the smaller sample set for albedo was due to rain, and at the AUI site, the smaller data set for albedo was due to an interruption by Icelandic horses.

For comparisons between sites, I used Analysis of Variance (ANOVA) up to 20 m when including the drained wetland at the Agricultural University of Iceland, because of its smaller patch size (n=4: 0, 4, 16, 20 m; 8 and 12 m measurements were excluded since only at the drained patch were transects taken at 4 m intervals to maximize data). I used the full transects up to 50 m for the other sites at their 5 m intervals (n=11) to keep comparisons between transects along the same scale. I also compared within sites by comparing transects using student's t-tests when comparing two transects together, or two-way ANOVA without replication when comparing three or more transects in Excel (without replication because we have no reference for treatment effects — Anderson and Davis 2013). For transect comparisons within Þúfa drained wetland I included the normally distributed 1 m measurements in between. By using two-way ANOVA tests, differences in soil moisture/albedo within a site and between sites were explained, and also if distance from drainage ditches (or streams in the undisturbed wetlands) influenced these patterns (Anderson and Davis 2013). Two-way ANOVA were used within Þúfa, the AUI drained wetlands, and between sites, and student’s t-tests were used within Prestbakki drained wetland and the undisturbed wetland at the AUI. Non-normally distributed data were not tested, so they are not included in the statistical results presented here. Those excluded were the near-surface soil moisture transects at undisturbed wetlands, some soil moisture transects from the Þúfa (3) and AUI (2) drained patches, and two albedo transects from the Þúfa drained patch.

For the hydrometer samples (n=14 tested) a statistical program called GRADISTAT (Blott and Pye 2001) was used to give an overview of the descriptive statistics for most samples and some of the dry sieved samples. The GRADISTAT program works by providing calculations from Folk and Ward (1957 – Blatt et al. 1980), an approach integrated into an Excel spreadsheet and designed to accommodate individual modification (Blott and Pye 2001). To do this, one has to input the percentage of sediment in each size class through weight/percentage retained in sieves (Blott and Pye 2001). The geometric Folk and Ward (1957) parameters are calculated by extracting specific values from the cumulative percentage curve using linear interpolation for known points, and can also be used in conjunction with tests for smaller grain sizes. These calculations are based on a log-normal distribution with metric size values. If more than 5% of the sample falls in the pan, it is best to use a combination of sieve plus sedimentation results so as not to skew the outputs, so here the sieve weights were combined with the values obtained through hydrometer suspension (eq. 6). The output is then the mean ($\bar{\chi}$), standard deviation (σ), skewness, kurtosis, and cumulative percentage values (statistical formulae and an example of outputs are provided in Appendix A) (Blott and Pye 2001). Previous studies have used this program in conjunction with other methods regarding the fine portions of soil (see Strauss et al. 2012, Verpaelst et al. 2017, and Alexanderson and Bernhardson 2019). For this study, I put in the weight retained for each sieve size, along with percentage of sediment suspended, and used the statistical output given for the approximate descriptive statistics. The program provided an indication of the variation in soil texture between sites, although the small number of samples would likely skew results. Obtaining descriptive statistics using this program for gradation/hydrometers was the only statistical analysis done for soil samples; all other statistics were performed on near-surface transects only.

To calculate infiltration rates, the difference in mm between readings was divided by 30 s (i.e. 2 mm / 0.5 min = 4 mm min^{-1}). Cumulative infiltration was calculated by adding together the differences in mm. Infiltration curves were created by first hand-drawing a curve onto the graph of in-situ field measurements. Then, I used a curve fit website (mycurvefit.com and later, MATLAB) to fit a curve on top of the hand-drawn one in order to derive an equation from it. The decay constants (k) for each specific infiltration trial that produced a visible infiltration curve were determined using an adapted simple regression to determine k as the slope of the best fit line between *ln*y and time (t) (Ajayi et al. 2016).

CHAPTER FIVE: RESULTS

In this section I initially provide a brief summary of the weather conditions during the study period and place them in terms of regional climatology (section 5.1). As sample collection took place in two regions of Iceland at three different sites, the results here are then portioned off into each site. In section 5.2 in southeastern Iceland, hydrological and soil results for Prestbakki, and section 5.3 in southern Iceland, for the Þúfa wetland sites are described. Section 5.4 then goes over results in western Iceland at Hvanneyri and the corresponding undisturbed wetland at the Agricultural University (see Fig. 1.1). Infiltration rates are explained as the average of 5 minute readings (Orradottir et al. 2008). Finally, section 5.5 describes some comparisons between sites, for soil characteristics, infiltration, soil moisture, albedo, and any statistical analyses used.

5.1 Climatology of Study Sites

5.1.1 Precipitation Averages near Study Sites

A long dataset (30 year precipitation averages) at Reykjavík and Kirkjubæjarklauster illustrate the well-known fact that May is one of the driest months of the year, if not the driest (see Figure 5.1). Monthly data averages since 1949 for Reykjavík show variation in precipitation totals (Figure 5.2).

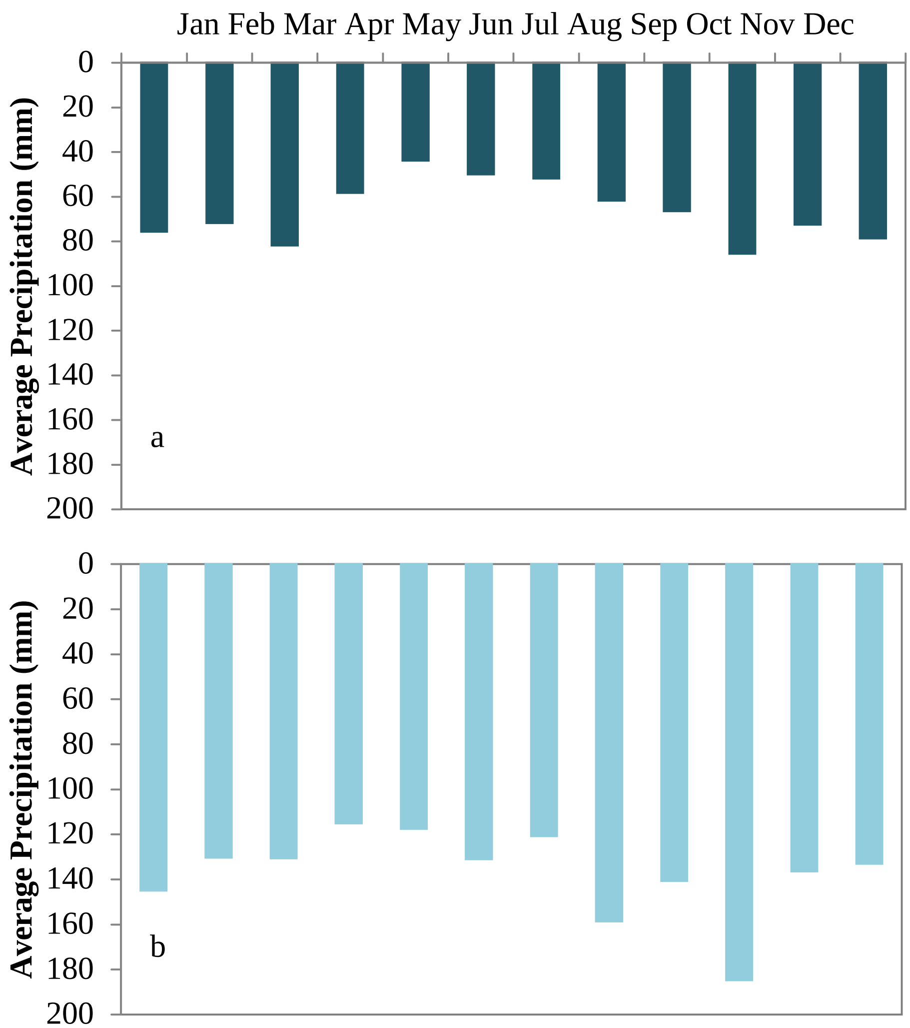


Figure 5.1: The 30 year monthly precipitation average at Reykyavík (a) and Kirkjubæjarklaustur (b) from 1961-1990 (source: Climatological data 2012, Iceland Meteorological Office (IMO), https://en.vedur.is/climatology/data/).

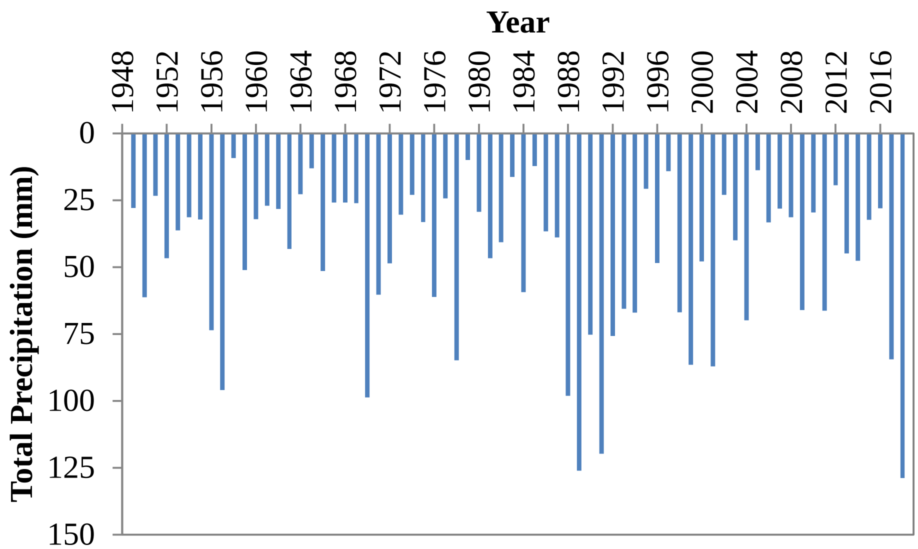


Figure 5.2: Total May precipitation, Reykjavík, from 1949 to 2019 (source: Climatological Data 2012, IMO).

5.1.2 Temperature and Windspeed of Sites

Elevation at each study site was less than 200 m a.s.l, confirming that all sites were in the lowlands of Iceland. Average spot windspeeds were 2.1 m s^{-1} at Prestbakki drained patch, 1.3-1.9 m s^{-1} at the Þúfa farm, and 0.7 m s^{-1} at the AUI. Air temperature was warmest at Prestbakki (14- 15°C) versus 9.5°C and 10.5-11.5°C at the AUI and Þúfa farm, respectively. These spot measurements can be compared to the HOBO logger air temperature data and with data from the Iceland Meteorological Office (Table 4). Little precipitation occurred during fieldwork (light rain events <1 mm), but in the south, precipitation followed a similar trend from 1958 – 2002 for Hella and Kirkjubæjarklaustur data (not shown; June and July statistically significant – $p < 0.001$).

Table 4: Weather data from study sites (Agricultural University of Iceland to Prestbakki), with complements of climate data from the Icelandic Meteorological Office (June-July 2018 monthly averages).

	Air Temp (°C)	Dew Point (°C)	Relative Humidity (°C)	Wind Speed (ave) (m s^{-1})	Elevation (m)	Cloud Conditions (description)	Cloud Conditions (tenths)	Precipitation (mm)	Light Intensity (W m^{-2})
Agricultural University of Iceland									
Drained wetland	10.5	4.4	71.8	0.7	49	clear, sunny			
HOBO logger									
mean	11.1	5.8	69.9						118
sd	1.1	0.5	4.6						65
Undisturbed wetland						overcast, partly cloudy			
HOBO logger									
mean	14 - 15								
sd	0.08 - 2.1								
IMO (Hvanneyri station, 2018)[1]	8.6 - 10.3			4.2 - 4.5			0.7	50 - 53	
Þúfa Region									
Drained wetland[2]	9.5 - 14.7	7.2 - 11.5	60 - 87.6	0.4 - 1.7	101	overcast, partly cloudy, light rain			
HOBO logger									
mean	12.4-18.4								121
sd	0.8 - 2.4								51
Undisturbed wetland	15.1	11.9	74.6	1.9	83	overcast, light rain			
HOBO logger									
mean	19.7	11.3	67.8						106
sd	1.1	0.5	2.0						43
IMO (Hella station, 2018)	9.5 - 11.1			3.8 - 6.2			0.7	83	
Prestbakki (Kirkjubæjarklauster)									
Drained wetland	14.3	13.9	67.2	2.1	46	clear, sunny			
HOBO logger									
mean	18.5								
sd	3.5								
Undisturbed wetland	10.1	11.1	97.8	1.9	41	overcast, rain			
HOBO logger									
mean	11.5								58
sd	0.5								29
IMO (Kirkjubæjarklauster, 2018)	4.3 - 4.6		77.6 - 77.8	3.3 - 3.4			0.6	121 - 124	

[1]Data from the Icelandic Meteorological Office shows a range of the average for June - July

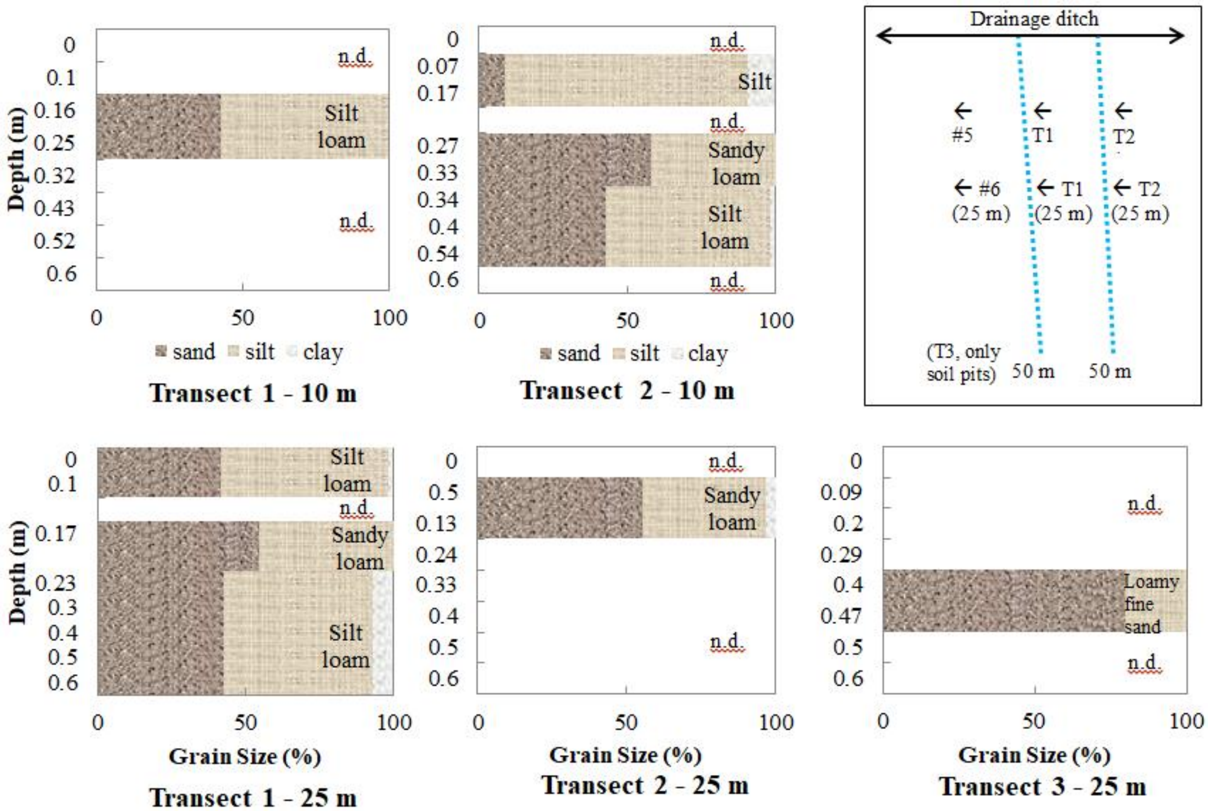
[2]Ranges for the drained wetland patch in Þúfa are for the 4 days on site

5.2 Southeast: Prestbakki Wetlands

Prestbakki drained wetland patch and the undisturbed wetland were located off of Prestsbakkavegur road in an active volcanic region of Iceland, and roughly fell within the region classified as Gleyic Andisols (Fig. 2.1) (Arnalds et al. 2016). Prior to visiting, we received confirmation from a local farmer and scientist, Ms. Rannveig Ólafsdóttir (MSc, AUI; supervised by Dr. Hlynur), that these sites contained tephra and drained/undisturbed wetlands and that we had permission to sample them.

5.2.1 Soil Textural Properties and Characteristics

Soil texture results obtained from soil pits along transects at the Prestbakki drained patch show a fair amount of sand sized particles, with soils retained > 75 µm 10-40% of the time. They were located at different depths, as shown in Figure 5.3. These soils varied with about 50% being coarse textured, and the rest fine textured. Sandy loam layers are present around 0.2 – 0.3 m depth (transect 1, 25 m and transect 2, 10 m), with loamy fine sand present around 0.4 m at 25 m (transect 3) (Fig. 5.3). The other layers present are silt loam and one layer of silt in the soil pit at transect 2, 10 m from 0.1-0.2 m depth.



5.3: Soil grain size (sand/silt/clay %) at Prestbakki drained wetland for soil pits on transects 1, 2, and 3 (labeled). Note that soil texture is included for the different layers (United States Department of Agriculture categories), and that y-axes are not the same. N.d. indicates no data. Diagram in top right corner shows location of soil pits (not to scale).

5.2.1.1 Grain size analyses

The hydrometer sample (n=1) tested for grain size analysis using GRADISTAT has a geometric mean ($\bar{\chi}$) of 58 µm based on Folk and Ward's (1957) method (Blatt et al. 1980, Blott and Pye 2001). This is very coarse silt and very fine sand, and very leptokurtic (long tailed). Because of all the small particulates this sample is fine skewed. The dry sieve samples (n=12) range from $\bar{\chi}$ averages of 173 – 466 µm. The dry sieve samples are very fine skewed (2), fine skewed (1), coarse skewed (7), and very coarse skewed (2), with 2 samples falling under mesokurtic descriptions, a majority platykurtic (short tailed – 8), and a couple very platykurtic. The dry sieves are all sand/gravelly sand types (Appendix B).

Bulk density ranges from 0.5 to 1.4 g cm^{-3} ($\bar{\chi}$=0.78±0.18, n=47), and porosity ranges from 0.47 to 0.80 ($\bar{\chi}$=0.71±0.07). Degree of saturation for the soil pit layers is 1, indicating completely wet soil, with the exception of the first layer in the soil pit at 10 m, transect 2 (0.85), which is at a depth of 0 to 0.07 m from the surface.

5.2.1.2 Loss-on-Ignition

LOI results show some variance between different layers at Prestbakki. Soil layers from 0 to 0.5 m depth contain a high degree of organic matter (13-24%), except for 2 samples ~4-5% (Figure 5.4). However, there were fewer samples tested for the bottom section of soil pits at Prestbakki. All of the samples except for the two small values lie above the 12% C content described by Arnalds et al. (2016), indicating higher organic matter than found in other studies (Arnalds 2008, Arnalds and Oskarsson 2009).

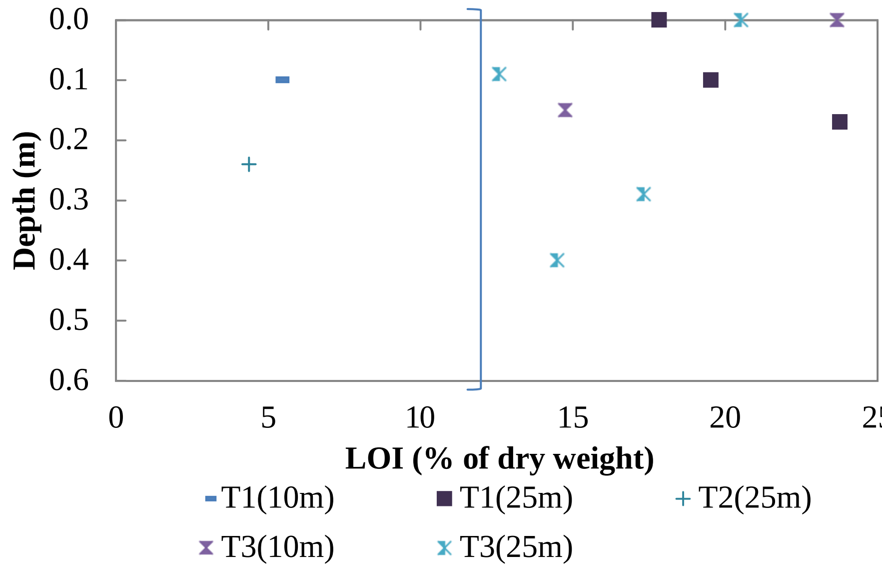


Figure 5.4: Scatterplot of Loss-on-Ignition in Prestbakki drained wetland for both soil pits on transects 1 and 3, and transect 2 (25 m) at respective depths. Blue bracket indicates the 12% C upper limit for Gleyic Andisols (Arnalds et al. 2016).

5.2.2 Soil Moisture

At Prestbakki, like other sites, there is a noticeable drawdown in moisture at the drainage ditch location (Figure 5.5). The ditch drawdown effect last for about 0 m (ditch) m until 10 m. At the undisturbed wetland (Figure 5.6), there are sizeable drops in surface moisture at 10 m, 35 m, and 45-50 m, while at the other meter markings the soil remains generally saturated. Student's t-test results showed a significant difference between near-surface soil moisture of the drained and undisturbed wetland patches, at $p < 0.001$. There was no significant difference in moisture within Prestbakki drained transects ($p = 0.72$). Figure 5.7 shows the soil moisture results in the soil pits, with varying volumetric soil moisture contents, although the soils are at least at 80% (θ). Soil layers near tephra sometimes show lower moisture content. Mixed soils and organics are saturated at most depths (Figure 5.7a-b, 5.7d).

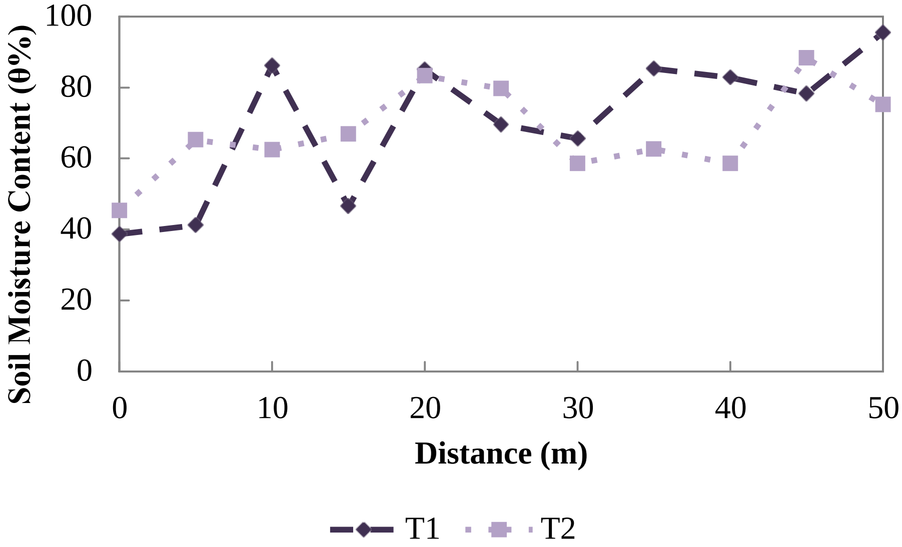


Figure 5.5: Near surface soil moisture (θ%) at Prestbakki drained wetland starting from 0 m (ditch) to 50 m (interior), for transects 1 and 2 (T1, T2).

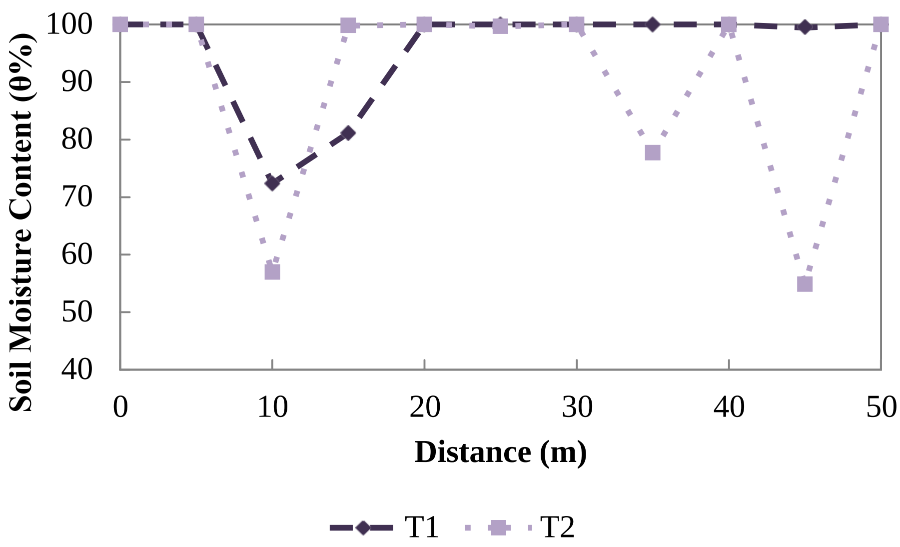


Figure 5.6: Near surface soil moisture (θ%) at Prestbakki undisturbed wetland starting from 0 m (stream) to 50 m (interior), for transects 1 and 2 (T1, T2).

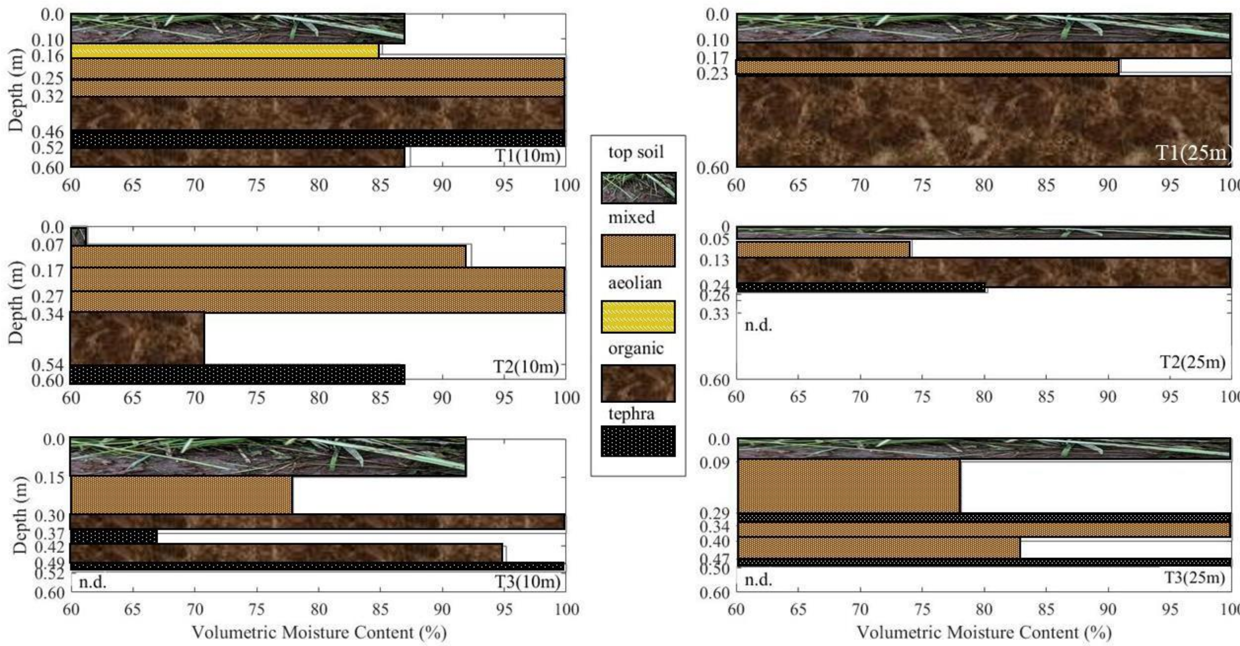


Figure 5.7: Volumetric soil moisture content (%) was determined in lab for the Prestbakki drained wetland based on samples obtained in the field. Materials are classified as top soil, aeolian, organic, tephra, and mixed (aeolian/tephra, tephra/organic, organic/aeolian, or all three together in a single horizon). Note that the y-axes differ. N.d. indicates no data.

5.2.3 Infiltration Rates

Three infiltration tests at Prestbakki varied, with a range in final rates of 0.02-0.09 mm s^{-1}, except for a test taken 50 m from the ditch, which was located in a shallow depression leading to ponding. Figure 5.8 shows both infiltration rates (mm s^{-1}) and cumulative totals (mm). Infiltration rates during the tests leveled out between the first 5 minutes and up to 20 minutes from the start of the test runs. For the other three tests along the ditch (and slightly upslope), infiltration capacity ranged from 0.13 to 0.37 mm s^{-1}. The graphically derived rate of decay (k) for the infiltration curve shown in Figure 5.8 is 0.72 (R^2 = 0.99). The saturated hydraulic conductivity for these trials (k_{sat}) was ~ 0.1 mm s^{-1}. Figure 5.9 shows an approximation of two infiltration curves produced from these tests, with the trial 1 rate clearly higher than the trial 2 rate.

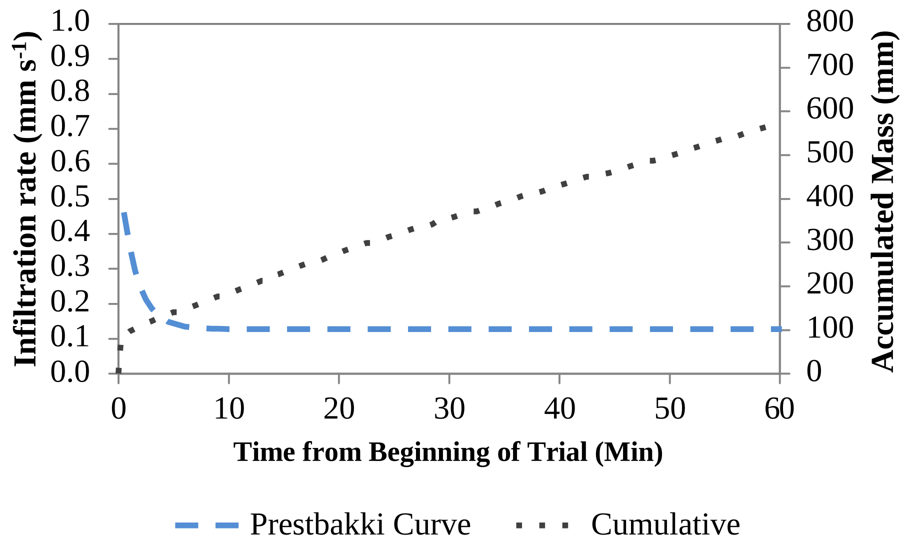


Figure 5.8: Trial 1 infiltration curve (mm s^{-1}, blue dashed line) and cumulative infiltration (mm, black dotted line) shown at Prestbakki near transect 1(drained).

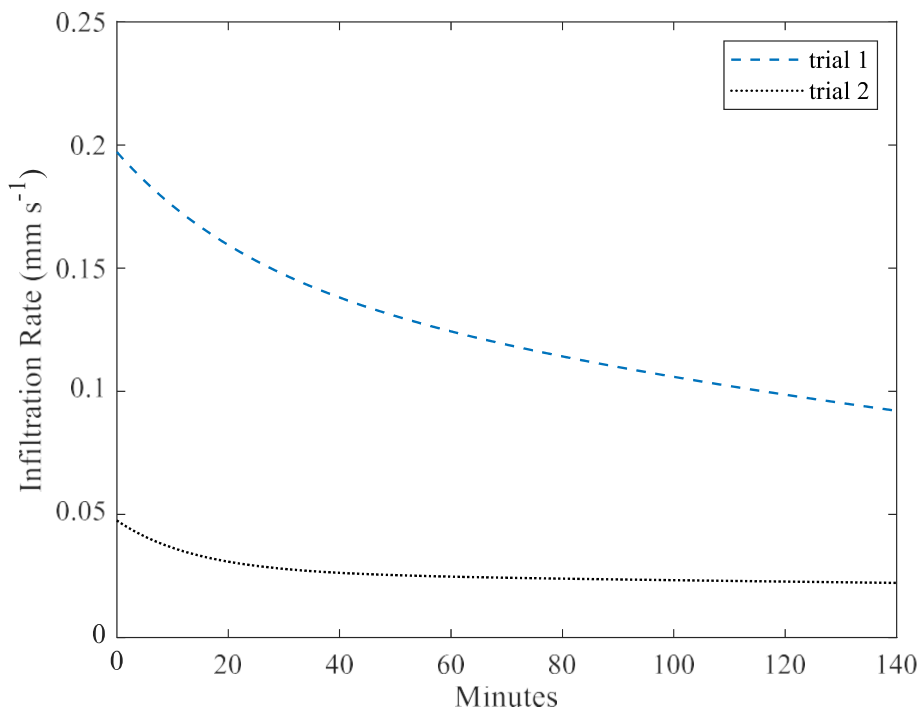
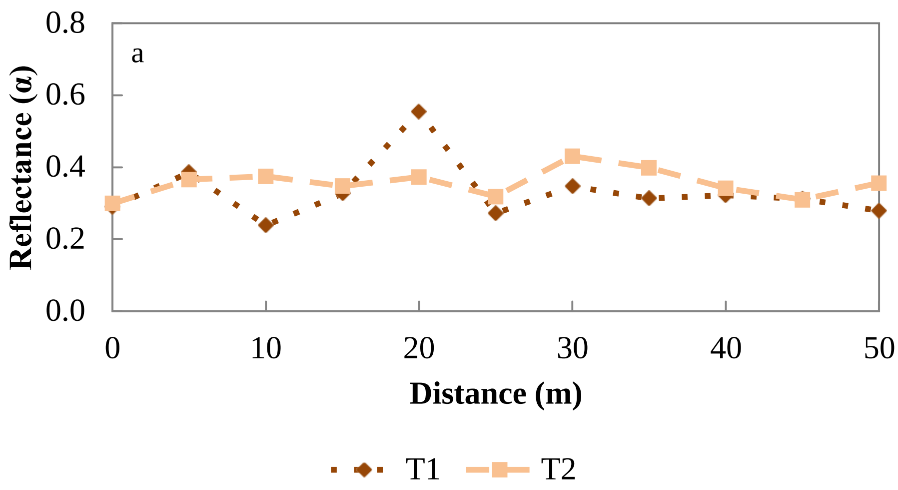


Figure 5.9: Infiltration trials 1 (blue dashed line) and 2 (black dotted line) at Prestbakki with infiltration rates in mm s^{-1}, plotted against time in minutes.

5.2.4 Surface Albedo

Albedo in the drained patch is slightly more variable than at the drained wetland as seen by the fluctuations along transect T1 (Figure 5.10a), compared to the undisturbed patch (Figure 5.10b) which has steady a albedo signal. The albedo estimates along the intact wetland transect are slightly lower than the drained patch ($\bar{\chi}$=0.25 vs 0.34). A student's t-test result confirms this pattern ($p < 0.001$). Distance from ditch is not significant.



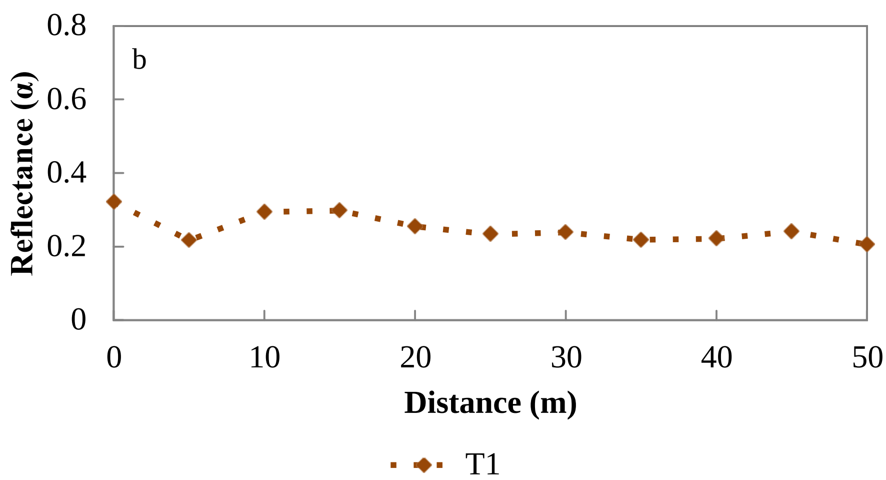


Figure 5.10: Albedo measurements along transects at Prestbakki for transects 1 and 2 (T1, T2), starting from 0 m (ditch) to 50 m (interior) at the drained patch (a); and for one transect (T1), starting from 0 m (stream) to 50 m (interior), at the undisturbed wetland (b).

5.3 South: Wetlands in Þúfa

This region in Iceland includes Selfoss, a large residential area. There are few remaining intact wetlands nearby, due to extensive wetland drainage in South Iceland (Arnalds et al. 2016). The study site fell under the classification of Histic Andisols, with a mixture of organic and volcanic materials.

5.3.1 Soil Textural Properties and Characteristics

Soil texture was determined from 13 samples obtained from the drained wetland in Þúfa (Figure 5.11). Further data (soil identification, texture, color, pH, bulk density/porosity, moisture and organic content, and temperature measurements) can be seen in Appendix B. Designated horizon/subordinate IDs are approximations based on field/lab observations. Hydrometer results show mostly silt loam soil, with three that are not: sandy loam is present around 0.15 m depth in transect 1 (25 m), 0.5 m in transect 3 (10 m), and silty clay loam around 0.4 m depth in transect 4 (25 m). This is probably as a result of the mixing processes from wind.

Bulk densities here range from 0.6 to 1.1 g cm^{-3} (0.81±0.09, n=38), and porosity ranges from 0.59 to 0.76 (0.70±0.04). Degree of saturation was at 100%, except for the horizons around ~0.3-0.5 m depth, which were found in one transect and in the ditch (Figure 5.12). The depths with a drop in degree of saturation all have lower volumetric water contents (θ=46-58%) than the rest of the layers in the fourth transect and at the ditch.

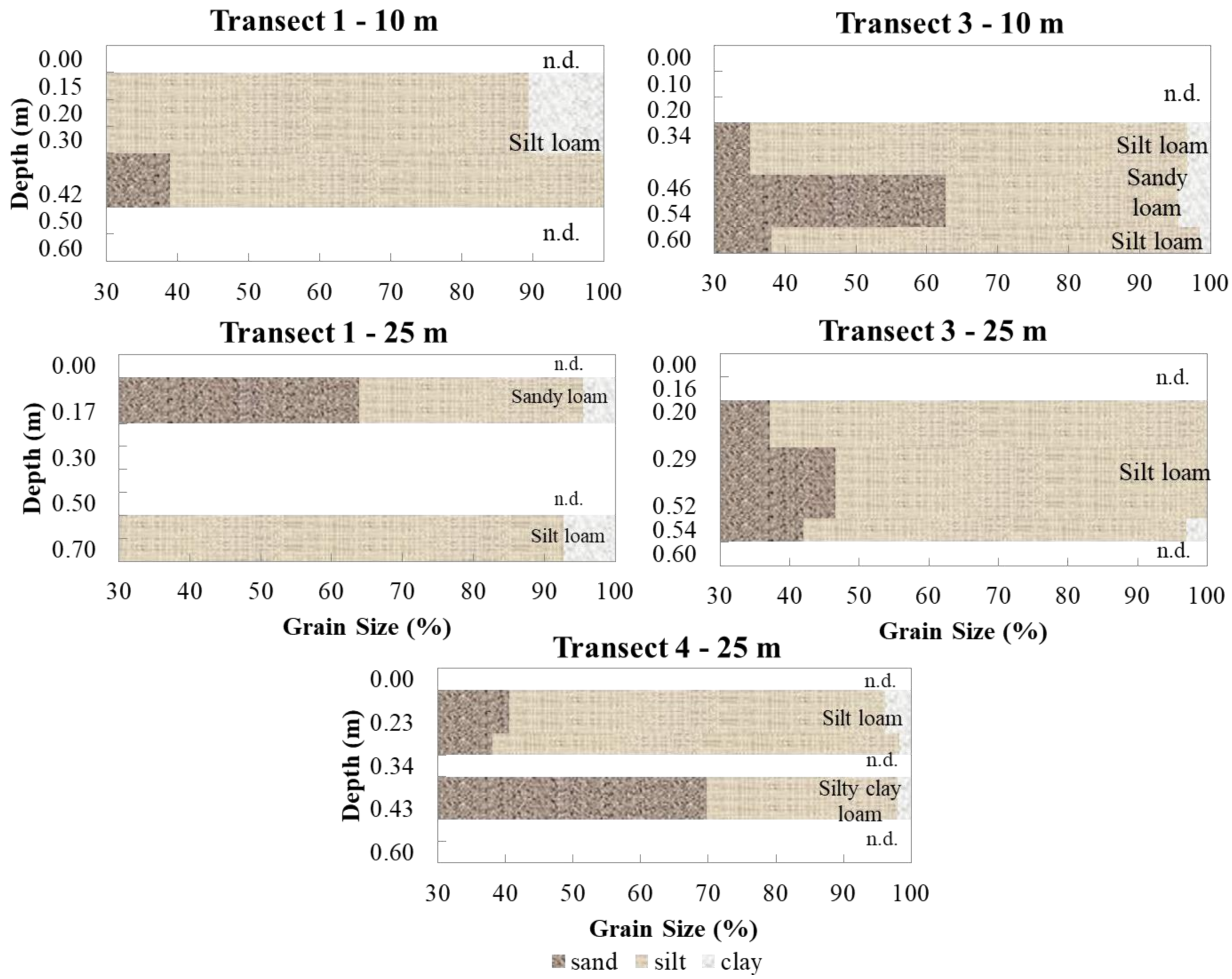


Figure 5.11: Soil grain size (sand/silt/clay %) at Þúfa drained wetland for soil pits on transects 1, 3, and 4 (labeled). Note that soil texture is included for the different layers (United States Department of Agriculture categories), and that y-axes are not the same. N.d. indicates no data.

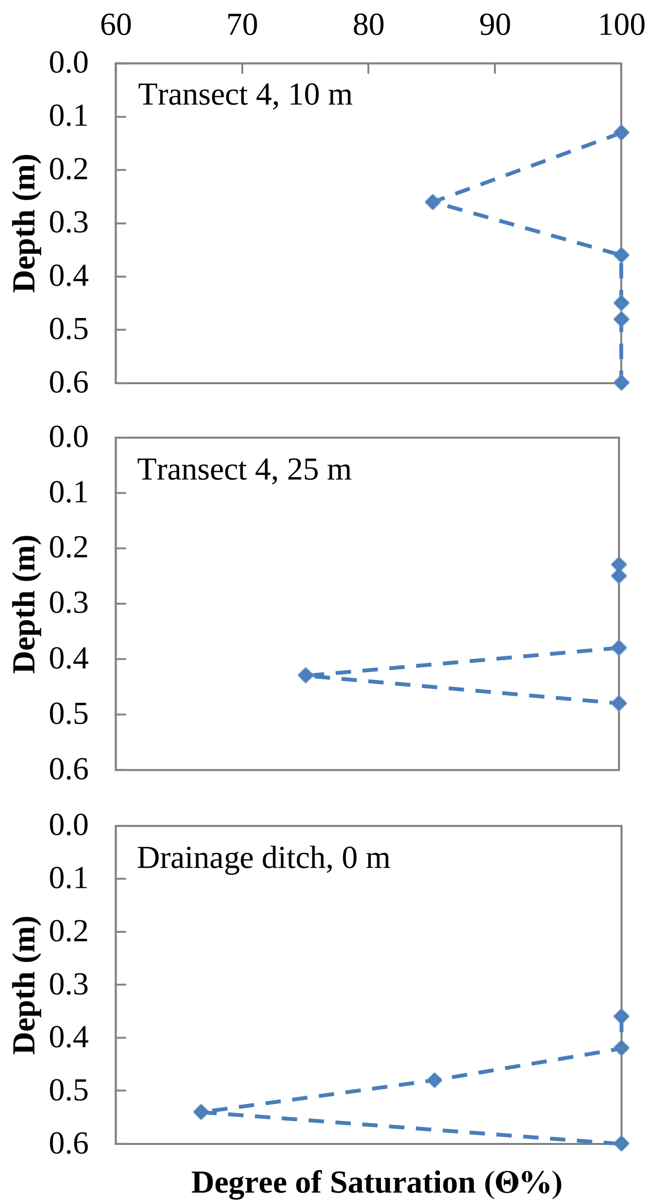


Figure 5.12: Degree of saturation (Θ%) at the drained wetland in Þúfa, shown for transect 4 – soil pits at 10 m, 25 m (a, b) and the drainage ditch (c).

5.3.1.1 Grain size analyses

The hydrometer samples (n=13) for Þúfa have a geometric $\bar{\chi}$ of 48-76 µm based on Folk and Ward's (1957) method (Blatt et al. 1980, Blott and Pye 2001). These numbers translate to very coarse silt or fine sand, that are moderately to well sorted soils except for one poorly sorted sample (transect 1, 10 m: 0.15 to 0.30 m below the surface). All samples are very fine skewed, indicating a positive skew with an excess of fines, except for in the 3^{rd} transect (10 m, 0.46-0.54 m depth) which has a symmetrical skew, and the 4^{th} transect (25 m, 0.48-0.6 m depth), which is coarse skewed. They range from very to extremely leptokurtic, except for transect 3 (25 m, 0.2-0.29 m depth) which is platykurtic. Additionally, two dry sieve samples (transect 2, 10 m: 0.45-0.6 m depth) were classified by the GRADISTAT program as poorly sorted, very coarse sand, although they were also fine skewed, but, platykurtic.

5.3.1.2 Loss-on-Ignition

LOI results for Þúfa (see Figure 5.13) show that depths around 0.2 m and 0.35 m are generally comparable horizontally, although one sample at 0.2 m is higher (29% loss) while top soil is lower (10-19%). At the bottom halves of pits, values range between 14 and 20%. Many of the horizons regardless of depth are near 20% organic content. The majority (15 of 19) of samples here fell in the soil organic category between the organic content of 12-20% C (blue brackets) (Arnalds et al. 2016).

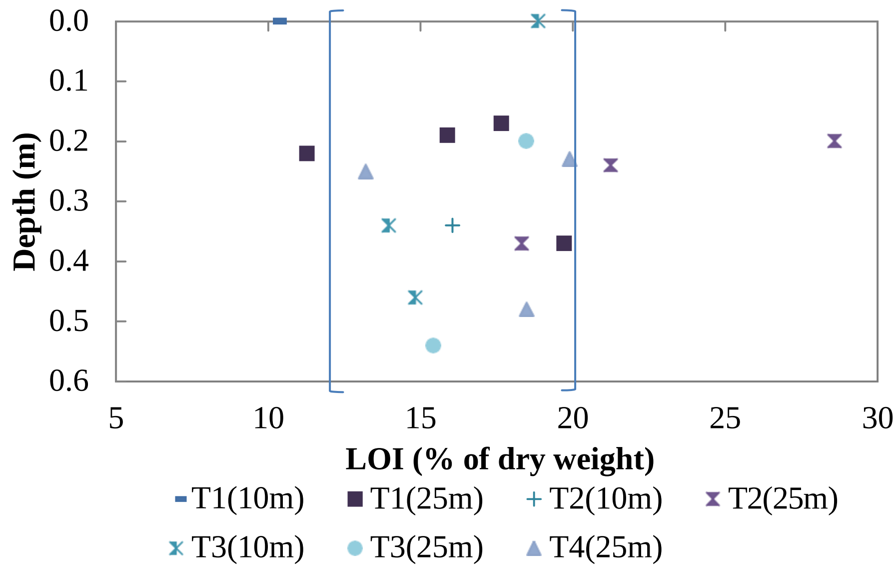


Figure 5.13: Scatter plot of Loss-on-Ignition in Þúfa drained wetland for both soil pits on transects 1, 2, 3, and transect 4 (25 m) at respective depths. Blue brackets indicate the 12-20% C content range for Histic Andisols (Arnalds et al. 2016).

5.3.2 Soil Moisture

For near-surface soil moisture results at Þúfa, ditch drawdown at the drained patch was until 5 m distance (see Figure 5.14). At the undisturbed wetland, there was drawdown from the stream up to 10 m along the transect (Figure 5.15, view from stream). At this site, the wetland soil moisture is based on lab values not field estimates. Student t-test analysis did not show a difference in means between the intact wetland soil moisture and the drained patch ($p > 0.05$).

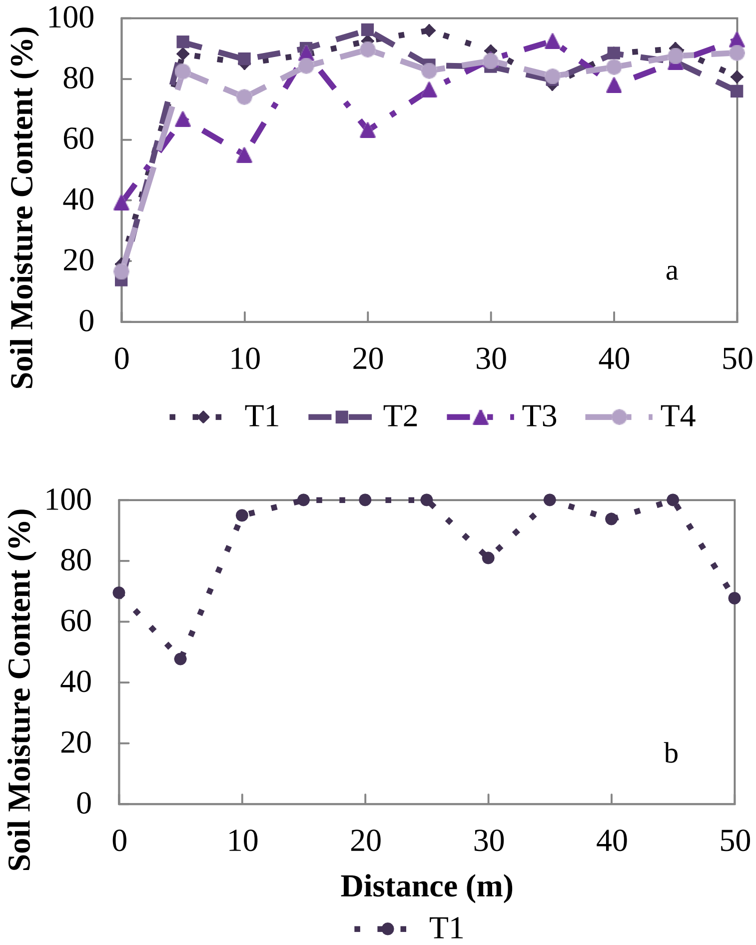


Figure 5.14: Near surface soil moisture (θ%) at Þúfa drained wetland (a) starting from 0 m (ditch) to 50 m (interior), for transects 1, 2, 3, and 4 (T1, T2, etc.). Below, the undisturbed wetland soil moisture (b) starting from 0 m (river) to 50 m (interior) for one transect; note the fluctuations here.

Figure 5.15: Thufur seen at the Þúfa undisturbed wetland patch, looking northeast. Picture taken 28th June, 2018.

The soil pit moistures below (Figs. 5.16-18) show firstly all of the soil pits at 10 m from the drainage ditch (Figure 5.16), then the soil pits at 25 m distance from the ditch (5.17), and lastly, a drainage ditch profile taken on 3rd July, 2018 (5.18). Tephra is clearly visible in around 0.2 m depth and 0.4-0.6 m depth for most of the soil pits. Organic horizons tend to have high soil moistures ($\theta \approx 80\%$), except for at 25 m on transect 4 and the drainage ditch, while tephra falls slightly lower, between 77% and 94%. Along transect 1, both pits, and the second transect, at 25 m the soil pits are saturated (~ ≥90%). Transect 3 is highly saturated, with volumetric moisture contents above 85%, while the pits along transect 4 vary slightly in their moisture content between 52-97% (10 m) and 57-98% (25 m). The drainage ditch has lower content between 46% and 84%. Full details can be found in Appendix B.

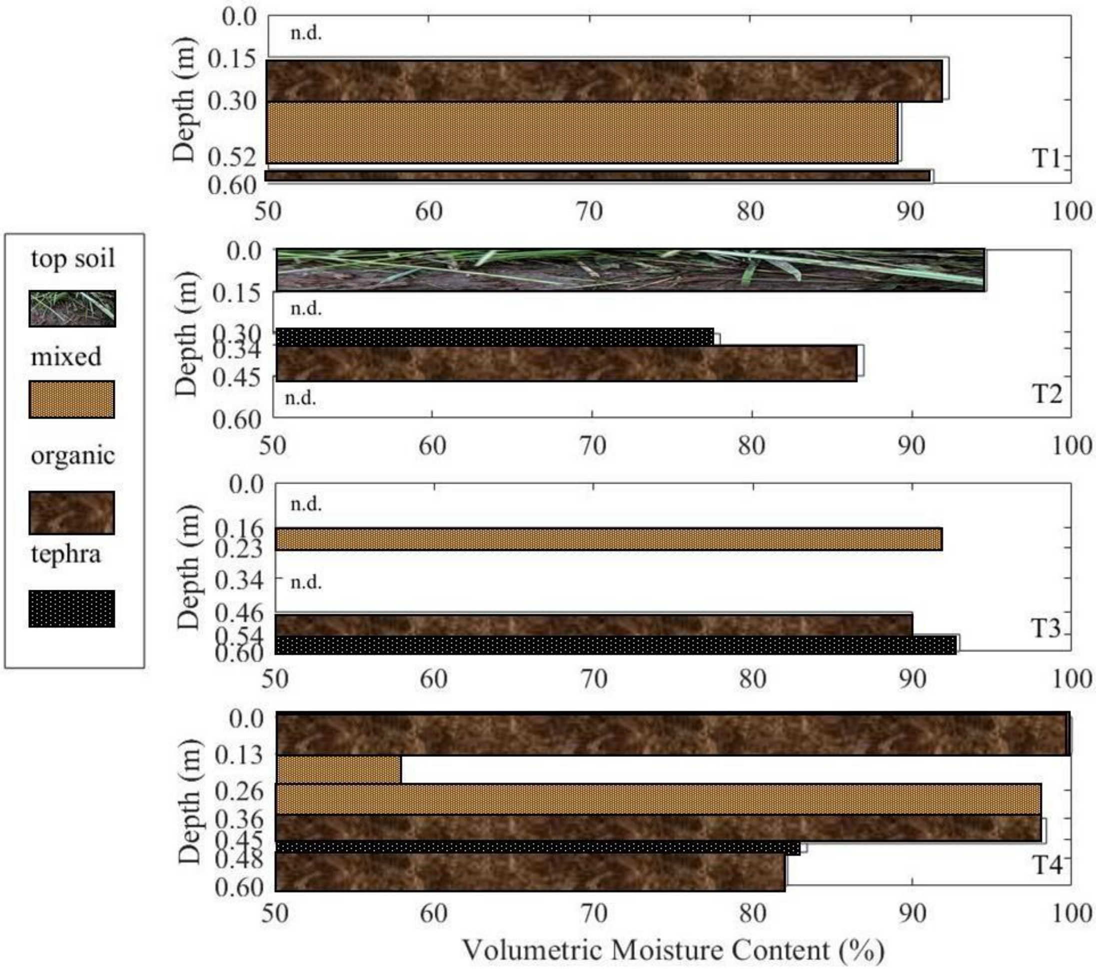


Figure 5.16: Volumetric soil moisture content (%) was determined in lab for the Þúfa drained wetland based on samples obtained in the field (10 m distance). Materials are classified as top soil, organic, tephra, and mixed (aeolian/tephra, tephra/organic, organic/aeolian, or all three together in a single horizon). Note that the y-axes differ. N.d. indicates no data.

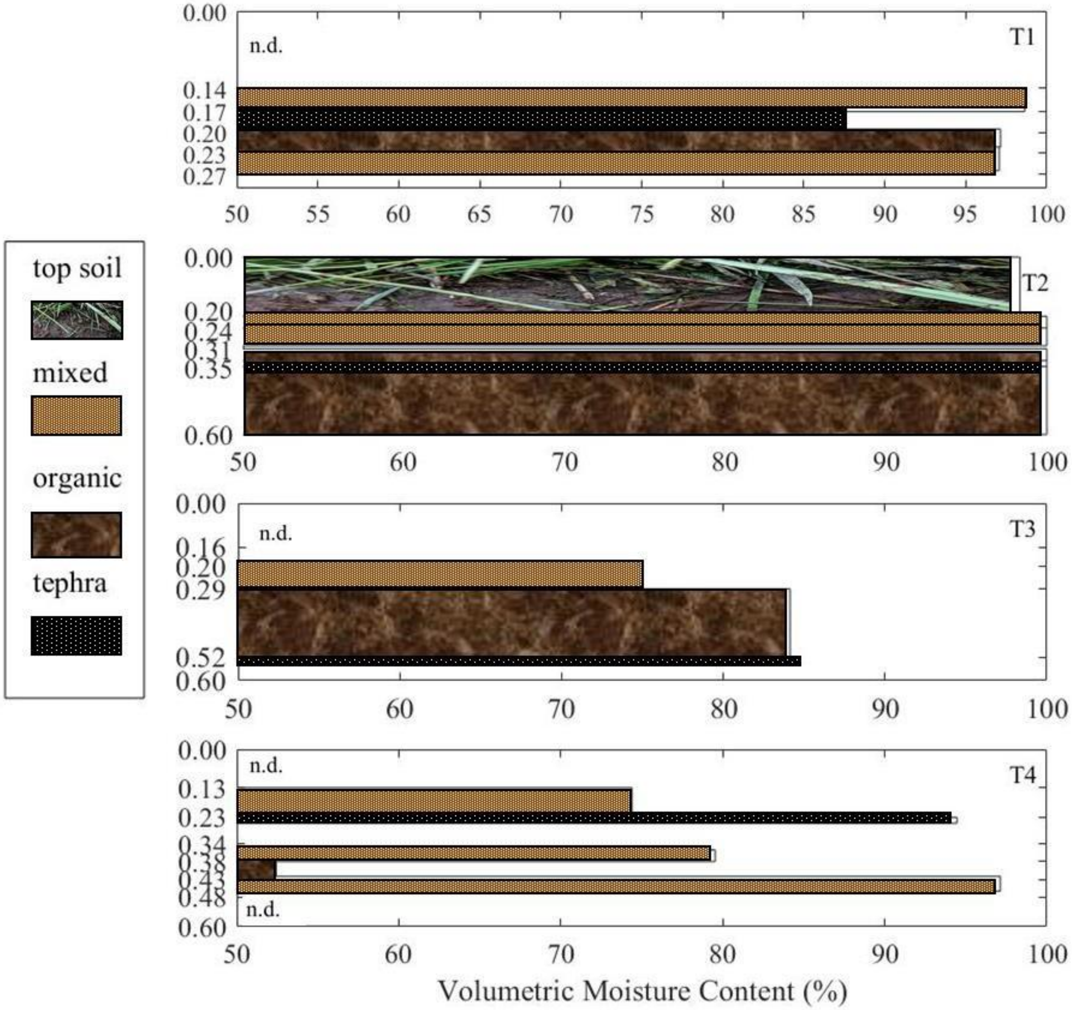


Figure 5.17: Volumetric soil moisture content (%) was determined in lab for the Þúfa drained wetland based on samples obtained in the field (25 m distance). Materials are classified as top soil, organic, tephra, and mixed (aeolian/tephra, tephra/organic, organic/aeolian, or all three together in a single horizon). Note that the y-axes differ. N.d. indicates no data.

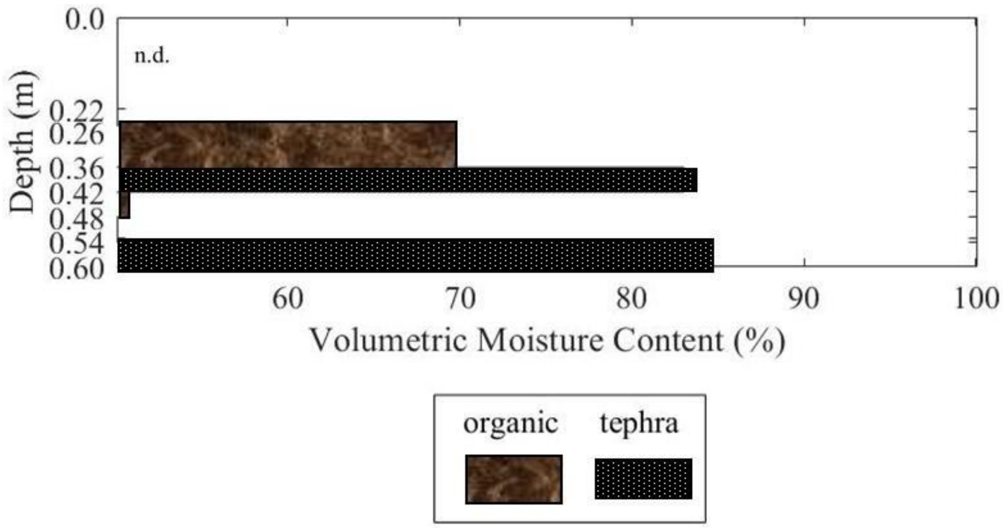


Figure 5.18: Volumetric soil moisture content (%) was determined in lab for the Þúfa drained wetland based on samples obtained in the field (ditch samples). Materials are classified as organic or tephra. Note that the y-axes differ. N.d. indicates no data.

5.3.3 Infiltration Rates

Infiltration rates at Þúfa are from three trials, with final rates ranging from 0.006 – 0.03 mm s^{-1}. Figure 5.19 below shows an infiltration curve at Þúfa. Cumulative infiltration of that trial ended at 173 mm, and infiltration leveled out within 10 minutes. Maximum infiltration ranged from 0.03 to 0.53 mm s^{-1}. The graphically derived rate of decay for the curve was 0.3 (R^2 = 0.96). The average k_{sat} for these tests was 0.02 mm s^{-1}.

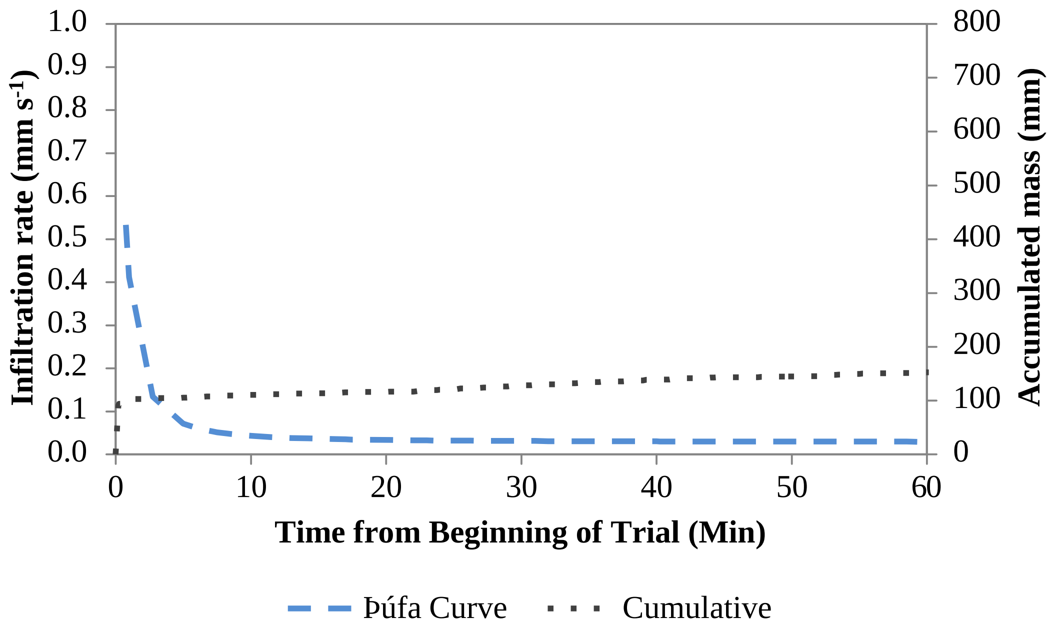


Figure 5.19: Trial 1 infiltration curve (mm s^{-1}, blue dashed line) and cumulative infiltration (mm, black dotted line) shown at Þúfa near transect 1(drained).

5.3.4 Surface Albedo

In Figure 5.20, transects of surface albedo are plotted with distance from the ditch in the drained patch, and distance from the stream in the undisturbed wetland patch. In the drained wetland, a student's t-test of albedo measurements comparing transects 2 and 4 (per 5 m readings) did not yield any significant results (n_{T2} = 11, n_{T4} = 11), however, when using all values of transect 2 (per 1 m), the result was significant ($p < 0.05$, assuming equal variances; n_{T2} = 51, n_{T4} = 11). A two-way ANOVA without replication test comparing two transects from the drained patch with the undisturbed wetland transect shows that albedo differs significantly between the drained patch and the intact wetland at Þúfa ($p < 0.001$). Total sample sizes here varied between patches (n_d = 22 versus n_w = 11), however, comparing one drained transect to the intact wetland transect at a time yielded similar result. The drop in undisturbed wetland albedo at 5 m is due to bare soil.

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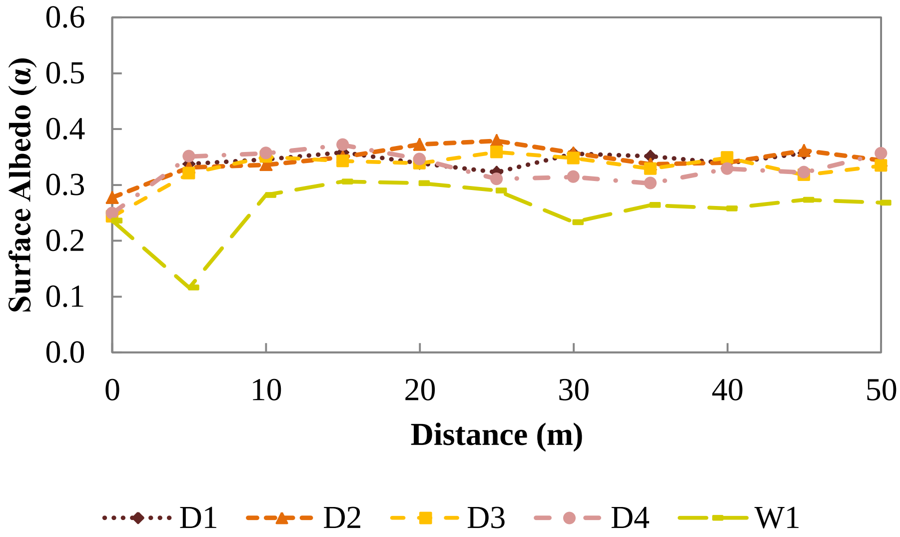

Figure 5.20: Albedo measurements along transects at Þúfa for transects 1, 2, 3, and 4 (D1, D2, etc.), starting from 0 m (ditch) to 50 m (interior) at the drained patch; and for one transect (W1), starting from 0 m (stream) to 50 m (interior) at the undisturbed wetland.

5.4 West: The Agricultural University

Peat soils (Histosols) here are found on the grounds of the Agricultural University of Iceland in Hvanneyri. There was no indication of tephra, although Icelandic Histosols do exhibit some influence from volcanic soils (Arnalds et al. 2016).

5.4.1 Soil Textural Properties and Characteristics

The soil profile at the west site is composed of organic material, which was identified as 0.0 to 0.15 m depth (Figure 5.21). Soil textures (n=4) that had sufficient sample were collected for textural analysis. At transect 1 (10 m), 0.3-0.4 m depth consisted of fine sand, whereas at the same depth but 25 m distance, the soil was of silt loam. At transect 2, 25 m, the texture was of fine sand around a similar depth, and then changed to sandy clay loam below 0.41 m (Fig. 5.21).

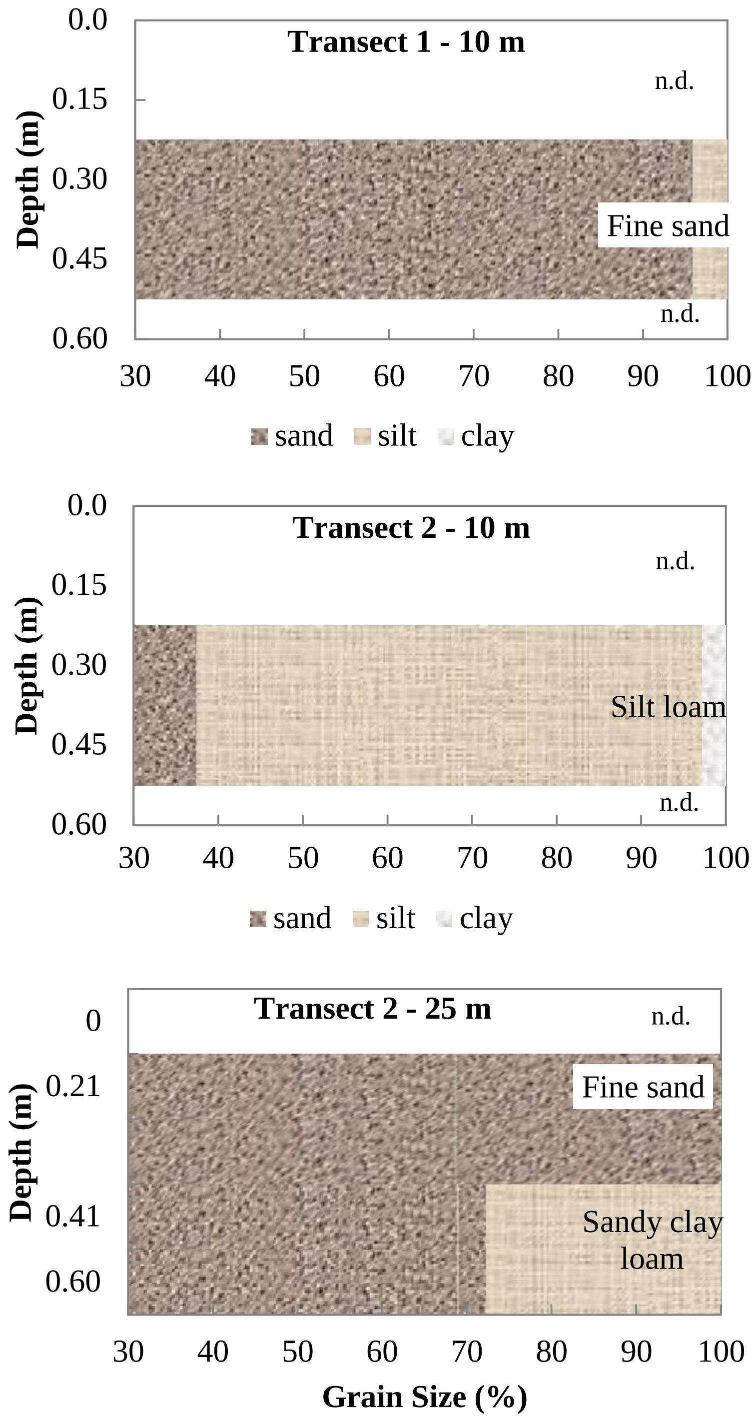

Figure 5.21: Soil grain size (sand/silt/clay %) at Hvanneyri drained wetland for soil pits on transects 1, 3, and 4 (labeled). Note that soil texture is included for the different layers (United States Department of Agriculture categories), and that y-axes are not the same. N.d. indicates no data.

Bulk density ranges overall from 0.22 to 1.1 g cm^{-3} ($\bar{\chi}$= 0.58±0.32 g cm^{-3}, n=9). However, bulk densities between transect 1 (10, 25 m) and transect 2, 25 m are lower ($\bar{\chi}$= 0.29±0.05 g cm^{-3}, n=4) than in transect 2, 10 m ($\bar{\chi}$= 0.79±0.25 g cm-3, n=4). Porosity ranges from 0.59 to 0.92 ($\bar{\chi}$=0.8±0.13). Degree of wetness for the soil pits ranges from 0.9-1.0, except for where a dip (~0.7-0.85) occurs in the third layers around 0.4-0.45 m depth. These slight fluctuations in saturation can be seen in Figure 5.22.

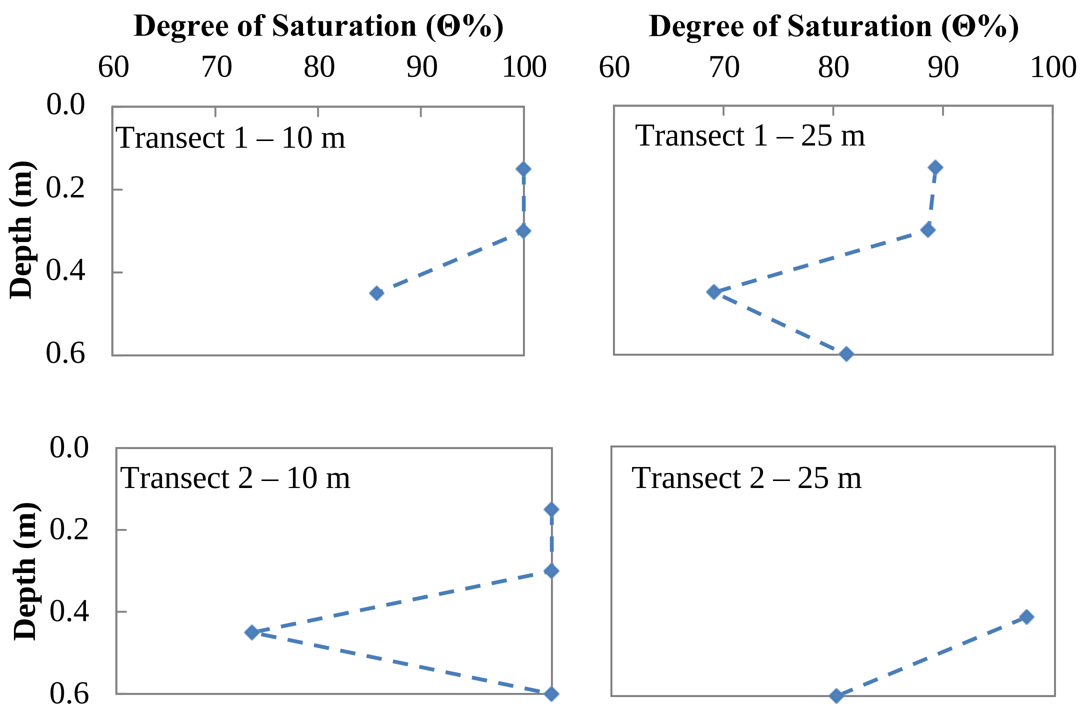

Figure 5.22: Degree of saturation (Θ%) at the drained wetland in Hvanneyri, for transect 1 – soil pits at 10 m, 25 m and transect 2 – soil pits at 10 m, 25 m.

5.4.1.1 Grain size analyses

The dry sieve samples (n=2) at the University range from $\bar{\chi}$ = 678 and 710 µm. Along the first transect, these are at 0.3-0.45 depth at 10 m and 0.15 to 0.3 at 25 m. Both samples are poorly sorted and very coarse sand, while the 10 m pit also contains very fine gravelly sizes (19.8%).

The 10 m sample is symmetrical and platykurtic, and the 25 m sample is very fine skewed and mesokurtic.

5.4.1.2 Loss-on-Ignition

A frequency histogram for LOI shows that of the 11 samples tested, 10 of the samples lost greater than 20% of their weight in organic matter, verifying their classification as Histosols (Figure 5.23) as described in Arnalds et al. (2016). For the top half of all the soil pits (0.0 to 0.3 m), there is a higher percentage of organic matter (60-70%) than further down in the soil profile (0.4-0.5 m: 50-53%).

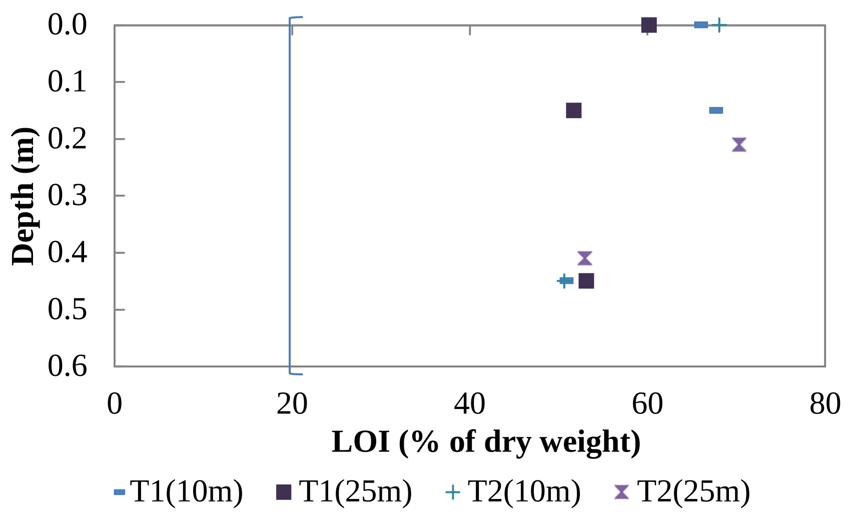

Figure 5.23: Scatterplot of Loss-on-Ignition in Hvanneyri drained wetland for both soil pits on transects 1 and 3, and transect 2 (25 m) at respective depths. Blue bracket indicates the 12% C upper limit for Gleyic Andisols (Arnalds et al. 2016).

5.4.2 Soil Moisture

Along transects the impact of ditch drawdown on soil moisture levels was up to 5 m (Figure 5.24). Soil moisture dropped off toward the end of transects (20-25 m distance) where there were some mosses present. Figure 5.25 shows the undisturbed transect to the west, which featured hummocky ground and some mosses atop thufur (refer back to Fig. 1.1).

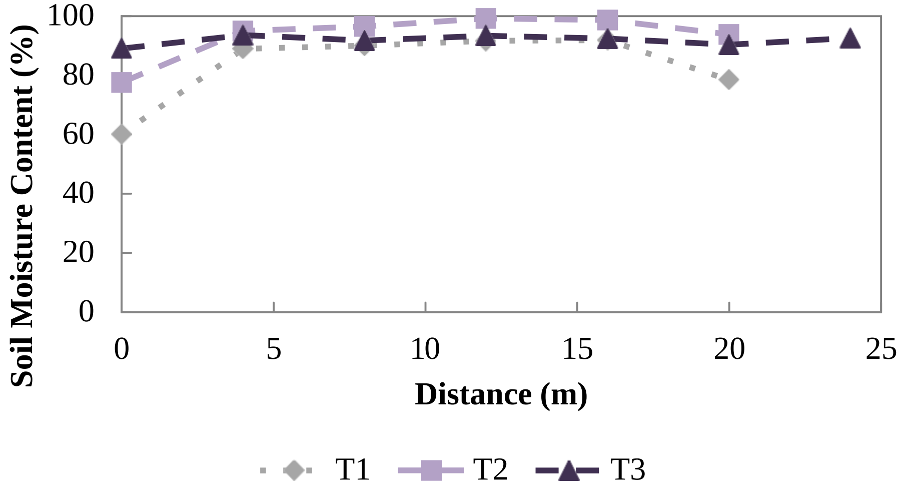

Figure 5.24: Near surface soil moisture (θ%) at Hvanneyri drained wetland starting from 0 m (ditch) to 20 m (interior), for transects 1, 2, and 3 (T1, T2, T3).

Student's t-test results showed a significant difference in soil moisture between the two patches ($p<0.05$) when comparing values for up to 20 m distance, indicating that the undisturbed wetland was wetter than the drained patch.

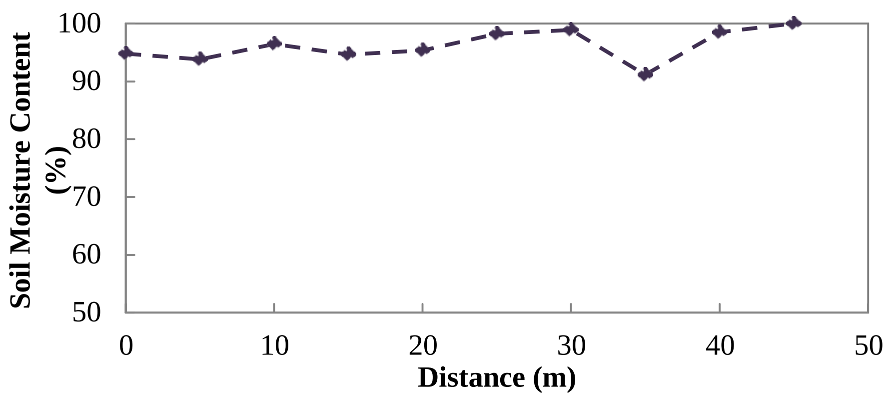

Figure 5.25: Near surface soil moisture (θ%) at Hvanneyri undisturbed wetland starting from the interior of the patch from 0 to 50 m, for one transect .

Volumetric water content ranged from 49 to 100%, with the majority saturated (100%) (82±16%, n=15). These lab moisture contents are found in Figure 5.26. Soil moisture results at depth are ~80% to 100%, except for one layer at 10 m (transect 1) which was 49%. The soil pits show a drop in moisture content at 0.3 m depth in comparison to the upper sections. The exception is for transect 2 at 10 m, where saturation increases in the bottom 15 cm.

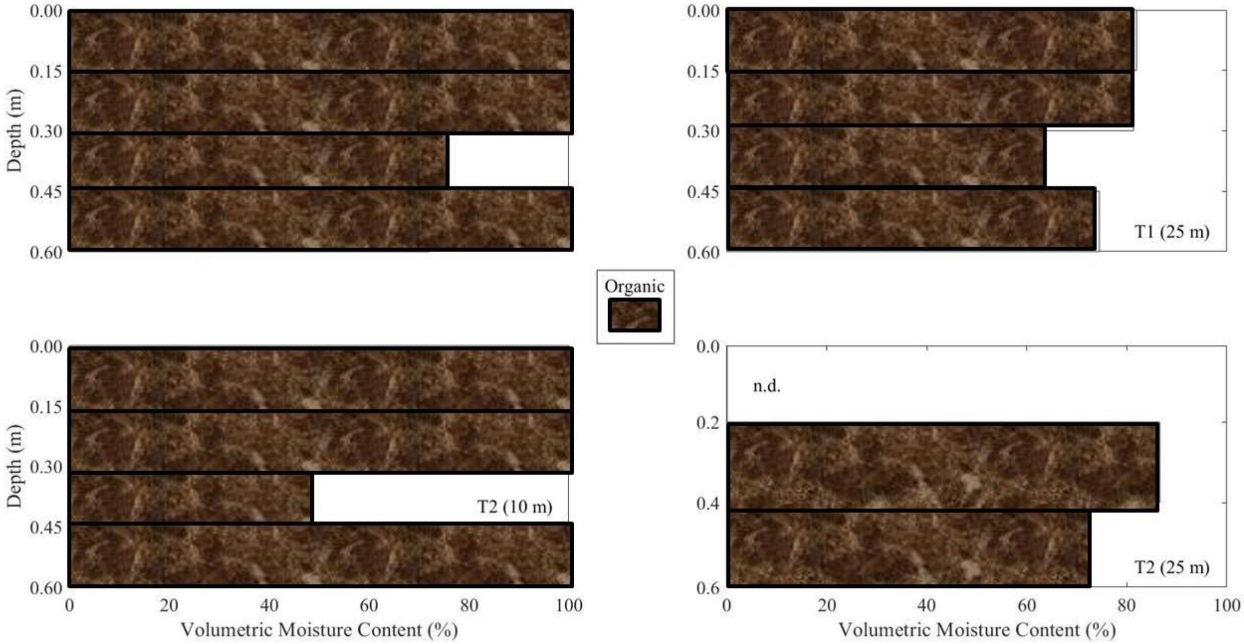

Figure 5.26: Volumetric soil moisture content (%) was determined in lab for the Hvanneyri drained wetland based on samples obtained in the field. Materials are classified as organic. Note that the y-axes differ. N.d. indicates no data.

5.4.3 Infiltration Rates

Final infiltration rates range from 0.02 to 0.07 mm s^{-1}. Infiltration tests (n=2) yielded maximum infiltration rates of 0.03 mm s^{-1} and 0.37 mm s^{-1}. For the first test (see Figure 5.27), the initial (f_0) infiltration capacity was 0.37 mm s^{-1}, the constant (f_c) capacity was 0.07 mm s^{-1}, and the k-constant value was graphically derived at 0.38. After 10 minutes during the first test, it was clear that the surface reached a constant capacity, although water continued to accumulate in the soil at a steady rate. Final cumulative infiltration at the end of the 2.5 hour long test was 744 mm of water. The second test (data not shown) infiltrated only 112 mm of water over the 62 minutes of test time, while fluctuating between 1-2 mm min^{-1}.

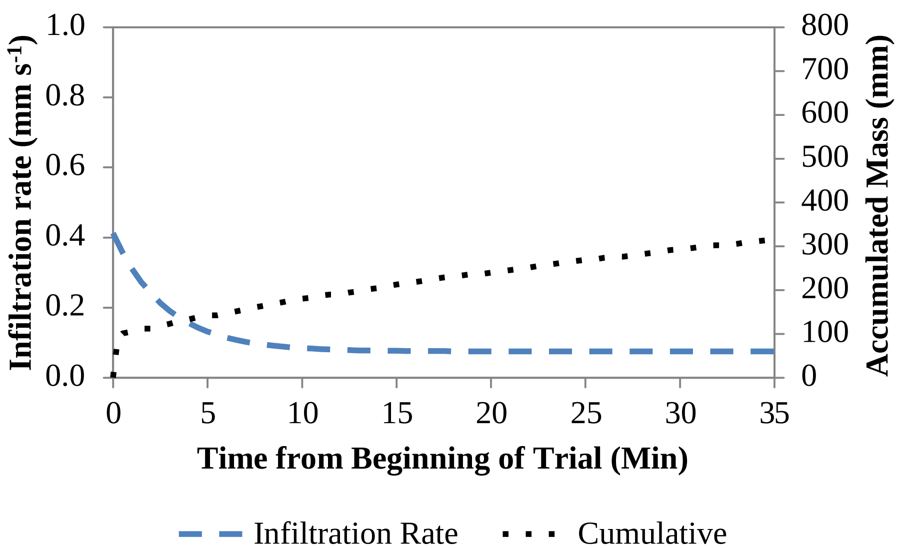

Figure 5.27: Trial 1 infiltration curve (mm s^{-1}, blue dashed line) and cumulative infiltration (mm, black dotted line) shown at the Agricultural University of Iceland near transect 1 (drained).

5.4.4 Surface Albedo

At the grounds on the Agricultural University of Iceland (AUI), surface albedo was lower in the undisturbed wetland than in the drained wetland. Albedo estimates ranged from 0.29 to 0.36 across three transects in the drained patch typical of vegetated surfaces (Oke 2002), with an average of 0.33 (n=6 for transects, n=18 total) (see Figure 5.28). Albedo estimates ranged from 0.19 to 0.32 across the intact wetland, with a lower average of 0.27 (n=11). Analysis of variance (ANOVA) between the albedo transect measurements in the drained patch at Hvanneyri and the undisturbed wetland, for the first 20 m, showed a statistically significant result of $p < 0.001$, indicating that the drained patch had a higher surface reflectance. There was no significant difference in surface albedo within the drained transects, or with distance from the ditch. It should be noted that the transects in the undisturbed wetland were taken in the middle of the area, which may additionally explain why there is no significance with distance.

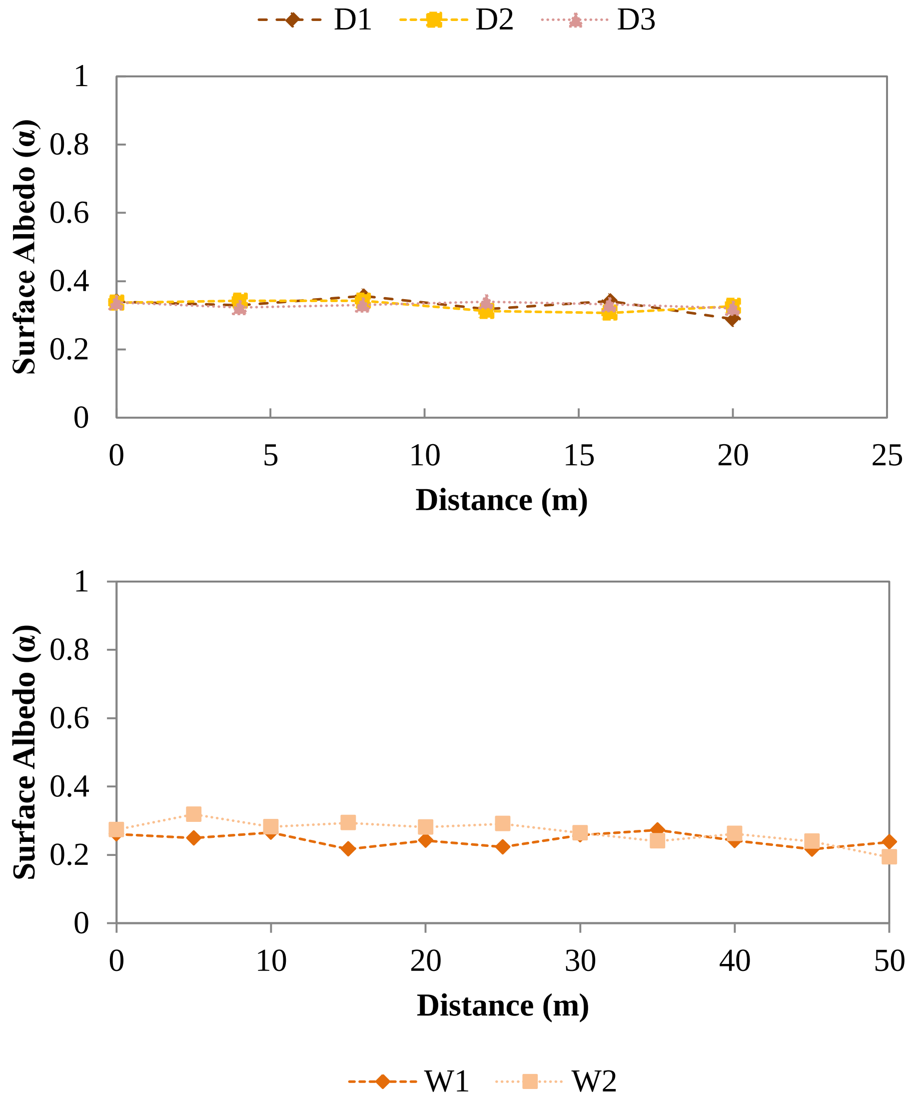

Figure 5.28: Albedo measurements along transects at Hvanneyri for transects 1, 2, and 3 (D1, D2, D3), starting from 0 m (ditch) to 25 m (interior to fence) at the drained patch (a); and for transects 1 and 2 (W1, W2), starting from the interior of the patch from 0 to 50 m, at the undisturbed wetland (b). Note that the x-axes vary.

5.5 Study Site Comparisons

In this section, comparisons in soil texture, soil moisture information, infiltration, and surface conditions are made across study sites. This includes any statistical tests run between more than one site and descriptions of the varying conditions for sites.

5.5.1 Soil Comparisons

Loss-on-Ignition results between the Þúfa and the Prestbakki drained wetlands were not statistically significant. LOI results from the Agricultural University of Iceland were abnormally distributed, and thus, not included. In the south (Þúfa/Prestbakki) the LOI means were similar at 15.8% and 17.4%. At the AUI, high porosity and low bulk density estimates fall within previously determined values (Arnalds et al. 2016) except for at 10 m on transect 2. LOI results also show the previously determined organic content results in wetland soils for the Histosols (1/11 >20% C) and Histic Andisols (15/19 >12, <20% C, one layer not shown), but not for Gleyic Andisols (2/11 <12%, with one horizon 12.6%). This indicates there was a higher organic content in Gleyic Andisol soils than that found by Arnalds et al. (2016).

5.5.2 Near Surface Moisture at All Study Sites

Looking at frequency histograms of all the drained sites together (Figure 5.29), a greater variation in soil moisture content is seen at Prestbakki that at the other 2 sites. Þúfa and the AUI histograms lean towards the right, whereas Prestbakki has more fluctuations in its distribution.

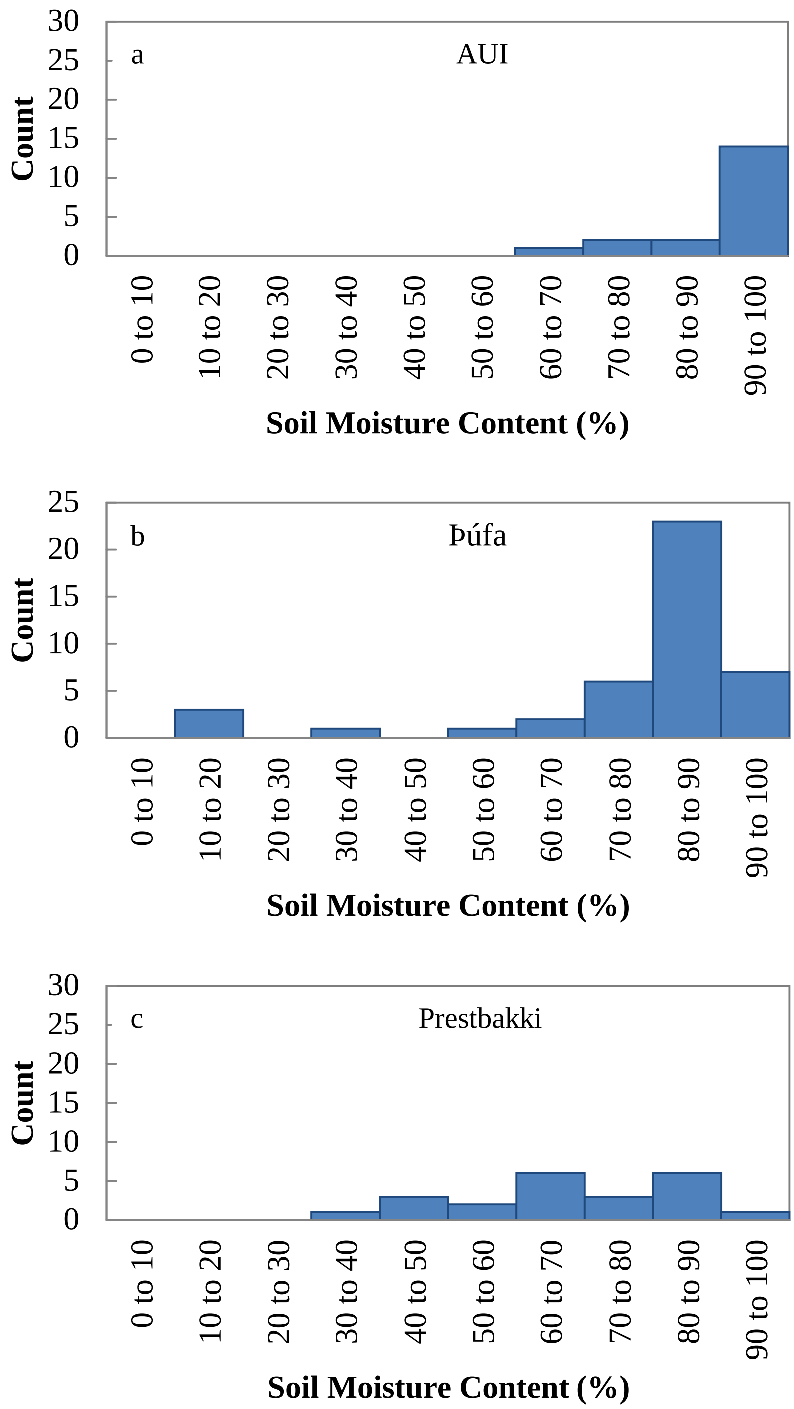

Figure 5.29: Frequency distribution of near-surface soil moisture at each drained wetland site: Agricultural University of Iceland (a), Þúfa (b), and Prestbakki (c).

The other two sites show that they are more right skewed towards high saturation in the 80-100% range. The maximum near-surface soil moisture content at all sites is comparable, while the minimums vary (Table 5). There is a greater standard deviation at the Þúfa and Prestbakki farms, likely from their larger sample sizes.

Table 5: Summary table of near-surface soil moisture ranges for drained and undisturbed wetland transects in western and southern Iceland (n = sample size, $\bar{\chi}$ = mean, σ = standard deviation).

Site	Disturbed (Drained) Patch					Undisturbed (Intact) Patch				
	Min	Max	$\bar{\chi}$	σ	n	Min	Max	$\bar{\chi}$	σ	n
Agricultural University of Iceland	60	99	90	9	19	60	100	93	11	11
Þúfa	14	99	82	15	124	48	100	87	18	11*
Prestbakki	39	95	69	16	22	55	100	92	15	23

*Soil moisture values for Þúfa undisturbed wetland obtained through lab testing.

Two-way Analysis of Variance (ANOVA) was conducted to determine if there were significant differences between near-surface soil moisture at the different sites, and if these differences were related to transect or related to distance from the drainage ditch. The differences found were between drained patches and also between undisturbed wetlands. Results indicated that near surface soil moisture was significantly different between some drained sites. A two-way ANOVA showed there was no difference in soil moisture at Þúfa or Prestbakki between sites, however, the difference was significant when looking at distance from ditch ($p < 0.05$). Overall, comparing all three sites together gave a $p < 0.05$ between transects, with no significance found for distance from drainage ditches.

Student's t-test results indicated significant differences in volumetric near-surface soil moisture content between Prestbakki drained patch and the AUI (p-value < 0.001), although a two-way ANOVA did not show a significant difference between transects, but did with distance

($p < 0.05$). A student's t-test between the Þúfa drained wetland and the AUI drained wetland gave a p-value < 0.005.

Cumulative infiltration was highest at Prestbakki (789 mm), next at Hvanneyri (744 mm), and lastly at Þúfa (172 mm) of water (Figure 5.30). Ground surface ponding was observed at the 50 m mark near transect 1 at Prestbakki, and water pooling was observed in soil pits at 10 m and 25 m from the drainage ditch. At 10 m, pooling was approximately 4 and 8 cm from the bottom of the pit, while at 25 m pooling was ~6-7 cm in depth. At Þúfa, pooling was observed at 10 m from the ditch and was about 7-9 cm depth. There was no pooling at 25 m from the ditch. When comparing cumulative infiltration curves between Hvanneyri, Prestbakki, it is clear that there is not much difference in infiltration at these sites. The occurrence of tephra in the soil column does not make a major difference in rates, at least during wet conditions. In Table 6, the different infiltration final rates, capacities, and decay rates for the infiltration curves are shown.

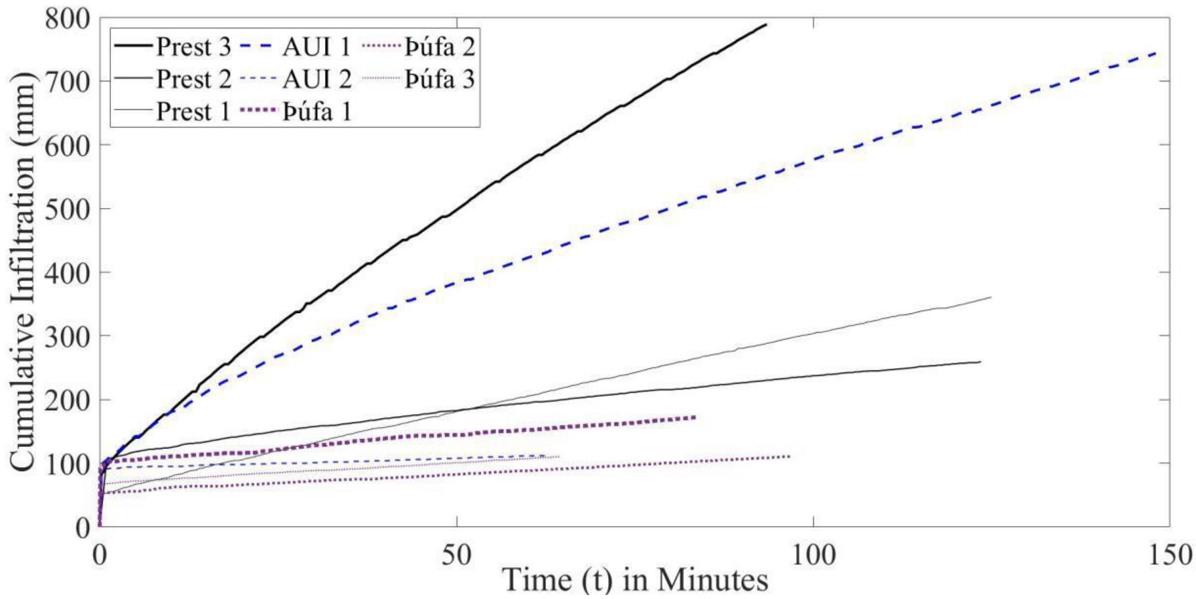

Figure 5.30: Cumulative infiltration amounts for eight (8) of the ten (10) trials run; the other two led to ponding (1 at Prestbakki, 1 at a separate western site; data not shown). Tests near Kirkjubæjarklaustur are black, tests at the Agricultural University of Iceland are blue, and tests at Þúfa are purple.

Table 6: Related infiltration ranges and rates for various sites, not limited to this study. Sites not in Iceland are indicated.

Location (Lat/Long)		Infiltration (mm s^{-1}) capacity: maximum range	Infiltration (mm s^{-1}) capacity: final	decay rate (k)
AUI	*(64°33'37"N / 21°45'23"W)*	0.03 – 0.37	0.02 – 0.05	0.38
Þúfa	*(63°58'51"N / 20°17'06"W)*	0.03 – 0.53	0.006 – 0.03	0.30
Prestbakki	*(63°49'51"N / 18°1'59"W)*	0.13 – 0.37	0.02 – 0.09	0.72
Gunnarsholt[1]	*(63°52'N / 20°12'W; ~100 m a.s.l.)*		0.03 – 0.1	
Hafnarskogur[1]	*(64°30'N / 21°55'W; ~30 m a.s.l.)*		0.008 – 0.03	
Central America[2]			0.02 – 0.06	
Tenerife (Canary Islands, Macaronesia)[3]				
	vitric andisols		0.08 – 0.12	
	nonvitric andisols		0.03 – 0.14	

[1]Orradottir, 2008
[2]Forsythe, 1975
[3]Neris et al., 2013

5.5.3 Surface Albedo

In the comparisons between all 3 sites, there were no significant differences in the albedo between drained patches or between the undisturbed wetland patches. The only differences observed were at Prestbakki drained wetland, which had a slightly higher maximum (0.55), and at the undisturbed patch in Þúfa, which has a lower minimum (0.12). These differences can be seen in Table 7.

Table 7: Summary table of albedo ranges for drained and undisturbed wetland transects in western and southern Iceland (n = sample size, $\bar{\chi}$ = mean, σ = standard deviation).

Site	Disturbed (Drained) Patch					Undisturbed (Intact) Patch				
	Min	Max	$\bar{x}$	σ	n	Min	Max	$\bar{x}$	σ	n
Agricultural University of Iceland	0.3	0.4	0.33	0.02	18	0.2	0.3	0.26	0.03	22
Þúfa	0.2	0.4	0.34	0.02	122	0.1	0.3	0.30	0.05	11
Prestbakki	0.2	0.6	0.34	0.06	22	0.2	0.3	0.25	0.04	13

CHAPTER SIX: DISCUSSION

6.1 Variation in Soil Moisture and Surface Albedo

6.1.1 Soil Moisture Regime

Hypothesis: Do we see a difference in soil moisture content between wetlands of different soil types?

Near-surface Soil Moisture

Soil moisture is affected by local topography, vegetation, and antecedent moisture conditions. Spatially, soil moisture varies due to changes in microtopography, or over large scales based on water storage inputs/outputs, and requires greater replications within pit and mound topography for representation (Anderson and Davis 2013, Woo 2012).

Soil moisture was elevated owing to a wet May, which had a recorded precipitation in Reykjavík of 129 mm for the month (Iceland Monitor 2018). High antecedent moisture conditions contributed to a broader distribution of soil moisture frequency in the southeast at Prestbakki drained wetland: this was likely due to greater volcanic ash content, since soil moisture was elevated at the drained patches in Þúfa and the Agricultural University of Iceland ($\theta_{\bar{\chi}}$=>80%). Higher variation in soil moisture content near Kirkjubæjarklauster may be attributed to greater amounts of observed tephra in Gleyed Andisols with depth/surface, although from our lab tests there is no evidence of a change in organic content. Near surface soil moisture here had larger soil moisture means and ranges than restored peatlands ($\theta_{\bar{\chi}}$=0.77-0.8, range 0.31-0.47) or fields with blocked drainage ditches (θ=0.77-0.78, range 0.51-0.74) in Quebec from June to July (Petrone et al. 2004). Conversely, they were also higher in other arctic soils; the near surface soils of dry tundra in northeast Greenland were not highly saturated (θ_{dry} = 5-25% θ_{moist} = 25-55% – Jørgensen et al. 2014), while in Alaskan wet meadow tundra/taiga, gravimetric water content (θ_g) ranged from ~0.7-4.5 g g^{-1} in the tundra, and ~0.5-3 g g^{-1} in the taiga (Gulledge and

Schimel 1998), while in our Icelandic wetland soils the southern sites ranged from 1-3 g g^{-1}, and 2-4 g g^{-1} for Histosols (data not included).

Vertical Soil Moisture

Changes in saturation at depth are controlled by soil characteristics. The decreasing degree of saturation in the lower layers of the Histosol soils is most likely due to continuing (although slightly decreased) elevated amounts of organic matter since at lower levels organics tend to lose porosity, which limits percolation (Labadz et al. 2010). This decrease was also found in a sampled site of different parent materials with similar organic content (not included in these analyses). Conversely, at Prestbakki, the lower degree of wetness in the topsoil layer appears related to a ratio of lower volumetric soil moisture content than porosity at that depth. In Þúfa, on transect 4 at 25 m, the drop in saturation can be accounted for by soil texture, with a lower clay/silt than the above silt loam, so less water would be retained (see Fig. 5.11). Additionally, while these horizons with drops in degree of saturation are composed of organic/aeolian, organic, and tephra/organic materials, respectively, the soils here do not differ much in organic content than at Prestbakki, which did not show drops in wetness. For each of the horizons in Þúfa, they all are above, below, or contain volcanic ash. High porosity in Andisols contributes to drainage, such that gravitational drainage would likely affect soil water retention in these horizons, contributing to lower water content over porosity. For the other transects, they could be less affected by gravitational drainage because of the highly water retentive properties of Andisols.

Soil moisture between sites in southern Iceland is similar, which is perhaps reflected in that the moisture conditions are similar with regard to precipitation in the south, although Kirkjubæjarklauster does receive more rainfall being on the coast than Þúfa region (Climatological Data, IMO 2012, data not shown). Distance from the ditches being significant is related to the changes in organic content between the two sites, with thicker tephra layers at Prestbakki, but also because of the variation of frequencies in moisture there compared to saturated soils in the Þúfa site. Additionally, the significant difference in near-surface soil moisture between the drained and undisturbed sites at the AUI could be due to the flat surface in the drained patch compared to the thufur present in the undisturbed patch (Figs 1.1, 4.3f), since local topography/vegetation control soil moisture along with soil characteristics (Neris et al. 2012, Aalto et al. 2013, Anderson and Davis 2013). The different soil moisture frequencies at Prestbakki (θ=69 the lowest average, with 14/22 measurements below 80%), along with further drawdown to 10 m distance from the drainage ditch, rather than 5 m at the other 2 sites, contribute to the higher rate of infiltration. Although infiltration does not change much compared to the AUI site, Prestbakki had a higher final rate of infiltration than the other locations and greater cumulative infiltration.

6.1.2 Surface Albedo

Hypothesis: Do we see lower albedo values in the undisturbed wetland patches and higher values in the drained patches? Is there any notable difference between different soil types?

Variations in albedo can alter the thermal climate of soils through differing radiation receipts, which then affects soil moisture due to evapotranspiration changes (Oke 2002). Albedo is also altered due to the presence of moisture, while the albedo of peat soils is low compared to other soils (Oke 2002). Thus, albedo can be used to look at soil moisture variation: dry surfaces tend to have higher reflectivity and wetter ground shows lower reflectivity (Oke 2002). Changes in vegetation alter surface albedo and evapotranspiration; for example, increasing shrub dominance leads to a decline in albedo (Oke 2002, Blok et al. 2011).

Overall, the albedo transects follow relatively similar patterns as the soil moisture transects, but are not significant between locations for either drained wetlands or undisturbed wetlands. Also, they vary less than soil moisture (for examples, see: Figs. 5.14b and 5.20 (T1); Figs. 5.5 and 5.10a (compare T1 transects), and Table 7). Here, the main factors affecting surface albedo are water content and vegetation cover. Bare ground was mostly absent. Neither of these variables has a large spectral range, so it makes sense that neither do transects with their small standard deviations. Water content will lower an object's albedo, likely explaining why the undisturbed wetlands show a lower albedo than the drained patches, since they are more saturated. The wet soil affects the reflectance of those surfaces and contributes to these changes. However, because the surfaces are mainly grasses, the range of albedo values that could be measured are still small, within around 10-15% (natural vegetation <1 m height α=0.18-0.25) (Oke 2002). Elsewhere, grassland sites in Saskatoon (52°N) and Meadow Lake (54°N), Saskachewan albedos ranged from $\alpha \approx$ 0.15-0.25 in summer months (Betts and Ball 1997). Summer albedo in Troms, Norway (69°N) for graminoids lower than 15 cm height, and graminoids/dwarf shrubs below 1 m in height averaged $\alpha \approx$ 0.14-0.17, with up to ~ +0.04 or -0.03 difference in averages (te Beest et al. 2016).

Regionally, the significance between drained and undisturbed wetlands at Þúfa and separately, Prestbakki, could be due to landscape differences. The undisturbed wetland at Prestbakki had steep slopes, which would alter both moisture and radiation receipts. Thufur/biomass density of grasses were present and are the likely cause of observed surface ponding at the undisturbed area in Þúfa. These landscape cause differences in the angle of incidence, and short grasses under wet conditions reduce albedo (Eltahir 1998). At the Þúfa drained patch, transects which were significantly different indicate that it is necessary to sample surface albedo more frequently, as there is greater spatial variability. Significance differences between the undisturbed and drained patches at the AUI arises from water contents between 15-

20 m at the undisturbed wetland ($\theta_{undisturbed}$=0.22-0.29 vs. $\theta_{drained}$=0.29-0.24) and changes in vegetation (darker green in the undisturbed wetland). Within the drained wetland plant cover was altered, where more heightened grazing might have modified the angles of incidence here (Oke 2002). Referring back to the hypothesis for this study, we can say that undisturbed wetland albedo is lower than drained wetland albedo in all cases. However, there were no significant differences comparing between soil types at either drained or undrained saturation levels, suggesting soil type does not affect the surface albedo of the sampled wetlands.

Other studies of wetland albedo show variation within areas, with overall results closer to the albedo of the undisturbed wetland patches. In subarctic coastal marshes in the Hudson Bay Lowlands, mean albedo in the pregrowing season was 0.11 for the inner marsh, and increased in summer to 0.19 as a result of vegetation growth (Lafleur et al. 1987). During inundation where standing water and saturated soils are the dominant surface cover, albedo tends to be low and differs less (Lafleur et al. 1987, Sumner et al. 2011). Changes in albedo are an important factor when assessing the climate effects of land use change, since climate warming or afforestation could affect the albedo of these landscapes. For Finnish undrained and drained peatlands, mean July albedo for an open cultivated peatland (60°54′N) was 0.24, and lower in a drained pine forest at similar latitude (α = 0.12), while further north (67-9°N) saw a lesser difference in albedo (α – open undrained fen = 0.14, α - pine forest on mineral soil = 0.11) (Lohila et al. 2010). A warming effect was most noticeably different in spring with between undrained and drained, however, this effect would be smaller in a warmer climate (Lohila et al. 2010).

6.2 Variation in Soil Infiltration

Hypothesis: Do we see a difference in infiltration rates between wetlands of different soil types (higher in tephra—south, than in peat—west)?

Infiltration is affected by changes in soil texture, topography, soil moisture, and vegetation (Brady and Weil 2010, Dingman 2015). Sandy soils typically exhibit higher infiltration rates than silty/clayey soils, due to pore space and adhesion/cohesion properties of soil-water interactions. Volcanic soils exhibit a large range of infiltration rates due to high water retention and organic content (Arnalds et al. 2016).

Infiltration rates for drained patches were similar to other High Arctic undrained wetland patches and Low Arctic unfrozen Andisols (Woo and Young 1997; Orradottir et al. 2008). Infiltration rates in the drained wetland patches of the south (Þúfa) vary little from the rates of sandy loam type tephra and mixed materials compared to wetland soils in the west (AUI).

Low soil porosity and limited percolation can affect infiltration at the surface since soils can reach saturated hydraulic conductivity quickly and are more likely to become saturated during rain events (Dingman 2015). The lower bulk densities in the organic layers (D_b=0.6-1 g cm^{-3}) as well as the coarse silt/fine sand soils (Φ=0.6-0.8) at the Þúfa drained wetland likely explain their lower infiltration rates in comparison to Prestbakki. At the Þúfa drained wetland, silt loam soils in soil pits (except for at 17 cm depth—transect 1, 25 m, and 0.5 m depth—transect 3, 10 m) would restrict infiltration somewhat, while at Prestbakki and Hvanneyri, soils have at least 40% sand in soil pits except for at 0.1 m (transect 2, 10 m) and 0.3-4 m at 10 m in Hvanneyri (transect 2). Greater drawdown up to 10 m at Prestbakki could also allow for higher infiltration than Þúfa.

Rate of infiltration decay was greater at Prestbakki than the other two sites, and this could be due to variation in soil type (more tephra layers) as well as the overall higher bulk densities which would lower porosity (see Appendix B). At AUI, however, no surface ponding or below ground pooling occurred, perhaps implying a lower water table. The wetland there was also flatter than in the south, and the drainage ditch was quite shallow in comparison. Surface ponding at Prestbakki was topography driven (shallow slopes to the interior from the ditch). The pooling in soil pits that occurred in the two southern sites was perhaps saturation from below, because we did not experience much rainfall (<1 mm) over a day. Water storage capacity indicates that for Prestbakki transect 2, the capacity (10 m) was 4 cm out of 6 cm depth, while that pit had 4 cm pooling, so it was at capacity. The next pit (25 m) was not at capacity, but the horizons here were all at 100% degree of saturation. This is the same with transect 3, which had 8 and 6 cm of pooling at 10 and 25 m respectively, which have water storage capacities in the bottom horizons of 8/10 cm and 5/10 cm; these layers were also at saturation. At Þúfa, only the 10 m pits at transects 3 and 4 experienced pooling (9 cm pooling and 10/14 cm capacity for T3; 7 cm pooling and 10/15 cm capacity for T4). These layers are also at 100% saturation. At Þúfa this could also be aided by a loss in elevation of 4 meters from transect 3 to transect 4, westwards.

The occurrence of tephra has limited impact on infiltration, at least during wet conditions. There was no preferential flow observed here, either, as we did not encounter macropores whilst digging, so similar rates must be due to the similarities in soil texture between the sites, which were mostly silty/loamy soils. At Þúfa, the cumulative infiltration rate only had a maximum of <200 mm of water, much less than the other sites (~800 mm). The soil at the drained patch in Þúfa consistently showed tephra present around 0.2-0.4 m depth; its thickness was thinner than at Prestbakki. There was also more silt present than the sand sized particles at Prestbakki. At

Prestbakki, tephra horizons were 5-6 cm thick and occurred more frequently, potentially allowing for less water percolation further into the patch considering the mixture of materials there. However, the ditch likely affected infiltration at Prestbakki, because the ditch itself and near to the ditch showed signs of erosion, which would explain the higher infiltration rate.

6.3 Climate and Impacts

Prior research suggests that in Iceland volcanic eruptions could become more frequent in the future due to isostatic rebound which would lead to aeolian dust storms more often, and disrupt surface hydrological processes (Ágústtsdóttir 2015, Compton et al. 2015). These aerosols would reduce the albedo of the landscape and affect net solar radiation, impacting the local energy balances by increasing radiation absorption (Vernier et al. 2016, Wittman et al. 2017, Skiles et al. 2019). Lowered albedo means less energy would be reflected and more absorbed; as a result, more available surface energy would warm the air and increase the rate of evaporation. Higher evaporation rates can lead to increased infiltration rates and lower the surface water content of drained wetlands. Increased air temperatures could aid in arctic greening, which would further reduce albedo (Blok et al. 2011).

Increased precipitation can affect the overall water balance of the wetlands with increased ponding and pooling as seen in both the drained and undisturbed wetlands, even with the infiltration capacities measured at these sites. The high infiltration rates in these areas suggest minimal runoff especially from precipitation day events (Orradottir et al. 2008). At Prestbakki, this lack of runoff leads to surface ponding at surface depressions in the interior of the drained wetland. However, with precipitation likely increasing in coming years (Bintanja and Selten 2014), if the potential evaporation is lower than the amount of rainfall (especially in Kirkjubaejarklauster, where summer precipitation can exceed 100 mm a month), this would lead to more frequent saturation and runoff (Delworth and Manabe 1989), along with animal grazing and winter frost conditions which already encourage overland flow (Orrodottir et al. 2008; Arnalds et al. 2016).

Infiltration and soil moisture will likely change in the future as the climate changes. In Iceland, most models show an increased rise in precipitation (Gosseling 2017). An increase could lead to more surface ponding and a rise in the water table in wetlands. If evaporation does not keep up with precipitation, it could lead to runoff. However, our study is focused on the surface hydrology of wetlands and does not include climate data; as such, the limited data do not inform us about climate change implications.

6.4 Policy Implications

The Ministry of Agriculture in Iceland started an effort to restore some drained wetlands. From 1996 to 1997, two wetlands were chosen as restoration projects to see if raising the water table could achieve a similar wetland habitat to previous conditions. Hestur a 35 ha sloping mire (SW Iceland), was rewet in 1996 by blocking the ditches, which raised the water table, but resulted in a slower response from vegetation (Magnússon 1998). In southern Iceland, at Kolavatn, a 7 ha shallow, drained lake in a mire area (S Iceland), an outlet was filled up in 1997. Researchers found that the water levels consistently rose, and waterfowl began to visit, where there had not been any present before (Magnússon 1998; Biological Diversity 2001). Restoration is considered favorable, although it can be difficult. It would likely be easier in the many wetlands which ended up unused after drainage (Magnússon 1998; Why Iceland is filling in ditches 2018, https://www.ruv.is/frett/why-iceland-is-filling-in-ditches).

Of course, filling in ditches is not as easy as it sounds – Icelandic peat is not as good of a carbon sink as other peat soils because of frequent deposition of aeolian particulates and volcanic ash. However, restoration is considered favorable because most drained mires are as yet unused or have not been excavated, with some natural vegetation (Biological Diversity 2001). Wetland restoration in Iceland has been motivated by nature conservation, as well as to offset construction damages. International policy and climate change is increasingly factoring in carbon sequestration in vegetation and soil, with a growing interest in curbing Greenhouse gas emissions from drained wetlands (Aradóttir et al. 2013). Currently, however, policy is not an important driver of ecological restoration in Iceland (Aradóttir et al. 2013).

These results may affect policy decisions in showcasing the importance of wetland processes to local ecological systems. Knowing some of the characteristics of surface hydrology in drained wetlands helps provide information toward a better understanding of local wetlands. Restoring the drained wetlands would help reduce Iceland's Greenhouse gas emissions. It can as well provide new or restored habitats for migratory birds, but large-scale restoration efforts would be costly.

CHAPTER SEVEN: CONCLUSIONS

7.1 Limitations of Study

As with all scientific inquiry, this study was not without complications. Limited funds only allowed for two weeks of data collection rather than the 3-4 weeks planned. As an American, I was not able to apply for NSTP funding, which could have extended my stay. The CUPE 3903 strike also affected my timeline somewhat by pushing beginning of the study into June instead of May, meaning that conditions were not as expected. The aforementioned antecedent moisture conditions from May of course produced results different than I had anticipated and altered the sampling design (i.e. infiltration tests were made near ditches for drained sites). Study sites selected were on private lands, logistics and safety issues prevented data collection for several previously identified sampling locations. Mode of transportation was too big to allow access to many rural sites, thus, only a few study sites could be visited. This, in turn, led to a re-shuffling of how to sample the sites, although sample sizes were small nonetheless. A small sample sizes made for limited statistical tests than those originally planned for. Because not all data were normally distributed, some soil moisture results could not be statistically tested. Human error in infiltration runs and soil sample analysis affected some point measurements.

7.2 Conclusions

This study highlights human modification on coastal Icelandic inland wetlands, which were altered by drainage in the latter half of the 20th Century. Studies of wetland hydrological processes in Iceland are limited except Scheffel (2018) and Orradottir et al. (2008)'s studies on Andosols in gravelly sand and wetland soils. Infiltration rates and soil moisture/albedo along transects were collected to assess differences between wetland soil types and the hydrological impacts from ditching. Referring back to the study hypotheses for this project, the results can be summarized as follows.

1) Higher bulk density in mineral soils of the Andisols, in comparison to organic layers and Histosols, with corresponding lower infiltration rates: Half the samples tested for the Agricultural University of Iceland fell within the expected Db range, while for Andisols, HA had slighty higher bulk denities, and the minimum to average densities for both HA/GA fell within range.

2) Higher soil moisture content in saturated wetlands compared to the drained patches; in terms of reflectance, undisturbed wetland soil will have a low albedo, while drier patches will have higher albedos: soil moisture was significantly higher in undisturbed wetlands in the southeast and west but not near Selfoss, and also varies the most near Kirkjubæjarklauster for both drained and undisturbed conditions. As expected, albedo is lower in undisturbed conditions than it is in drained conditions, even with the excessive precipitation in 2018.

3) Higher infiltration rates will occur in the Andisol soils (sandy) compared to the Histosols (peat): soil composition differs between Histosols and Andisols, however, infiltration rates and estimated k_{sat} values are similar. Southern Iceland trials had a higher f_0 (Histic Andisols) and f_c (Gleyic Andisols), with Histosol rates falling in between.

Soil moisture results imply that under wet conditions, the organic soils contain more water overall, with less variation, than in the south/southeast. In wetlands, evidence suggests there is limited tephra influence on infiltration compared to gravelly sandy soils (Scheffel 2018), while infiltration rate and capacity rates falls within the range of Andisols previously tested in Iceland (Orradottir et al. 2008).

7.3 Significance and Implications

This project helps to fill in the gap about surface hydrology of Icelandic inland wetland patches, for which we have ecological and biological information to inform these processes. This research also gives current landowners some data about the wetland patches mainly used for grazing or left alone on their land. These results could help inform policy makers as they look into creating and amending future policies with climate warming in mind. Changes in land use and climate will impact local surface hydrological processes on these wetland patches. As previously noted, these areas are distinct and important ecosystems for the habitat and possible survival for at minimum 20 migratory wader species. They also provide important functions for local climate patterns as regulation, through water storage. Acting as carbon sinks, Icelandic wetlands are in danger from afforestation and construction, among other potential disturbances. Impacts from aerosols such as volcanic ash and aeolian distribution lead to specific processes that are unique to this region of the world, meaning that changes to these characteristics still have unforeseen results, such as their effects in a warming climate. Further information on the surface hydrologic features of Icelandic wetlands would provide clarity on processes in these habitats.

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APPENDICES

Appendix A: Soil Statistics Example

Grain size statistics were derived from the article and program of Blott and Pye 2001.

Shown below are the different formulas that the program runs using the using the Folk and Ward method (Figure A-1) (Blott and Pye 2001).

(d) Logarithmic (original) Folk and Ward (1957) graphical measures

Mean	Standard deviation	Skewness	Kurtosis
$M_Z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$	$\sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6{\cdot}6}$	$Sk_I = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)}$	$K_G = \frac{\phi_{95} - \phi_5}{2{\cdot}44(\phi_{75} - \phi_{25})}$

Sorting (σ_1)		Skewness (Sk_1)		Kurtosis (K_G)	
Very well sorted	<0·35	Very fine skewed	$^+$0·3 to $^+$1·0	Very platykurtic	<0·67
Well sorted	0·35–0·50	Fine skewed	$^+$0·1 to $^+$0·3	Platykurtic	0·67–0·90
Moderately well sorted	0·50–0·70	Symmetrical	$^+$0·1 to $^-$0·1	Mesokurtic	0·90–1·11
Moderately sorted	0·70–1·00	Coarse skewed	$^-$0·1 to $^-$0·3	Leptokurtic	1·11–1·50
Poorly sorted	1·00–2·00	Very coarse skewed	$^-$0·3 to $^-$1·0	Very leptokurtic	1·50–3·00
Very poorly sorted	2·00–4·00			Extremely leptokurtic	>3·00
Extremely poorly sorted	>4·00				

(e) Geometric (modified) Folk and Ward (1957) graphical measures

Mean	Standard deviation
$M_G = \exp \frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$	$\sigma_G = \exp\left(\frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6{\cdot}6}\right)$
Skewness	**Kurtosis**
$Sk_G = \frac{\ln P_{16} + \ln P_{84} - 2(\ln P_{50})}{2(\ln P_{84} - \ln P_{16})} + \frac{\ln P_5 + \ln P_{95} - 2(\ln P_{50})}{2(\ln P_{25} - \ln P_5)}$	$K_G = \frac{\ln P_5 - \ln P_{95}}{2{\cdot}44(\ln P_{25} - \ln P_{75})}$

Sorting (σ_G)		Skewness (Sk_G)		Kurtosis (K_G)	
Very well sorted	<1·27	Very fine skewed	$^-$0·3 to $^-$1·0	Very platykurtic	<0·67
Well sorted	1·27–1·41	Fine skewed	$^-$0·1 to $^-$0·3	Platykurtic	0·67–0·90
Moderately well sorted	1·41–1·62	Symmetrical	$^-$0·1 to $^+$0·1	Mesokurtic	0·90–1·11
Moderately sorted	1·62–2·00	Coarse skewed	$^+$0·1 to $^+$0·3	Leptokurtic	1·11–1·50
Poorly sorted	2·00–4·00	Very coarse skewed	$^+$0·3 to $^+$1·0	Very leptokurtic	1·50–3·00
Very poorly sorted	4·00–16·00			Extremely leptokurtic	>3·00
Extremely poorly sorted	>16·00				

Figure A-1: Formulae shown for original logarithmic Folk and Ward 1957 calculations for graphical derivation of descriptive statistics, and modified geometric calculations.

Appendix B: Soil Characteristic Tables

The tables below include supplementary soil characteristics for the drained patches at Prestbakki (Table 8), at Þúfa (Table 9), and the patch at the Agricultural University of Iceland (Table 10). These tables show horizon identifications, and the different characteristics tested for in lab: moisture contents, bulk density, texture, Loss-on-Ignition, and pH measurements. Also shown are some of the in-situ data: volumetric moisture gathered with the Theta probes and HOBO SmartSensor 10HS, and soil temperature data at depth. Soil pits are labeled as odd numbers = 10 m distance (1 = Transect 1, soil pit 10 m; 3 = transect 2, soil pit 10 m, 5 = transect 3, 10 m, and 7 = transect 4, 10 m), and even numbers = 25 m distance (2 = Transect 1, soil pit 25 m; 4 = transect 2, soil pit 25 m, 6 = transect 3, 25 m, and 8 = transect 4, 25 m). D stands for soil samples collected along the side of a ditch.

Table 8: Soil Information for pits at Prestbakki drained patch (Prestsbakkavegur road, Rte. 202).

Pit No.	Layer		Horizon Identification				1. Moisture Content			2. Bulk Density (g/cm3)			3. Texture (%)			4. LOI (% DW)	5. pH	6. Temp
	Depth (m)	*Thickness (cm)*	*Field*	*Master/ Sub*	*Color*	*Texture (USDA)*	*Lab (%)*	*Theta (%)*	*10HS (%)*	*Db*	*Poros.*	*Deg. Sat.*	*Sand*	*Silt*	*Clay*	*500°C*		*(°C)*
1	0	10	Top Soil		7.5YR 2.5/1		87	91	0.45	0.76	0.71	1					5.6	16
1	-0.1	6	Aeolian		10R 3/6		85	92	0.46	1.04	0.61	1				5.28	5.7	15
1	-0.16	9	Aeolian / Organic		2.5YR 2.5/1		100	90	0.47	0.58	0.78	1	43	57	0		5.2	14
1	-0.25	7	Tephra / Organic		GL1 2.5/N		100	90	0.50	0.57	0.78	1					5.5	13
1	-0.32	14	Organic		7.5YR 2.5/3		100	94	0.49	0.56	0.79	1					5.7	13
1	-0.46	6	Tephra		GL1 2.5/N		100	63	0.41	0.54	0.80	1					5.9	12
1	-0.52	8	Organic		7.5/YR 2.5/3		87	96	0.46	0.89	0.66	1					5.7	12
2	0	10	Top Soil	O	7.5YR 2.5/1	silt loam	100	42	0.46	0.72	0.73	1				17.83		11
2	-0.1	7	Organic		7.5YR 2.5/2		100	97	0.46	0.68	0.74	1				19.54		10
2	-0.17	6	Tephra / Organic	E	5YR 3/1	sandy loam	91	100	0.49	0.88	0.67	1				23.77		9
2	-0.23	37	Organic	Oe	10YR 2/2	silt loam	100	100	0.48	0.71	0.73	1	43	51				9
2			Tephra beyond 60 cm				84			1.00	0.62	1						
3	0	7	Top Soil		7.5YR 2.5/1		61	88	0.46	0.75	0.72	0.85					5.8	12.5
3	-0.07	10	Aeolian / Organic / Tephra	Eo	10R 3/1	silt	92	67	0.40	0.69	0.74	1	9	82			5.8	11
3	-0.17	10	Organic / Tephra		10YR 2/1		100	93	0.48	0.61	0.77	1					5.5	10.5
3	-0.27	7	Aeolian / Organic / Tephra		10R 3/1	sandy loam	100	92	0.47	0.64	0.76	1					6.2	10
3	-0.34	20	Organic	Oe	10 2.5/1	silt loam	71	85	0.46	0.89	0.67	1	43	56			6.3	9
3	-0.54	6	Tepra		GL1 2.5/N		87	81	0.48	0.92	0.65	1					6.2	9
4	0	5	Top Soil		7.5YR 2.5/1		100	80	0.45	0.68	0.74	1					5.8	14
4	-0.05	8	Aeolian / Organic / Tephra	Eo	5YR 3/2	sandy loam	74	91	0.45	1.12	0.58	1	55	41			6.0	12.5
4	-0.13	11	Organic		10YR 2/1		100	100	0.50	0.92	0.65	1					6.0	12
4	-0.24	2	Tephra		GL1 2.5/N		80	100	0.48	1.08	0.59	1				4.37	5.7	10
4	-0.26	3	Organic		7.5YR 2.5/3			100	0.50	0.92	0.65	1					6.5	9
4	-0.29	4	Tephra		GL1 2.5/N			94	0.44	0.80	0.70	1						9
4	-0.33	27	Organic		7.5YR 2.5/3			100	0.52	0.92	0.65	1						9
5	0	15	Top Soil		7.5YR 2.5/1		92	99	0.48	0.65	0.76	1				23.68	6.0	10.5
5	-0.15	15	Aeolian / Organic / Tephra		10R 3/1		78	95	0.48	0.99	0.63	1				14.76	6.1	10
5	-0.3	7	Organic		10R 2.5/2		100	94	0.46	0.59	0.78	1					5.6	9.5
5	-0.37	5	Tephra		GL1 2.5/N		67	69	0.40	1.04	0.61	1					5.8	9
5	-0.42	7	Organic		2.5Y 2.5/1		95	79	0.51	0.61	0.77	1					5.8	9
5	-0.49	3	Tephra		GL1 2.5/N		100	94	0.44	0.75	0.72	1						9
5	-0.52	8	Organic		7.5YR 2.5/1			94	0.47			1						8
6	0	9	Top Soil		7.5YR 2.5/1		100	97	0.48	0.72	0.73	1				20.53	5.9	9.5
6	-0.09	20	Aeolian / Organic	Oe	5YR 3/4		78	100	0.46	1.00	0.62	1				12.59	6.4	9
6	-0.29	5	Tephra		GL1 2.5/N		100	71	0.45	0.84	0.68	1				17.34	6.4	9
6	-0.34	6	Aeolian / Organic	Oe	2.5YR 3/2		100	100	0.50	0.74	0.72	1					6.1	8.5
6	-0.4	7	Tephra / Organic	Oe	5YR 3/1	loamy fine sand	82	100	0.50	1.39	0.47	1	80	20		14.49	6.2	8
6	-0.47	3	Tephra		GL1 2.5/N		100	81	0.48	0.87	0.67	1					5.9	8
6	-0.5	10	Organic	Oe	7.5YR 2.5/1			100	0.49			1					6.1	8

Table 9: Soil Information for pits at the drained patch in Þúfa off of Landvegur road (Rte. 26).

Pit No.	Layer		Horizon Identification				1. Moisture Content			2. Bulk Density (g/cm3)			3. Texture (%)			4. LOI (% DW)	5. pH	6. Temp
	Depth (m)	Thickness (cm)	Field	Master/ Sub	Color	Texture (USDA)	Lab (%)	Theta (%)	10HS (%)	Db	Poros.	Deg. Sat.	Sand	Silt	Clay	500°C	min	(°C)
1	0	15	Top Soil		10R 2.5/2			93								10.19		11
1	-0.15	15	Organic	Oe	5YR 2.5/1	silt loam	92	94		0.78	0.71	1.00	30	60	11			9
1	-0.3	22	Tephra / Organic	E	5YR 3/1	silt loam	89	85		0.74	0.72	1.00	39	61				8
1	-0.52	3	Tephra		5Y 2.5/1			89										8
1	-0.55	5	Organic		5YR 2.5/1		91	93		0.91	0.65	1.00						8
2	0	14	Organic		10R 2.5/2			95	0.19								3.9	11
2	-0.14	3	Aeolian / Organic	E	2.5YR 3/4	sandy loam	99	95	0.12	0.72	0.73	1.00	64	32	4		5.4	11
2	-0.17	3	Tephra		GL1 2.5N		87	89	0.22	0.76	0.71	1.00				17.66	5.1	11
2	-0.2	3	Organic		5YR 2.5/1		97	90	0.23	0.84	0.68	1.00				15.88	5.3	12
2	-0.23	4	Aeolian / Organic		2.5YR 3/3		97	90	0.49	0.87	0.67	1.00				11.27	5.6	11
2	-0.27	8	Tephra / Organic		5YR 3/1			93	0.47								6.0	11
2	-0.35	2	Tephra		GL1 2.5N			90	0.48								6.4	11
2	-0.37	8	Aeolian / Organic		10R 3/4			100	0.50							19.72	6.2	10
2	-0.45	13	Tephra / Organic		5YR 3/1			89	0.43								6.4	9
2	-0.58	3	Tephra		5Y 2.5/1			92	0.36								6.3	9
2	-0.61	9	Organic	Oe		silt loam		91	0.36				24	69	7		5.8	8
3	0	15	Top Soil		10R 2.5/2		95	93	0.39	0.65	0.76	1.00						11
3	-0.15	15	Organic		2.5YR 3/4		82	85	0.42									8
3	-0.3	4	Tephra		GL1 2.5N		77	89	0.46									8
3	-0.34	11	Organic	Ee	5YR 3/1	silt loam		94	0.48				35	62	3	16.05		8
3	-0.45	15	Organic	Oe	5YR 3/3	sandy loam		86	0.46				63	33	4			9
3				B		silt loam	82									13.60		11
4	0	20	Top Soil		10R 2.5/2		98	94	0.49	0.64	0.76	1.00						10
4	-0.2	4	Aeolian / Organic		2.5 YR 3/4		100	94	0.47	0.63	0.76	1.00				28.60		10
4	-0.24	6	Tephra / Organic		5YR 3/2		100	97	0.48	0.65	0.75	1.00				21.24		9
4	-0.3	1	Tephra		GL1 2.5N			95	0.43									9
4	-0.31	4	Organic		5YR 3/1		100	98	0.50	0.74	0.72	1.00						8
4	-0.35	2	Tephra		GL1 2.5N		100	92	0.36	0.80	0.70	1.00						9
4	-0.37	23	Organic				100	88	0.36	0.81	0.69	1.00						

Pit No.	Layer		Horizon Identification				1. Moisture Content			2. Bulk Density (g/cm3)			3. Texture (%)			4. LOI (% DW)	5. pH	6. Temp
	Depth (m)	Thickness (cm)	Field	Master/ Sub	Color	Texture (USDA)	Lab (%)	Theta (%)	10HS (%)	Db	Poros.	Deg. Sat.	Sand	Silt	Clay	500°C		(°C)
5	0	16	Organic		10R 2.5/2			64	0.45							18.87		10
5	-0.16	7	Tephra / Organic / Aeo		2.5YR 4/6		87	84	0.48	0.78	0.71	1.00						10
5	-0.23	11	Organic		3YR 3/4			90	0.39									9
5	-0.34	12	Tephra / Organic		5YR			87	0.41							13.96		8
5	-0.46	8	Organic		50YR 3/3		81	89	0.40	0.90	0.66	1.00				14.82		8
5	-0.54	6	Tephra		6L1 2.5N		85	48	0.38	0.82	0.69	1.00						8.5
6	0	16	Organic		10R 2.5/2			94	0.47									10
6	-0.16	4	Org/Aeo		2.5YR 3/4			92	0.45									9
6	-0.2	9	Teph/Org/Aeo	Bei	2.5YR 3/4	silt loam	75	83	0.50	0.75	0.72	1.00	37	63	0	18.46		8
6	-0.29	23	Organic	Oe	5YR 3/3	silt loam	84	94	0.46	0.83	0.69	1.00	47	53	0			7
6	-0.52	2	Tephra	B	GL1 2.5N	silt loam	85	91	0.45	0.87	0.67	1.00	42	55	3			8
6	-0.54	6	Organic					63	0.40							15.42		8
7	0	13	Organic		10R 2.5/2		100	69	0.41	0.78		1.00					5.5	8.9
7	-0.13	13	Organic / Aelioan		2.5YR 3/4		58	66	0.44	0.85		0.85					5.7	8.2
7	-0.26	10	Tephra / Organic		5YR 3/1		98	90	0.47	0.90		1.00					5.8	7.8
7	-0.36	9	Organic		5YR 3/4		98	77	0.43	0.85		1.00					5.9	7.5
7	-0.45	3	Tephra		GL1 2.5N		83	78	0.45	0.85		1.00					5.9	6.8
7	-0.48	12	Organic		10YR 3/3		82	96	0.44	0.86		1.00					5.6	6.8
8	0	13	Aeolian / Organic		10R 2.5/2		0	81	0.46								5.6	8.8
8	-0.13	10	Aeolian / Organic / Tephra	Bei	2.5YR 3/4	silt loam	74	92	0.47	1.01	0.62	1.00	41	56	4		5.6	8
8	-0.23	2	Tephra	B	GL1 2.5N	silt loam	94	72	0.44	0.75	0.72	1.00	38	60	2	19.91	5.6	7.9
8	-0.25	9	Aeolian / Organic / Tephra		2.5YR 3/2			93	0.43		0.70					13.20	5.6	7.5
8	-0.34	4	Aeolian / Organic (MIA)		2.5YR 3/6		80	93	0.45		0.70	1.00						7.5
8	-0.38	5	Organic	Oe	10R 3/3	silty clay	52	88	0.46		0.70	0.75	70	28	2		5.9	7
8	-0.43	5	Tephra / Aeolian		10R 3/1		97	83	0.46	0.79	0.70	1.00					5.8	6.9
8	-0.48	12	Organic		10YR 3/3			99	0.44							18.49	5.6	7.5
D	0	22	Organic					60	0.41									10.3
D	-0.22	4	Tephra / Aeolian					18	0.36									10.9
D	-0.26	10	Organic				70	42	0.39	0.86	0.67	1.00						10.9
D	-0.36	6	Tephra				83	27	0.29	0.76	0.71	1.00						11
D	-0.42	6	Organic				51	50	0.39	1.07	0.59	0.85						10.8
D	-0.48	5	Tephra					56	0.40									10.8
D	-0.53	1	Tephra				46	38	0.37	0.83	0.69	0.67						10.8
D	-0.54	6	Aeolian / Tephra				84	29	0.40	0.82	0.69	1.00						10.5

Table 10: Soil Information for pits at the Agricultural University of Iceland.

Pit No.	Layer		Horizon Identification				1. Moisture Content			2. Bulk Density (g/cm3)			3. Texture (%)			4. LOI (% DW)	5. pH	6. Temp
	Depth (m)	*Thickness (cm)*	*Field*	*Master/ Sub*	*Color*	*Texture (USDA)*	*Lab (%)*	*Theta (%)*	*10HS (%)*	*Db*	*Poros.*	*Deg. Sat.*	*Sand*	*Silt*	*Clay*	*500°C*	*min*	*(°C)*
1	0	15	Top Soil	O	7.5YR 2.5/1		100	93		0.30	0.89	1.00				65.41	5.5	8.5
1	-0.15	15	Organic	Oe	7.5YR 2.5/1		100	92		0.34	0.87	1.00				67.09	5.5	8
1	-0.3	15	Organic	Oe	7.5YR 2.5/1	fine sand		91			0.89	0.86	96	4	0		5.0	7.5
1	-0.45	15	Organic	Oe	7.5YR 2.5/1			95									5.2	6.6
2	0	15	Top Soil	O	7.5YR 2.5/2			97			0.92	0.89				60.21	5.3	8.2
2	-0.15	15	Organic	Oe	7.5YR 2.5/2			99		0.22	0.92	0.89					5.1	8
2	-0.3	15	Organic	Oe	7.5YR 2.5/2			98			0.92	0.69				51.74	4.2	7.6
2	-0.45	15	Organic	Oe	7.5YR 2.5/2			100			0.92	0.81				53.17	4.8	6.8
3	0	15	Top Soil	O	7.5YR 2.5/2		100	98			0.67	1.00				68.13	5.2	8.6
3	-0.15	15	Organic	Oe	7.5YR 2.5/2		100	96		0.66	0.75	1.00					5.2	8.2
3	-0.3	15	Organic	Oe	7.5YR 2.5/2	silt loam		96		0.88	0.67	0.72	37.5	59.7	2.8		4.9	8
3	-0.45	15	Organic	Oe	7.5YR 2.5/2		100	100		1.10	0.59	1.00				50.67	5.0	6.8
4	0	21	Top Soil	O	7.5YR 2.5/2			97		0.30	0.89					5.19	5.3	8.4
4	-0.21	20	Organic	Oe	7.5YR 2.5/2	fine sand		91			0.89	0.97	100	0	0	70.33	5.5	7.6
4	-0.41	19	Saturated Organic	Oe	10YR 2/2	sandy clay loam		100			0.89	0.80	72.2	27.7	0	52.97	5.1	6.6