Factors contributing to the unnaturally low water table of Moanatuatua Scientific Reserve, Waikato, New Zealand

A thesis
submitted in partial fulfilment
of the requirements for the degree
of
Master of Environmental Science
at
The University of Waikato
by
Constance Mary Daws

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2018

Abstract

Water table regime in peatlands (depth below the peat surface) is an important driver in biochemical processes. A deep water table can lead to increased rates of peat decomposition resulting in surface subsidence, release of carbon and changes to the vegetation cover. This study focused on the factors responsible for the unnaturally deep and highly fluctuating water table regime at Moanatuatua, a remnant peat bog, in contrast to the hydrologically pristine Kopuatai bog, with a shallow, more stable water table.

Moanatuatua Scientific Reserve in the Hamilton basin is the 1.1 km^2 remnant of a former 75 km^2 raised peat bog, and Kopuatai bog covers an area of 96 km^2 on the Hauraki plains. Native bog vegetation in the Waikato is dominated by two species from the Restionaceae family of vascular plants, *Empodisma robustum* and *Sporadanthus ferrugineus*. Water table measurements at Moanatuatua were obtained from nine pressure transducers across an east to west transect of the bog. At Kopuatai, water table measurements were taken from a single reference site. At both bogs evaporation and rainfall were measured by eddy covariance towers. Three years of measurements (1 September 2015 – 31 August 2018) were used to compare the two sites.

The water table at Moanatuatua was consistently very deep for a peat bog and had a strong seasonal cycle resulting in a deeper water table in summer and a shallower water table in winter, with a mean depth of -601 mm below the surface for the three-year study period. Kopuatai also showed a seasonal pattern although the water table did not reach the same extreme depths with a mean water table depth of -25 mm. The water table at Moanatuatua followed the domed shape of the peat surface, but remained well below the peat surface for the duration of the study. The pattern of water table depth across Moanatuatua indicated that the border drains do not cause a drawdown effect on the water table across the entire transect of the bog. Similar water table depths were found 18 years ago suggesting that the hydrological regime at Moanatuatua has not altered much in this time.

Evaporation rates from Moanatuatua were higher than Kopuatai. Mean daily evaporation from Moanatuatua was 2.2 mm and Kopuatai 1.8 mm for the entire study period. Eliminating wet canopy influences the evaporation rate at Moanatuatua was 2.0 mm day^{-1} and at Kopuatai of 1.45 mm day^{-1}. Mean annual water balance inputs into the bog (rainfall – evaporation) were 587 mm at Moanatuatua and 872 mm at Kopuatai. If the late successional vegetation at Moanatuatua were replaced with early successional vegetation as present at Kopuatai, it is estimated that an average water balance would have been of 741 mm, resulting in more water available for potential water table recharge.

Acknowledgements

I would like to thank:

Firstly my supervisor Dave Campbell, who helped me throughout the duration of my study. With unwavering commitment to the project and the patience of a saint when it came to helping me write code in MATLAB. Dave, your knowledge and passion for peat bogs is contagious and I appreciate all the time and energy you have given me, your flexibility when it came to working around my family and your understanding of the time constraints made this thesis achievable. Also Louis Schipper, who agreed to be my secondary supervisor. Thank you for your input and assistance when I needed it, mostly positive reinforcement and lunch room chats.

Joss Ratcliffe, for your invaluable knowledge of peatlands, writing MATLAB code and open access to your on-desk library. Spending your study break uploading my evaporation data was beyond the call of duty, and the time you spent helping me make my data presentable. Having your input and being able to talk to someone who was also working on Waikato peat bogs made studying never dull. Chris Morcom, for assisting me out at Moanatuatua to get my last data download and Aaron Wall for giving me some great ideas for displaying my data in a coherent manner.

Lynley Gailey and J.D & R.D Wallace Farms for permitting access to the field sites across their land.

I would like to acknowledge the Department of Conservation for the funding I received to undertake my studies on Moanatuatua Scientific Reserve, and for supporting equipment purchase. The wider peatland research programme at the University of Waikato is funded by a contract to Manaaki Whenua Landcare Research. I also appreciate the Masters Research Scholarship I received from the University of Waikato.

Finally, I would like to thank my mum for looking after her grandchildren, Amelia and Dylan when I wasn’t available, and my children for always smiling even though I spent hours away each week. And mostly, my sincere gratitude goes to my husband Marcus, who helped me achieve my dream to complete, not only my bachelor’s degree, but also my Masters in Environmental Science. Thank you for supporting me over five and a half years by giving me the time to come to university, for looking after the kids when I had to work overtime, even though you already had a lot on your plate, for tolerating my stress levels and finally your unwavering belief in me. Thank you for your ongoing support and positivity.

Table of Contents

Introduction

1.1 Global and New Zealand peatland distribution

Peatlands are ecologically important due to their distinct biota and are environmentally important as carbon sinks (Schipper & McLeod, 2002; Yu et al., 2010). Globally, peatlands contain around the same amount of carbon as the atmosphere (Clymo & Bryant, 2008), and store an estimated 20 % to 30 % of the world soil organic carbon (Chimner et al., 2016). Peatlands are estimated to cover 3 % of the land surface of the planet are found in all climatic zones, although their largest extents are located in cooler wetter areas (Figure 1.1) (Xu et al, 2018).

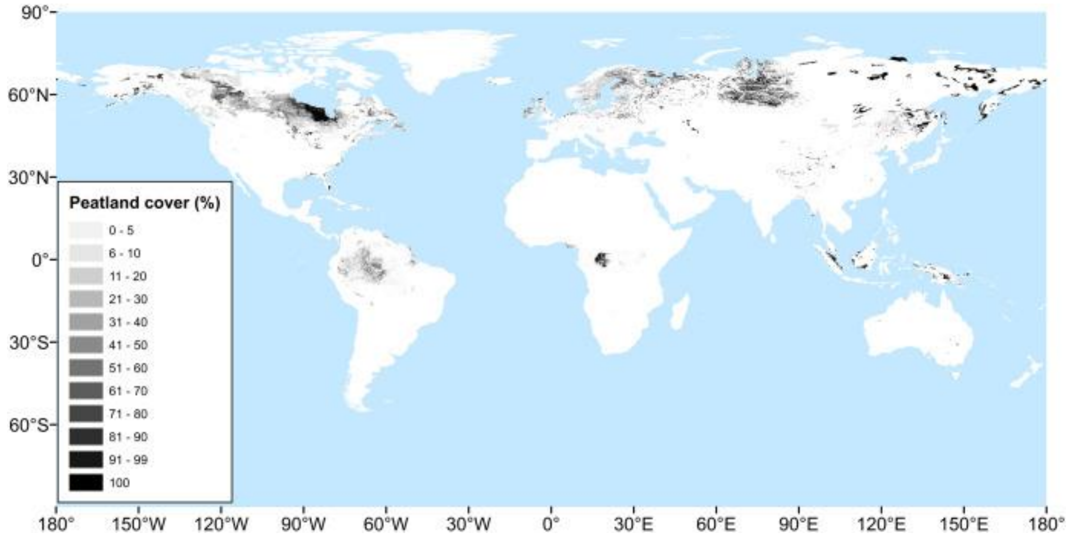


Figure 1.1 Global peatland distribution derived from PEATMAP (Xu et al, 2018).

Peatlands are a subset of wetland ecosystems and half of the global wetlands have been lost, this includes 90 % lost in New Zealand in just 150 years (Clarkson et al., 2013) (Figure 1.2). In New Zealand 16 % of historic wetlands remain in the South Island and 5 % in the North Island (Ausseil et al., 2011). Peatlands cover an estimated 166,000 km^2 of New Zealand (Davoren, 1978) with 940 km^2 found in the Waikato region, 80 % of which have been drained mostly for pasture (Pronger et al., 2014) Preserving these few fragile ecosystems, both globally and locally, is important to save their ecosystem services, including preventing fluxes of carbon leaving the bog system. The water table of a peatland, which is a result of a bog's water balance, is one of the main controls on ecosystem functioning (Labadz et al., 2010) and is the main control preventing oxidation of stored carbon being released to the atmosphere (Clymo & Bryant, 2008)

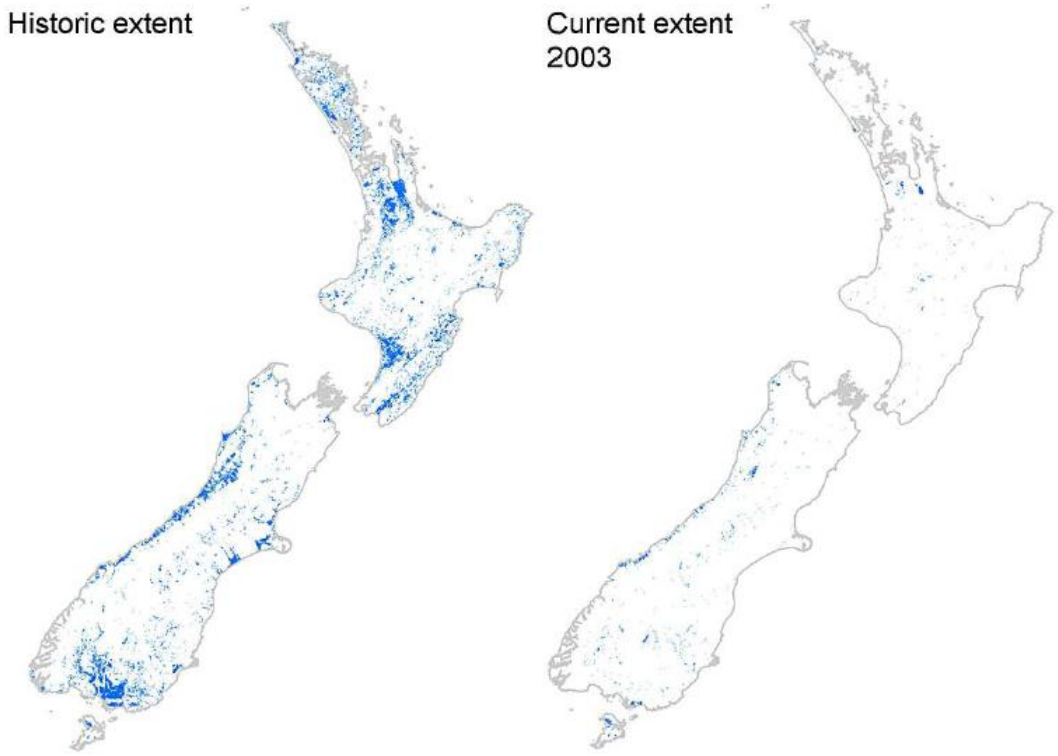


Figure 1.2: Maps of current and historic extent of freshwater wetlands (blue areas) in New Zealand. Wetland extent, historic – 2003 (Ausseil et al., 2011).

1.2 Hydrology and ecology of peatlands affected by low water tables

Water input to a peatland can include streams, ground water, overland flow, flooding, subsurface flow and will always include precipitation (Campbell and Jackson, 2004). Peatlands can lose water through evaporation and subsurface flow in pore spaces in the peat; the flow of water is determined by the hydraulic conductivity of the peat (Labadz et al., 2010) which increases with depth. Overland flow also occurs as the soil tends to be close to saturation therefore surface inundation can occur rapidly (Ingram, 1983).

The water balance of an ombrotrophic peat bog is usually controlled by inputs of precipitation exceeding outputs via evaporation and lateral seepage. When precipitation dominates then the water table will be maintained at or near the surface. Therefore the water balance of an ombrotrophic peat bog can be found using a simple water balance equation including precipitation (P) and evaporation (E). For example a change in water storage (ΔS) can be established using $\Delta S = P - E$. This change in water storage will translate to a change in water table height. The water table depth below the peat surface impacts on the biological, chemical and physical, properties of peat (Laiho et al., 2003). If the water table is lowered for a prolonged period of time these properties will usually change. The surface of a bog is known to oscillate with water table fluctuations, as the peat matrix responds to changes in effective stress (Fritz et al., 2008). Along with the added water the vegetation can also aid in the surface elevation changes due to gas bubbles found on the root hair fibres beneath the peat surface (Hodges & Rapson, 2010). Peat surface fluctuates higher in pristine bogs with unaltered peat, whereas in highly mineralised peat the peat matrix is less flexible due to compacted pore space reducing the magnitude of oscillation (Price & Schlotzhauer, 1999).

Water tables fluctuate seasonally, but if a low water table is maintained then the peat will decompose at an accelerated rate resulting in the peatland converting from a CO_2 sink to a CO_2 source (Goodrich et al., 2017). Other impacts of a sustained low water table can include an alteration in vegetation and peat consolidation and subsidence (Labadz et al., 2010). As the environment becomes more favourable to invasive species the invasive species can continue to alter the chemical and physical composition of the bog (Laine et al., 1995). Afforestation can occur and a change to vegetation with deeper roots that can reach the new water table will begin to thrive (Clarkson et al., 1999; Laine et al., 1995). This can lead to higher rates of transpiration, substrate oxygenation and surface warming and therefore continue the lowering of the water table

In the Northern Hemisphere the dominant peat formers are *Sphagnum* mosses and most research has focused in this area (Clymo, 1983). Although *Sphagnum* mosses are also found in New Zealand, the most common peat forming vegetation are representatives of the restiad family of vascular plants. This family is also found in Australia and southern Africa but often in drier conditions (Ingram, 1983). Peat bog vegetation has to be adapted to the water logged environment and in the case of New Zealand's *Empodisma robustum* can alter its environment to ensure that the peat surface stays just at or above the water table (Hodges & Rapson, 2010). Native vascular peatland vegetation can help reduce evaporative water loss from the peat surface, with a dense canopy and small leaf surface area along with water conservation via stomatal control (Campbell & Williamson, 1997). Pristine bogs such as Kopuatai maintain a water table that is at or near the surface and is vegetated with predominately *E. robustum*. Alternatively some peatlands have been progressively drained for agricultural, forestry and urban development, which results in a lowered water table. One such peatbog is Moanatuatua where the remaining bog extent grows native vegetation, but the surrounding area is now is used for pasture.

1.3 Hydrology and ecology of Moanatuatua Scientific Reserve

Moanatuatua Scientific Reserve is a small 1.4 km^2 remnant at that was once 75 km^2 (Figure 1.3) (Clarkson et al., 2004). The surrounding land has been drained for agriculture and ring drains surround the reserve causing further draw down of the water table (Clarkson et al., 1999). In New Zealand peat converted to pasture subsides at about 2 cm year^{-1} (Pronger et al., 2014). Previous studies on the hydrology of Moanatuatua bog show that the water table is affected by the border drains by about 20 m towards the center of the bog (Grimshaw, 2000). When restoring a bog to its original state or preventing further lowering of the water table changing the hydrology of the surrounding land is better than just trying to alter the internal hydrology of the bog itself (Littlewood et al., 2010) although this is often not an option.

Figure 1.3: Aerial photo of the remaining unconverted Moanatuatua bog (Waikato Regional Council, 1999)

1.3.1 Drainage history

Moanatuatua has a history of drainage and conversion to pasture and horticulture which began in the 1800s with the European confiscation of land of the Waikato area in 1893 (Smallfield, 1939).

Mr. Young from the Monavale District on the Moanatuatua plains suggested Moanatuatua swamp, being one of the richest swamp lands in the Waipa, be drained and made recommendations to the house of Parliament to drain the 89 km^2 swamp and sell it as crown land (MacKay, 1912).

In 1915 a government engineer Mr Thompson stated that the peat depth varied from 30-40 ft. (9.14 – 12.19 m) across most of the swamp but drainage was yet to begin due to the cost (New Zealand Herald 1915).

Drainage and conversion proved difficult due to fast re-establishment of native vegetation (Cranwell, 1939) and large areas had yet to be converted, by the 1930's most of Moanatuatua was covered in native vegetation and only at the edges the peat was shallow enough to be developed. Drainage was recommended for the area but with maintaining a high water table in summer (Smallfield, 1939). During the 1950s considerable drainage occurred (Wallace, 1978) and with continued conversion most of the original bog had been converted by 1974, with the remaining extent at close what is there now (Matheson, 1979).

Between 1925 and 2004 the peat surface has subsided by an estimated 2.53 m (Mckenzie, 2004).

The water table was at or close to the surface in the 1930s and *Sporadanthus ferrugineus* was the dominant vegetation in the centre of the bog (Cranwell, 1939), and even after conversion of Moanatuatua by burning and cultivation, the water table remained near the surface (Campbell, 1964). Over 10 years later in 1977, after almost all of the bog had been drained, however, at the remaining extent the water table remained near the surface and was not influenced by drainage (Matheson, 1979). But recent studies suggest that in 20 years there was a steep decline and by 2000 the mean water table depth of 580 mm below the surface was reached (Campbell et al., 2014).

1.4 Overarching aim of the thesis

This aim of this thesis is to determine the main factors responsible for maintaining an unnaturally low water table (WT) within Moanatuatua Scientific Reserve. Knowing why the WT is low is paramount in order to understand appropriate hydrological manipulation or management strategies that may lead to the bog's recovery to more natural conditions. The hypothesis is that the main driver for the low water table is increased evaporation rates from the late successional vegetation, namely *S. ferrugineus* and the shrub *Epacris pauciflora,* and that the bordering farm drains only cause a localised impact along the edge of the bog.

1.5 Thesis objectives

Using three years of water table measurements and eddy covariance (EC) measurements of evaporation rate the relationship between the water table depth and evaporation has been examined under different environmental drivers. The results were then compared with the hydrological regime at an unmodified peat bog (Kopuatai) to understand what the differences are and how any negative impacts can be reduced or reversed.

1.5.1 Objective one:

Utilise data from the established hydrological transect network of nine water level pressure transducers over a three year period 1 September 2015 – 31 August 2018, to describe the water table regime spatially and over time. This will predominantly investigate the spatial aspect of the water table across a 675 m transect of Moanatuatua bog in relation to the border drains. The survey data from each site will also be used to obtain the shape of the peatland surface and investigate the magnitude of peat surface oscillation.

1.5.2 Objective two:

To utilise EC measurements of evaporation, and measured rainfall, to compose seasonal and annual water balances at Moanatuatua. Then to compare and contrast with measured water balances of the hydrologically intact Kopuatai bog, in the Hauraki Plains. The EC measurements will be used to quantify whether there is a sufficiently large difference in water balance between the sites to explain water table regime differences.

1.6 Thesis outline

Chapter two is a literature review with more detailed information on the hydrological functioning of peatlands and how they differ globally. This chapter will then focus on New Zealand peatlands and how they have been affected by drainage and land conversion. It will review how the drainage has affected the water table of the peatlands compared with unmodified peatlands and subsequent ramifications are from this.

Chapter three will give a description of the study sites at Moanatuatua and Kopuatai bogs and the methodology employed in this study. Moanatuatua is ecologically significant as it is one of the few remaining peatlands in the Waikato where New Zealand endemic *S. ferrugineus* grows (Clarkson et al., 1999). Kopuatai has been chosen as a reference site to compare the water table regime of the two contrasting bogs, as it is a relatively unmodified large bog system where the edge effects of drainage and land conversion have much less impact on the internal ecosystem (Thompson et al., 1999). The dominant plant species at Kopuatai towards the centre of the bog is *Empodisma robustum*.

Chapters four and five will focus on the results for the two objectives, with a brief introduction, methods used for each section study will be described in detail in these chapters along with results.
Chapter four will describe the water table regime at Moanatuatua from data collected during a three year period, the water table regime at Moanatuatua will also be compared with Kopuatai. Chapter five will use data obtained from the eddy covariance towers and measured rainfall at Moanatuatua and Kopuatai bogs and describe differences in evaporation regimes at the two sites. The data will be used to establish individual seasonal and annual trends at both sites to obtain the water balance over a three year period.

Chapter six is a discussion that draws together the results supplied in chapters four and five and establishes the main factor/s responsible for the maintenance of the un-naturally low water table at Moanatuatua, and recommend strategies to prevent further degradation or recovery to a more natural water table.

Literature Review – Hydrological and ecological functioning of peatlands

2.1 Defining peat

Peat is the product of accumulation of dead plant material found in wetlands, mostly at the surface although a portion of it comes from the root system (Clymo, 1983). The definition of peatlands differs from region to region with varying minimum depths of peat from 10 cm to 100 cm and soil descriptions which can contain anywhere from 18 – 50 % organic matter (Yu et al., 2018) or even up to 99 % such as some *Sphagnum* peats (Clymo, 1983). The term peatlands in New Zealand includes areas that are currently saturated and those that have been drained for alternative land use (Campbell & Jackson, 2004). Under the New Zealand Soil classification system by Hewitt (2010) peat is classified as an Organic Soil which is poorly drained and can contain up to 70 % organic matter.

2.1.1 Peat formation

Peat forms in situ from the accumulation of plant matter in permanently saturated conditions (Ingram, 1982) often on a mineral substrate (Ivanov, 1981). The decay of the plant matter is inhibited due to the anaerobic conditions as a result of elevated water levels which are maintained due to the water balance of the peat and the vegetation’s composition and behavioural traits. The water levels are maintained due to an equilibrium between recharge and water loss (Ingram, 1982). *Sphagnum* peat forms as the moss dies off and the resulting litter accumulates on the surface whereas, peat formed from vascular species has below ground biomass addition from roots and rhizomes and can add organic matter as much as 2 m deep (Clymo, 1983). Peat accumulation happens at the base of the acrotelm (or top of catotelm) (refer to section 2.24 for further description on these two peat layers) when plant litter is deposited and subsequently consolidated by the weight of overlying material (Belyea & Clymo, 2001). Over time the peat builds ups to form a shallow layer of organic material that is above the regional water table creating a dome, and continues to grow.

2.2 Peatland Types

Peat is found in areas where the soil is poorly drained and the accumulation of plant litter exceeds or is equal to the rate of decomposition (Hewitt, 2010). Palustrine wetlands are those that have no moisture input from running water and includes swamps, fens and bogs (Shearer, 1997). These can be classified based on their nutrient (trophic) status which is intricately linked to their hydrology. The trophic status also dictates the vegetation types which can grow on the individual wetland types.

2.2.1 Swamps

Swamps (Figure 2.1) can support trees and other woody plants (Johnson & Gerbeaux, 2004) and have the highest trophic status of the three wetland types as they receive nutrients from mineral sediments found in nearby flooding rivers, groundwater and hill slope run off (Campbell & Jackson, 2004).

Figure 2.1 Kahikatea forest swamp, New Zealand (http://www.TeAra.govt.nz/en/photograph/12579/kahikatea).

2.2.2 Fens

Fens (Figure 2.2) commonly have higher nutrient concentrations than bogs (Shearer, 1997) due to water input from streams and groundwater but lack the nutrient input from mineral sediment found in flooding rivers (Campbell & Jackson, 2004). They are moderately acidic and range from oligotrophic to mesotrophic; resulting in lower trophic status than swamps (Johnson & Gerbeaux, 2004). Fen vegetation can include sedges, ferns, tussock grasses, restiads and scrub (Johnson & Gerbeaux, 2004).

Figure 2.2: New Zealand fen with tussock grasses (http://www.wetlandtrust.org.nz/Site/Why_Wetlands/Types_of_Wetlands.ashx)

2.2.3 Bogs

Bogs (Figure 2.3) are nutrient poor (oligotrophic) from having no nutrient input from mineral soils, streams or groundwater (Johnson & Gerbeaux, 2004). The only water input comes from nutrient poor precipitation. Bogs are typically raised above the surrounding land due to the accumulation of peat that rises above the regional water table (Shearer, 1997). Dominant vegetation includes mosses, cushion plants, lichens, sedges, restiads, grasses, ferns, shrubs and trees (Johnson & Gerbeaux, 2004).

Figure 2.3: New Zealand bog with tangle fern and restiads (http://www.wetlandtrust.org.nz/Site/Why_Wetlands/Types_of_Wetlands.ashx)

2.3 Diplotelmic stratigraphy of peat bogs

Peat bogs can be divided into two stratigraphic soil layers of differing characteristics and therefore referred to as diplotelmic (Ingram, 1978). The two individual layers are divided by the presence or absence of oxygen determined by the maximum depth of the water table. The aerobic upper layer and anaerobic bottom layer have been termed acrotelm and catotelm respectively (Ivanov, 1981).

The acrotelm is often referred to as the active layer and is more susceptible to decomposition due to the addition of oxygen as the water table fluctuates. This layer is considered the peat forming layer (Ingram, 1983). The acrotelm contains living and dead plant material and interacts with the atmosphere through exchanges of oxygen and water via precipitation and evaporation (Ivanov, 1981). The depth of water level fluctuation within the acrotelm determines its thickness. Water exchange can occur rapidly due to the high porosity of the accumulating organic matter in the upper layer, this material has a high hydraulic conductivity and high specific yield allowing water to move more easily though this surface layer (Ingram, 1983). The lowest position of the water table corresponds with the bottom of the acrotelm and top of the catotelm (Figure 2.4) (Ingram, 1978).

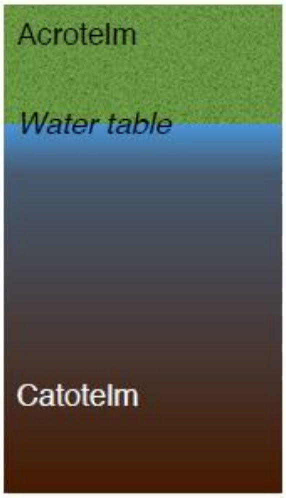


Figure 2.4: Stratigraphy of a peat bog. The acrotelm sits above the water table with the permanently saturated catotelm located below the water table.

Below this is the catotelm which is more compact and less affected by oxygen (Ingram, 1978). The size of the pores are reduced due to the pressure exerted on them from the overlying peat, level of the water table and atmospheric influences (Ivanov, 1981). The hydraulic conductivity is reduced due to a reduction in porosity from the compacted plant material this results in a strong resistance to flow (Ingram, 1983). The lack of oxygen in the catotelm reduces decomposition rates and therefore carbon fluxes are limited creating a store of organic carbon. Methanogenesis occurs in this layer due to anaerobic decomposition this process may affect the relative water level by increasing gas bubbles and thus increasing the height of the peat surface (Strack et al., 2005).

The relative thickness of the physically distinct layers influences plant growth, decomposition rates, and water movement. The boundary in between the acrotelm and catotelm is not linear or fixed and can vary both spatially (humps and hollows along a bog transect) and temporally with prolonged water level fluctuations (Ingram, 1983), such as seasonally or with long term changes in climate.

2.3.1 Shape of a raised peat bog

As peat accumulates on the surface of a mineral layer it begins to form a domed shape, with the central part of the bog rising up to 10 m higher than the margins (Ingram, 1982). The water table rises at the same rate as the peat surface, this process occurs over 1000's of years (Baird et al., 2008). This is possible as the water table is maintained due to the low hydraulic conductivity towards the margins of a bog (Baird et al., 2008). The lower hydraulic conductivity at the margins is fundamental not only for maintaining the water table but also for the growth of bog dome (Baird et al., 2008; Lapen et al., 2005). Seepage is also restricted through the catotelm as low hydraulic conductivity values in this layer suggest negligible amounts of flow (Baird et al., 2008).

There has been ongoing interest in peatland modelling. One of the earliest approaches was based on a simple steady-state model or a circular raised bog by Ingram (1987). This model assumed a single value for hydraulic conductivity and did not take into account changes in depth. Diameter and radius of the bog were also taken into account. Along with rainfall – evaporation. Later studies have adapted this model to take into account changes in hydraulic conductivity with depth i.e. Baird et al. (2008).

2.4 Water balance of a raised peat bog

Hydrology is a fundamental component affecting peat bog ecosystem functioning (Labadz et al., 2010). The overall water balance of a peat bog is expressed via water inputs, outputs and storage (Rydin et al., 2013). Water inputs in an oligotrophic bog are from precipitation (P) since there is normally negligible ground water inflow; outputs are evaporation (E) from the surface of soil and vegetation and transpiration from internal processes of the vegetation, overland flow from infiltration excess (R) and ground water export as lateral flow (F) (Ingram, 1983). Lateral flow in peatland is subjective to the hydraulic conductivity and change in head gradient (Δh) (Ingram, 1983).

The change in storage (ΔS) of water within a peat bog can be established using the equation

$$\Delta S = P - (E + R + F)$$

2.4.1 Precipitation

The main form of recharge into an ombrotrophic bog is through precipitation. However, groundwater may supply a small input into the bog through the base of margins surrounding the bog (Ingram, 1983). Precipitation into the system is commonly measured using tipping bucket rain gauges that automatically measure rainfall. Systematic errors in rain gauges can occur during high intensity rainfall. The rainfall rate may exceed the speed at which the bucket can tip and strong winds can lead to under estimation of precipitation due to rain drops not entering the bucket. Other errors include evaporation in the bucket before it has a chance to tip. All the errors result in an under estimation of rainfall (Molini et al., 2005).

2.4.2 Evaporation

The major controls on evaporation rates include meteorological factors of solar radiation, air temperature, humidity, wind speed, and vegetation physiology; such as stomatal control, leaf area and canopy height. Evaporation comes from either direct evaporation from moist land and vegetation surfaces or transpiration via internal plant processes (Ingram, 1983). Transpiration from plants has been estimated to be 80 to 90 percent of the total evaporation from the continents (Jasechko et al., 2013). Evaporation as a function of vegetation will be discussed in depth in the subsection 2.6 ‘Vegetation types’.

Evaporation can be measured using micrometeorological methods such as EC, which measures vertical turbulent transport of gas molecules. Fluxes of water vapour, carbon dioxide, methane, and nitrous oxide can be determined from vegetation, soil, water surfaces (Burba, 2013). Open water evaporation is often used to compared evaporation rates from wetlands and uses the Penman method (Ingram, 1983). Another approach is using the evaporation equilibrium (E_{EQ}), which is the evaporation rate which would occur over a wet surface without advective influences and less dependent on local energy partitioning (Thompson et al., 1999). Evaporation can then be compared with E_{EQ} as an index of total evaporation.

2.4.3 Overland flow

When precipitation occurs rapidly, over a long period of time or when the water table is already elevated, recharge rates can exceed infiltration rates of the peat resulting in overland flow (Ingram, 1983). Overland flow is not a major contribution to water loss as most water travels though the profile and exits horizontally. Water that starts as overland flow may end as lateral seepage if the water enters macropores and flows though the soil profile (Holden & Burt, 2003).

2.4.4 Groundwater discharge

Ground water discharge is usually small and normally occurs though the catotelm, but first travels though the acrotelm where the larger pore spaces allow water to move more freely (Ingram, 1983). The domed shape of a raised peat bog can be referred to as a ground water mound (Ingram, 1982) and the water table broadly resembles the shape of the raised peat surface with a drawdown towards the edges (Ingram, 1983). Groundwater flows from areas of high hydraulic head to areas of low hydraulic head, and is dependent on elevation head above a fixed datum. Therefore water flows from the centre of the bog to the edges when precipitation is adequate. This may occur more readily where there is a drain along the edges increasing the hydrological head from high at the centre of the bog to low at the drain. The hydraulic conductivity of peat is highly variable therefore can vary over several metres of magnitude both horizontally and vertically within just a few metres (Rycroft et al., 1975).

Porosity of the peat influences the flow of water. The porosity is higher in the acrotelm although pipes in the catotelm are common in upland peats in the UK. The low hydraulic conductivity of peat reduced downward seepage though the peat and this is exasperated in strongly humified peat layers (Schouwenaars, 1993). Little research has been done on the effect of macropores in New Zealand peat bogs, these large spaces allow for easier water transport from the peat and flow rates can increase due to drainage of the surrounding area (Labadz et al., 2010).

2.4.5 Specific yield

Specific yield of peat can provide information on how water is released from peat as a result of lowering the water table. Specific yield (Sy) can be defined as the ratio of water released from a material (rock or soil) under the influence of gravity in relation to the volume the material. Although this can be complicated by trapped air, non-steady-state conditions and hysteresis among others (Logsdon et al., 2010).

Therefore specific yield can be calculated using the equation

$$S_y = \frac{\Delta Vol/A}{\Delta h}$$

Where ΔVol was a fixed volume of daily water removed from a lysimetre, Δh was the change in water table height and A was the area of the lysimetre (Price, 1992).
Specific yield varies with depth and the physical properties of the peat such as the degree of decomposition and reduction is pore sizes, with lower values observed in decomposed peat (Price & Schlotzhauer, 1999). Fibrous peat, has larger pore spaces due to the fact it contains more than two-thirds fibres, has the potential to release more than 45 % of the stored water after lowering of the water table (Verry & Boelter, 1978). Price (1996) compared an intact peatland with a specific yield of 0.35 – 0.55 with a peatland disturbed by removal of the upper layer of peat which resulted in a specific yield of 0.04 – 0.06. With the higher the percentage the more degraded the peat (Price, 1996). This reduction in specific yield corresponds with a reduction in pore spaces due to compaction, Price suggests that the water balance of a disturbed site can be restored even though the peats physical properties cannot as easily be reversed.

2.5 Water table

Establishing the characteristics of a peat bogs hydrology can be achieved by monitoring changes in the water table (Labadz et al., 2010). The water table level is one of the most ecologically important hydrological properties in wetlands (Lafleur et al., 2005). The level of the water table is controlled by the water balance and precipitation has to match or exceed evaporation on an annual timescale for the water table to be maintained. The water table can be measured in two ways; (1) from the surface of the peat to the water table which is known as the relative water level (RWL); or (2) the absolute water level (AWL) which is with reference to a fixed datum below the peat surface (e.g. mean sea level). The difference between AWL and RWL is assumed to be minimal in mineral aquifers (Fritz et al., 2008), but the same is not true for peat with a oscillating surface level. The peat surface oscillates when the water table drops, reducing the pore water pressure and peat matrix, therefore the AWL fluctuations affects the RWL by causing the peat to move with the water table (Fritz et al., 2008) This is not the same for the RWL as this is relative to the peat surface which varies with consolidation and water absorption. The water table level is important, because if it is too low the top layer of plant litter will decompose and if it is too high plant growth is retarded due to low oxygen levels (Bonn et al., 2016). When peat decomposes the physical properties change, this can result in a lower water storage capacity and result in higher groundwater fluctuations. These fluctuations can lead to lower summer water tables, which will further drive the decomposition due to longer periods of oxidisation and microbiological activity (Schouwenaars, 1993).

2.6 Peat surface oscillation

Surface oscillation is a unique characteristic of peatlands and an important hydrological feature. The peat surface oscillates both daily and seasonally with the changing water levels (Fritz et al., 2008), and this surface level fluctuation is known in German as *Mooratmung*, or mire breathing (Ingram, 1983). Surface elevation of peat will respond to the level of soil moisture as the peat expands or contracts due to the highly deformable peat matrix (Fritz et al., 2008). Peat with larger pore spaces is more compressible and the level of oscillation is higher, compared to decomposed peat with smaller pore spaces or peat with a higher mineral content (Howie & Hebda, 2018; Price & Schlotzhauer, 1999). The main factor affecting the level of the peat surface is hydrostatic pore pressure and the elasticity of the peat matrix, although other causes include floating mats, atmospheric pressure and methane bubbles formed within the peat (Howie et al., 2009). Methanogenesis, a form of anaerobic decomposition gives rise to gas bubbles which move through the peat and may become blocked by the peat matrix restricting other gas from rising, forming a layer of gas in the peat elevating the peat surface (Strack et al., 2005). The water table can drop when air enters the pore spaces, or evaporation above the water table reduces pore volume thus lowering the peat surface. Therefore the peat surface is usually higher in winter and lower in summer as precipitation is reduced.

Surface oscillation can change spatially across a bog and is often correlated with changes in vegetation cover and/or peat thickness, with surface in the centre of the bog reaching higher elevations (Fritz et al., 2008). Plant community composition is strongly linked to surface elevation changes (Fritz et al., 2008; Howie & Hebda, 2018). In New Zealand *E. robustum* prefers to stay above the water table but in areas that have larger percentage of *Leptospermum scoparium* the peat surface does not oscillate as dramatically (Fritz et al., 2008). *E. robustum* can influence the surface elevation by using gas bubbles on the root fibres to effectively "float" on the water surface to ensure that the peat surface stays above the water table (Hodges & Rapson, 2010). *Sphagnum* peat has a low bulk density and increased water storage capacity ensuring that the peat remains saturated and the moss stays on or below the water table (Golubev & Whittington, 2018). As peat is compacted due to drainage and consolidation hydraulic conductivity decreases which can result in water limitations to plants as upward capillary flow is restricted (Price & Schlotzhauer, 1999). Water table movements can affect the root zone therefore the water table depth may be as important as surface oscillation for vegetation composition and survival.

2.7 Vegetation types

Plant species play an important role in the formation of peat and the vegetation is intricately linked to the hydrology affecting surface flow, groundwater and evaporation rates (Price et al., 2016). Different vegetation types result in different levels of transpiration as a result of water availability, leaf surface area and density of stomata on the leaf surface. Peat bog vegetation can help prevent evaporation from the bog surface due to the dense canopy and stomatal control preventing excessive transpiration (Campbell & Williamson, 1997). Therefore, as the dominant wetland vegetation on a peat bog is out competed, often due to lowered water tables, evaporation rates from the surface of the bog can change, impacting the water table regime and peat physiology (Frankl & Schmeidl, 2000).

Peatland vegetation can include woody plants, shrubs and mosses, and contribute to the main peat forming litter for an individual bog (Rydin et al., 2013). Peatland distribution varies throughout the globe dependant on the local climates water balance (McGlone, 2009). Most studies on peat bogs have been Northern Hemisphere-focused where peat bogs are dominated by mosses from the bog *Sphagnum* genus (Clarkson et al., 2004; Limpens et al., 2008) in contrast to peat forming vegetation in New Zealand which is predominately comprised of members of the Restionaceae family of vascular plants.

2.7.1 *Sphagnum* mosses and their hydrological importance

In the Northern Hemisphere the dominant peat forming vegetation on bogs are bryophytes, predominantly mosses from the *Sphagnum* genus (Littlewood et al., 2010; Rydin et al., 2013). Here, peat mosses are adapted to cold, water logged, low nutrient acidic environments (Rydin et al., 2013). Cold climates in the Northern Hemisphere account for 80 % of global peatlands with the remaining areas found in climates which are tropical to subtropical (Limpens et al., 2008). Other vegetation found in Northern hemisphere bogs includes sedges and shrubs. Tree species are found in the bogs although these are often sparse due to the poor soil aeration limiting growth (Laiho et al., 2003)

Sphagnum mosses lack vascular tissue and root structures causing them to be decoupled from the water table and highly susceptible to water table fluctuation (Golubev & Whittington, 2018). When water is not limiting evaporation from *Sphagnum* is higher than open water evaporation (Schouwenaars, 1993). Due to the lack of stomata mosses have no direct control over water loss though photosynthesis, and primary production decreases as the water table drops and evaporation rates are reduced (Schouwenaars, 1993). If moisture in the acrotelm becomes limited for a prolonged period of time the pore spaces in the peat are reduced, this causes a reduction in the pressure head near the surface, and eventually water will be drawn out of the cells in the *Sphagnum* leading to desiccation (Strack et al., 2009). Therefore to ensure survival *Sphagnum* helps maintain the water level above the regional water table level by drawing water upwards using capillary action in the small pore spaces between the leaves, branches and stems (Rydin et al., 2013). The moss acts like a sponge retaining water within its structure and can hold holds 15 times its dry weight (Clymo, 1983) adapting to a fluctuating water table by swelling and contracting in response to the water levels (Strack et al., 2009). Due to the structure of the mosses cell walls and biochemical properties of *Sphagnum*, peat formed from moss has low decomposition rates even when oxidized (Bengtsson et al., 2016).

2.7.2 Vascular restiad species and their hydrological importance

Peatland vegetation in the New Zealand is dominated by three species from the Restionaceae (restiad) family of vascular plants namely *E. robustum*, *E. minus* and *S. ferrugineus* (de Lange et al., 1999; Wagstaff & Clarkson, 2012). *Sphagnum* mosses are also found but do not contribute significantly to the formation of the peat therefore *Empodisma spp.* are the main peat former in northern New Zealand bogs (Campbell, 1964).

E. robustum plays an important role in water conservation as it has high canopy resistance and conservative evaporation rates that prevent evaporation (Campbell & Williamson, 1997). Campbell & Williamson (1997) measured summertime evaporation from Kopuatai bog and found extremely low rates, indicating strong canopy resistance. The sensible heat flux was the dominant energy flux during their study and latent heat flux only became dominant when the canopy was wetted after rainfall when the intercepted water was available for evaporation. The low rates of evaporation were suggested to be due to physiological adaptions of *E. robustum* of controlling water loss though its stomata, as well as the dense canopy, predominantly comprised of standing litter (Campbell & Williamson, 1997; Thompson et al., 1999).

E. robustum also helps maintain the high water table using a dense network of root hairs which help to maintain the high moisture content of the soil along with the reduced evaporation rates (Matheson, 1979). The matted root fibres act like a sponge with a water holding ability of 15 times its dry weight (Campbell, 1964) similar to *Sphagnum*. The matted root fibres result in lower hydraulic conductivity in the acrotelm of restiad bogs compared to that of *Sphagnum* bogs (Clarkson et al., 1999)

A study by Thompson et al., (1999) showed that the late successional *S. ferrugineus* loses more water to the atmosphere than *E. robustum* although they both show strong behavioural traits to prevent excessive water loss. Therefore, as the dominant vegetation on a peat bog moves towards a higher percentage of *S. ferrugineus* cover the higher evaporation rates from the surface of the bog can increase the depth of the water table away from the bog surface.

2.7.3 Restiad species succession

The successional gradient of successional vegetation in a restiad dominated bog moves from early successional sedges through to mid successional *Empodisma sp*. and finally late successional *S. ferrugineus*. As succession occurs nutrient availability decreases, acidity increases and surface peat becomes less decomposed. *S. ferrugineus* thrive in an environment with a low pH, low peat decomposition, and low nutrient level (low total phosphorus, potassium and nitrogen) whereas *E. robustum* has a much wider environmental range (Clarkson et al, 2004). Therefore in the later stages of development *S. ferrugineus* becomes the dominant cover with an understory of *E. robustum.* Ombrotrophic bog vegetation has adapted to the low nutrient environment where the only nutrients are from rainfall and therefore will outcompete potential rivals by growing tall and therefore intercept the precipitation first (Hodges & Rapson, 2010). As species succession moves towards a *S. ferrugineus* dominated bog evaporation rates will increase as *S. ferrugineus* has almost twice the evaporation rates from a dry canopy than that of *E. robustum,* which could consequently alter the hydrology of a long established bog (Campbell & Williamson, 1997; Thompson et al., 1999). Little is known about evaporation from the *E. pauciflora* which is also a late successional plant that is often found at sites where *S. ferrugineus* grows.

2.8 Peatlands affected by low water tables

Peatlands have been drained globally for various alternative land uses, including agriculture, roads and forestry, and the land use change often results in a lower mean water table (Chimner et al., 2016). Predicted climate change with altering hydrological regimes could also result in lowering of water table levels (Erwin, 2009). As the water table lowers, the vegetation composition changes in response to the hydrological regime and then further drives the low water table due to increased transpiration (Frankl & Schmeidl, 2000; Laine et al., 1995; Price et al., 2003). This second succession can last for decades and can change the carbon and nutrient cycling though the system (Laiho et al., 2003). Sustained low water tables can result in *Sphagnum* mortality and an increase in ericaceous shrub productivity (Laiho et al., 2003; Potvin et al., 2014). Even slight lowering of the water table can change the vegetation from native bog vegetation to shrubs and then trees (Frankl & Schmeidl, 2000). In Finland peatlands have been drained for forestry and have resulted in loss of wetland vegetation and the change in vegetation from *Sphagnum* to forestry has resulted in mineralised nutrients being released from the peat and leached into the ecosystem (Haapalehto et al., 2011; Laiho et al., 2003). South East Asia has more than half of the world's tropical peatlands (24.8 Mha) and in Malaysia and the Islands of Sumatra and Borneo only 10 % remain in unaltered conditions with at least 60 % being changed for alternative land use (Hooijer et al., 2012). In Southeast Asia the drained peatlands are more susceptible to fires due to the drier canopy and increased wood debris (Miettinen, et al., 2012). Several peatlands have been subjected to controlled burning, such as in upland UK where fires are used for vegetation clearance to encourage red grouse population for hunting (Brown, et al., 2013). The exposed peat can be vulnerable to wind erosion, and overland flow and the ecosystem can be affected with reductions in macroinvertebrate species (Brown et al., 2013). This can occur in areas that are burnt due to wild fires and controlled fires. Controlled fires may be important to an ecosystem that would naturally be subjected to wild fires but these have been prevented for human safety. In New Zealand only 10 % of peatlands remain post European settlement (McGlone, 2009).

2.8.1 Peat degradation

Peat degradation occurs when the water table drops and the peat is exposed to oxygen (Labadz et al., 2010). The exposed peat is mineralised releasing nutrients such as nitrogen and phosphorus (Haapalehto et al., 2011) which can result in changing the tropic status of the environment allowing alternative vegetation to creep in. The decomposing peat then subsides and consolidates reducing pore spaces (Hooijer et al., 2012), which in turn changes the hydraulic properties of the peat, e.g. specific yield and hydraulic conductivity. This can act in the bogs favour by preventing excessive loss of water though seepage (Price et al., 2003). Although downward seepage from a bog is low and decreases as the peat becomes more humified, seepage will still occur when adjacent land has been drained (Schouwenaars, 1993).

Peatlands store organic carbon and as the peat decomposes carbon dioxide is released into the atmosphere (Clymo & Bryant, 2008). Therefore, preventing further peat decomposition is an important factor in trying to mitigate increased rates of climate change.

2.8.2 Peatland restoration

Restoring a peatland hydraulic regime is the most important aspect of any restoration project t (Chimner et al., 2017; Schouwenaars, 1993). Hydrological restoration of a peatland can be achieved both externally and internally. Externally restoring the water table can be achieved through drain blockage and/or buffer zones (Schouwenaars, 1993), although the original state of the bog may be hard to achieve even after the water table is restored (Price, 1992). How long restoration takes depends on how long the area has been altered and how degraded peat is (Bonn et al., 2016). Drain blocking can restore water table depths although not necessarily identical to an unmodified site and additional water may need to be added during summer when water input is at a deficit (Holden et al., 2011). To restore these areas ditches were blocked and trees removed, and as a result the water table level came closer to the surface and some of the successional native bog vegetation had the chance to thrive (Haapalehto et al., 2011). In the case of a peatland with a low water table the main focus is on restoring the water table to a natural level to produce a more natural system. Internally restoration involves increasing the peat water storage abilities and restrict water level fluctuation (Schouwenaars, 1993). For this to occur native bog vegetation such as *Sphagnum* needs to thrive and restore the natural water holding capacity of the peat, when the peat has been restored to 30 – 40 cm thick it can become self-regulating and the water table fluctuations are no longer affected by the humified layer underneath (Schouwenaars, 1993). Most restoration studies have been conducted in the Northern Hemisphere on *Sphagnum* bogs that have been drained and mined, and the remaining peat is highly humified, the main priority has been to establish a hydrological regime that encourages *Sphagnum* growth and peat production.

2.9 New Zealand peatlands

New Zealand peatlands cover 0.73 % of the land surface (Clarkson et al., 2017). Post European settlement 90 % of peatlands have been drained and converted to alternative land uses such as agriculture (McGlone, 2009). Waikato peatlands started to form around 18,000 years ago as a result of the ancestral Waikato River leaving saturated depressions for long enough for peat to form, (Waikato Regional Council, 1999), an ideal wet and warm climate conditions around 10,000 years ago increased the rate of peat formation (McCraw & Geoscience Society of New Zealand, 2011). Over an estimated 1000 – 2000 years, as peat accumulated the bogs began to rise above the available ground water resulting in ombrotrophic conditions, allowing restiad species to thrive (de Lange et al., 1999). The Waikato Region contains half of all New Zealand peat; of this an estimated 30,000 ha (25 %) of 110,000 ha is all that remains as restiad peat bogs, with the other 75 % converted to agriculture (Pronger et al., 2014). Northern New Zealand restiad peat bogs include Torehape, Kopuatai, Moanatuatua (Clarkson et al., 2016) and the Whangamarino bog (Shearer, 1997) as well as bogs located in Northland. Bogs in northern New Zealand are unique as they are in an unusual environment with warm dry summers that create a climate that does not suggest the existence of raised peat bogs (McGlone, 2009).

2.9.1 Previous studies at Moanatuatua

Previous studies carried out at Moanatuatua have ranged from vegetation, peat properties, groundwater modelling, and the effect of burning amongst many others. Evaporation rates from the bog were studied by Thompson (1997) (published by Thompson et al., (1999), where evaporation was measured using the Bowen ratio energy balance method. Grimshaw (2000) used MODFLOW to simulate the groundwater hydrology at Moanatuatua and establish any influence the drains have on the water table. Hydraulic conductivity, hydraulic head, rainfall and evaporation were used in the model. Her conclusion was that climate variability had more influence on the water table and that the border drains only impact the water table a maximum of 20 m into the bog on either side, however current results show the drains may have more impact further into the bog than previously suggested. Both of these studies were conducted over relatively short time scales.

Fires occur naturally in peat bogs. *E. robustum* regenerates from seeds and can reach pre-fire height in six years, *S. ferrugineus* recovers within 12 years (de Lange et al., 1999). The last fire at Moanatuatua occurred in 1972 and *E. robustum* and *S. ferrugineus* have both since recovered. After the 1972 fire 23 species of plants were growing in Moanatuatua bog, Clarkson et al., (1999) found that six species had become extinct, which might be due to the low water table or competition for sunlight as vegetation cover increased. Fires that occur when the peat is dry result in burning of the overlying peat surface, if the water table is very low too much peat will be lost resulting in the loss of seed bank and rhizomes. Matheson (1979) suggested that fire

may be an important part of the Moanatuatua bogs life cycle and that it prevents *S. ferrugineus* from out competing all other vegetation.
Clarkson et al., (1999) investigated the peat health at Moanatuatua and found the nutrients in the peat were increasing, namely potassium which may be due the areal drift of nutrients from the adjacent farms.

Thompson et al., (1999) compared the evaporation rates of dense swards of *S. ferrugineus* between Kopuatai and Moanatuatua and noted that that water table at Kopuatai remained near the surface for the time of the study period whereas at Moanatuatua the water table was around -440 mm below the surface. This affected the dry bulk density which was higher at Moanatuatua and the volumetric peat moisture content was lower. The results showed that evaporation rates from *S. ferrugineus* dominated peat bog to be an average of 2.74 mm day^{-1} at Moanatuatua and 3.01 mm day^{-1} at Kopuatai (Thompson et al., 1999). In the earlier study by Campbell & Williamson, 1997) the average evaporation rate was 1.54 mm day^{-1} at Kopuatai where the vegetation is dominated by *E. robustum*. In a separate study of the CO^{2} balance during 1999 – 2000 water table measurements over the two year period had a mean of -580 mm (Campbell et al., 2014).

Study Sites and Methodology

3.1 Study sites

3.1.1 Location

Moanatuatua and Kopuatai are located in the Waikato Region of Te Ika-a-Māui, Aotearoa/New Zealand (Figure 3.1). Moanatuatua is located 17 km south-east of Hamilton (37°55.5′S, 175°22.2′E, altitude 65 m), is surrounded by pasture and bordered by ring drains. Kopuatai bog is located in the Hauraki Plains (37.387° S, 175.554° E) (Figure 3.1). The climate in the Waikato is mild with few frosts, mean temperatures of 13.0 – 14°C and moderate rainfall (annual mean 1112 – 2000 mm) (Chappell, 2014). Climate analysis shows that Moanatuatua is cooler than Kopuatai due to its inland location; both areas have winter rainfall maximums (Chappell, 2014).

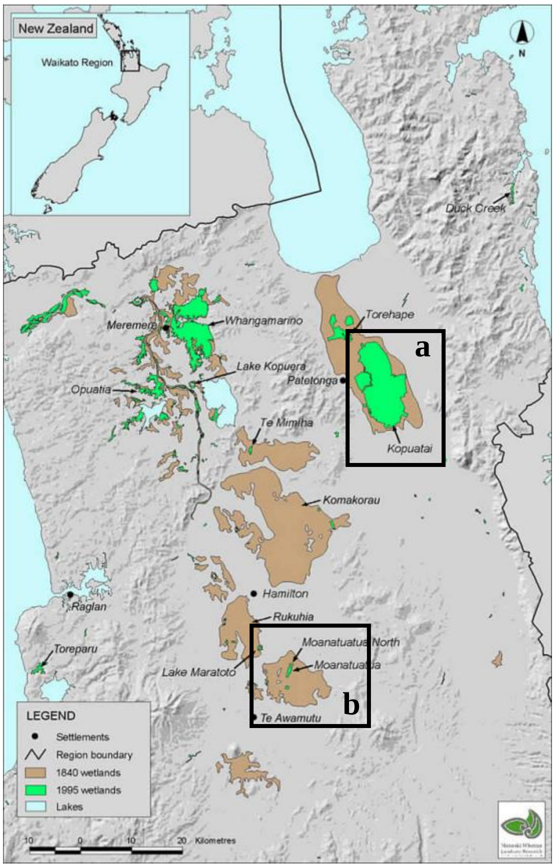


Figure 3.1: Waikato Region with historic and current wetland extent. The location of Kopuatai (a) and Moanatuatua (b) are indicated by the black boxes. Adapted from Manaaki Whenua, Landcare Research, (https://www.landcareresearch.co.nz/science/plants-animals-fungi/ecosystems/wetland-ecosystems).

3.1.2 Moanatuatua

Moanatuatua bog is a raised peat bog that was once an estimated 75 km^2 in extent and now only an area of 1.1 km^2 remains (Clarkson et al., 2004). Moanatuatua bog peats began to accumulate 13,000 years ago in a depression left behind in the Waikato River's ancient path (Clarkson et al., 1999). The bogs formed on weathered volcanic deposits which created an impermeable layer (Campbell, 1964). The present day bog remnant is surrounded by pasture developed on peat 8 – 12 m deep, with drains 1 – 2 m deep along the edge on both sides (Thompson et al., 1999). Most of the land area of Moanatuatua bog has been drained and converted to pasture and blueberry orchards, the most recent conversion occurred during early 1960s on farmland bordering the current site observed be Schipper & McLeod (2002). The water table sits unnaturally low with a mean of 580 mm below ground (Smith, 2003). This is low considering the water table at Kopuatai bog has a natural maximum annual water table depth of 30 mm during drought (Jordan P. Goodrich et al., 2017).

Deep drains on either side of Moanatuatua bog have resulted in lower water tables in the bog adjacent to the drains compared with the interior of the bog (Clarkson et al., 1999, Grimshaw, 2000). The western drain is deeper than the eastern drain in relation to the bog surface, and both drains border directly onto the edge of the bog. The western drain was deepened around 1999 (Clarkson et al., 1999). The eastern drain has a buffer strip between the edge of the bog and the neighbouring farm, and the pine trees that were there have been removed and replaced with newly planted manuka.

3.1.3 Kopuatai

Kopuatai peat dome is a raised peat bog with an area of 96 km^2 which is the largest undisturbed site remaining in New Zealand (Clarkson et al., 2014). Peat development at Kopuatai bog is was initiated in a fault-bounded palaeochannel depression approximately 11700 BP (Newnham et al., 1995). Present day Kopuatai has a peat depth of up to 14 m in some areas (Newnham et al., 1995). It is of national significance as it has important ecological functions and is one of six wetlands in New Zealand that is protected under the Ramsar list of Wetlands of International Importance (Ramsar, 2016).

3.2 Vegetation

The main peat-forming plant found in Moanatuatua is the restiad the “jointed wire rush” *E. robustum* (Goodrich et al., 2017) and the other restiad at Moanatuatua has the function of preserving the peat is the “cane or bamboo rush” *S. ferrugineus* (de Lange et al., 1999). Both are endemic to New Zealand (Wagstaff and Clarkson, 2012). *E. robustum* grows up to 0.7 m, its tangled foliage provides an understory to *S. ferrugineus* which stands up to 2.8 m tall and with a thick canopy (Campbell et al., 2014). Moanatuatua also contains two wetland woody species *Epacris pauciflora, & Leptospermum scoparium* which grow as a result of the low (Clarkson et al., 1999). Other species include *Gleicheni dicarpa* also known as tangle fern and the sedges *Baumea teretifolia* and *Schoenus pauciflorus* (Clarkson et al., 1999).

The *Empodisma* genus was recently separated into three distinct species, two of which occur in wetlands in Australia - *E. gracillium* and *E. minus*. *E. minus* is also found in New Zealand and it was thought that *E. minus* was found throughout peat bogs in New Zealand. However, after DNA sequencing by Wagstaff & Clarkson (2012), *E. minus* was separated into two distinct species, *E. minus* and *E. robustum* (Figure 3.2) the latter which only occurs north of 38° S in New Zealand. *E. robustum* was named due to its robust growth stature.
Vegetation on Kopuatai bog is similar to Moanatuatua although Kopuatai is dominated by *E. robustum* with a smaller percentage of *S. ferrugineus* (Thompson *et al.,* 1999) (Figure 3.2).

Figure 3.2: *Empodisma robustum* ground cover with *Sporadanthus ferrugineus* growing through it at Moanatuatua (left) and *E. robustum* – dominated Kopuatai (right).

There are two species of *Sporadanthus* plants in New Zealand. *S. traversii* is only found in the Chatham Islands and *S. ferrugineus* (Figure 3.3) is found in northern New Zealand. *S. ferrugineus* is often found in dense stands of 200 – 300 stems with a diameter of 0.2 – 1.5 cm and 1.85 – 2.3 m tall (de Lange et al., 1999). Habitat for the late successional *S. ferrugineus* is in raised peat bogs in an acidic environment (pH <5) along with other restiad plants. *S. ferrugineus* is endemic to New Zealand. The population at Moanatuatua is threatened by the lowering of the water table (de Lange et al., 1999). *S. ferrugineus* is classified as an ‘ at risk – relict’ as of 2012 under the conservation status of New Zealand plants (de Lange et al., 2013). The country has a responsibility to ensure its survival into the future, therefore knowing how it is affected by or affects low water tables is important.

Figure 3.3: *Sporadanthus ferrugineus* at Moanatuatua

3.3 Methodology

3.4 Water table regime

In order to determine the water table level several measurements were recorded. These included automatic measurements of water table depth below the peat surface, and manual measurements both of the water table level and the peat surface. The manual measurements can then be compared with the sensor measurements as a way of data quality control.

3.4.1 Pressure Transducer

Measuring the water table at Moanatuatua was done using an existing 675 m hydrological transect comprising of nine sites (Figure 3.4). At each site a data logging pressure transducer (Solinst Levelogger) was installed inside a PVC dipwell (Figure 3.4). In order to record the absolute water level (AWL) from a fixed datum at sea level, the pressure transducers were suspended on wire cables attached to a metal rod that had been inserted through the peat and into the underlying mineral sediment. Measurements of the water level in the dip well were recorded continuously and were then downloaded onto a computer during site visits. These data were verified using manual measurement of the AWL in the dip well.

Table 3.1: Moanatuatua hydrological transect monitoring locations and Solinst Levelogger details. Elevation is referenced to the top of the steel rod.

Type	SN	Site	NZGD2000	Northing	Easting	Elevation (m)
Levelogger	2046457	M1		683904.26	452922.57	63.86
Levelogger	2046462	M2		683899.02	452941.03	64.89
Levelogger	2048248	M3		683894.27	452970.70	65.10
Levelogger	2048251	M4		683880.31	453015.08	65.30
Levelogger	2050273	M5		683857.63	453116.74	65.89
Levelogger	2050275	M6		683826.61	453232.97	64.03
Levelogger	2050553	M7		683790.79	453387.94	65.68
Levelogger	2050555	M8		683752.72	453528.75	65.20
Levelogger	2050565	M9		683732.93	453572.19	63.47

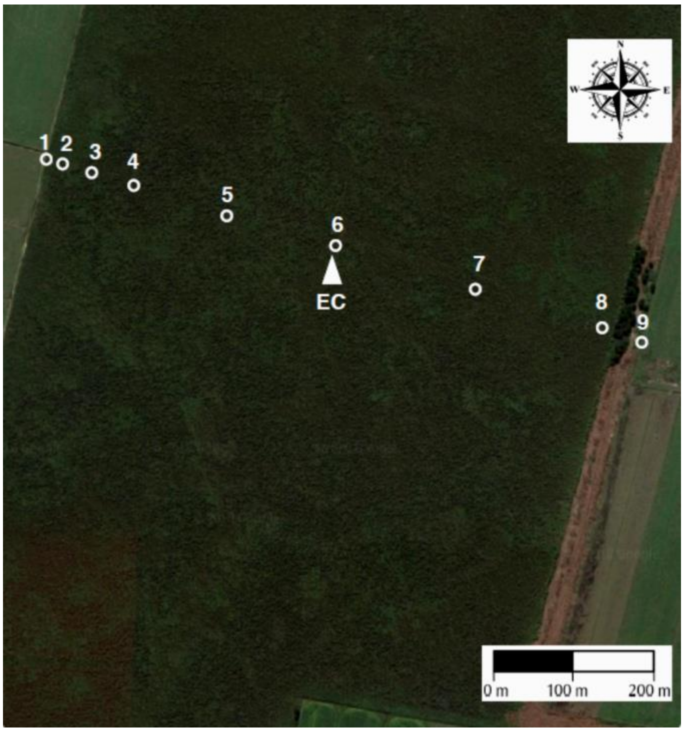
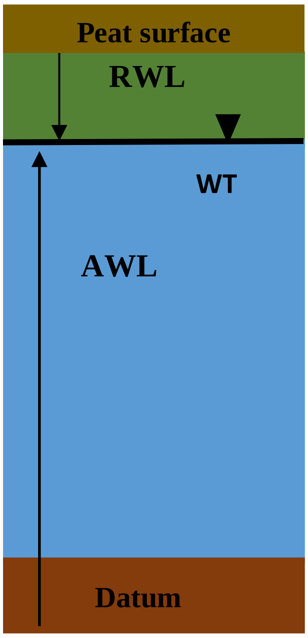


Figure 3.4: Google Earth image of part of Moanatuatua Scientific Reserve, showing the water table monitoring transect, with Solinst level logger sites labelled 1 – 9 (circle), and EC tower (triangle).

3.4.2 Manual water table measurements

Water table level is referenced to two different positions (Figure 3.5). The relative water level (RWL) is measured from the peat surface down to the water table and is affected by of the peat surface (PSO). The RWL is the water level depth relevant to the plants and other organisms. The absolute water level (AWL) is calculated from a fixed datum e.g. mean sea level and is not affected by the oscillating peat surface. In order to determine the shape of the water table across the bog, AWL is used.



Abbreviation	Term	Explanation
RWL	Relative water level	Vertical distance between water table and peat surface
AWL	Absolute water level	Vertical distance between water table elevation and stable datum e.g. mean sea level

Figure 3.5: Definition diagram showing the two methods for expressing the water table position.

At each site PVC dip well was installed next to the reference rod, and two metal tags were attached to the surface of the peat using galvanised steel nails (Figure 3.7; Figure 3.6). The tops of the reference rods were surveyed by a professional land surveyor on the 7 December 2015 and the heights were recorded (Table 3.1). Manual measurements of the AWL were taken inside the dipwell using a “bubbler” (a PVC tube attached to a bamboo pole with a fixed tape measure). Air was gently blown into the tube as it was inserted into the dip well. When air could be heard bubbling at the water surface the height of the pole against the top of the PVC dipwell was recorded (distance C) (Figure 3.7). This was done every time the pressure transducer data were downloaded.

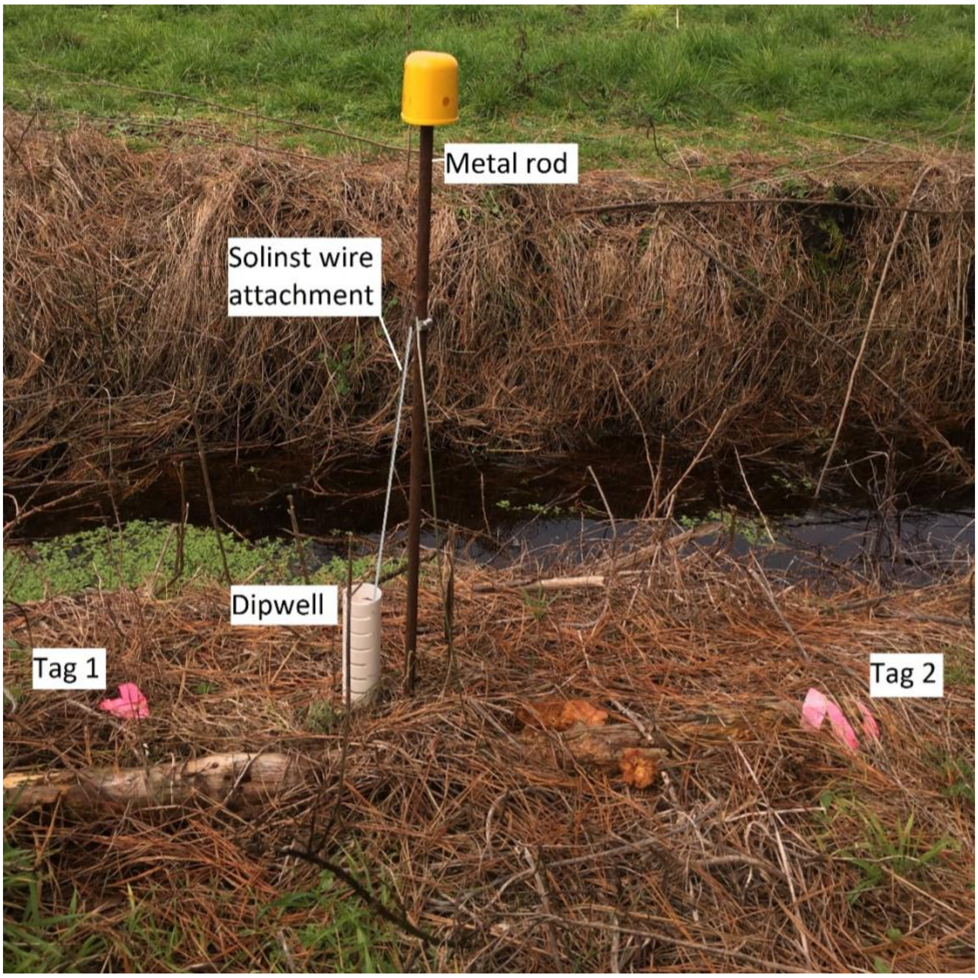


Figure 3.6: Site M9 (4 July 2018) next to border drain on eastern side of Moanatuatua

3.4.1 Manual water levels measurements

3.4.1.1 Relative water level

Depth of the water table below the peat surface (WTD) was calculated using (Figure 3.7)

WTD = – (C – HT)

Where HT is the height of the dipwell top above the peat surface

HT = A – B

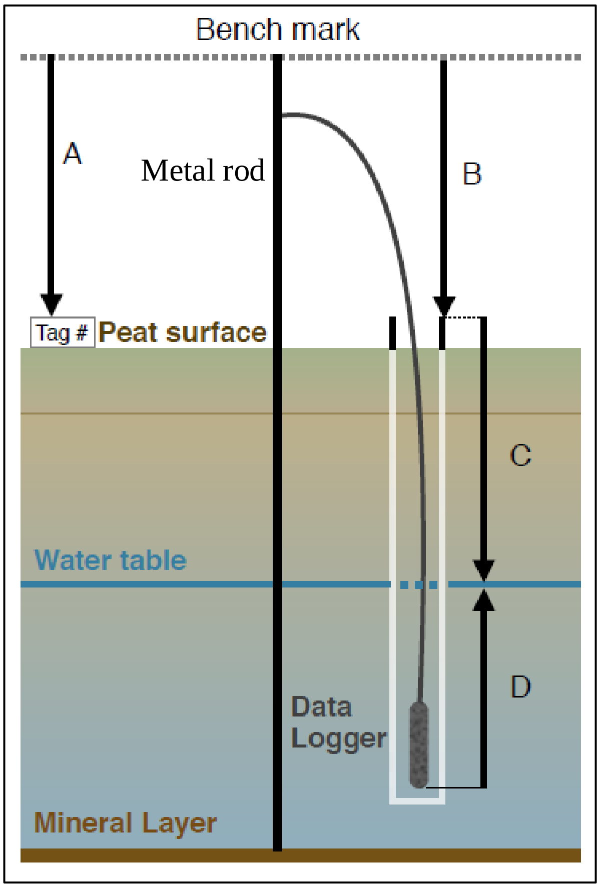


Figure 3.7: Schematic diagram of dipwell site setup at Moanatuatua. Measurement from top of metal rod to tag on peat surface (A), measurement from metal rod to top of PVC dipwell site (B), measurement from top of PVC pipe to water table (C), water depth measurements from Levelogger compensated for barometric pressure changes (D).

3.4.1.2 Absolute water level measurements

The height of the pressure transducer location above sea level was calculated using a bench mark (BM) where the elevation above sea level was based on mean of three repetitions of surveyed data obtained when probes were installed.

Probe height = BM – E – F, where E is the vertical distance from the top of the benchmark rod to where the wireline is attached, F is the distance from wire attachment to the base of sensor (Figure 3.8).

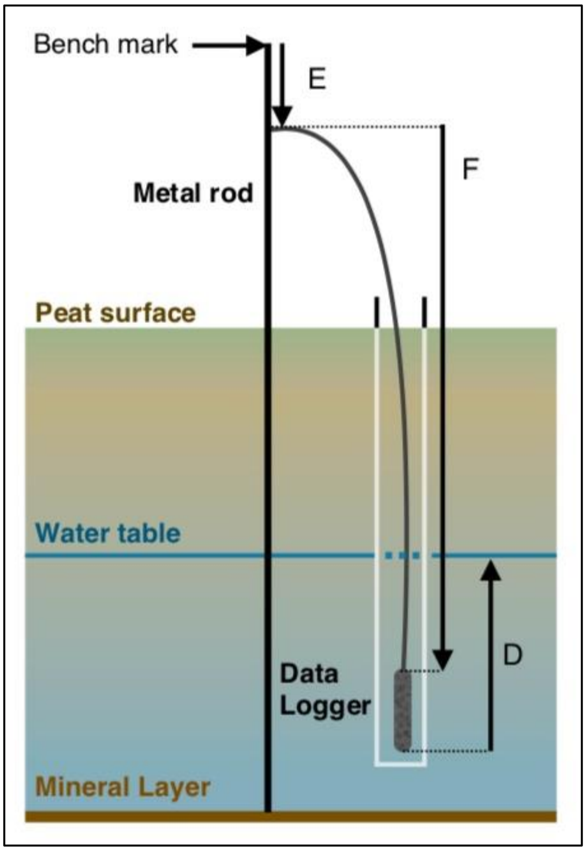


Figure 3.8: Schematic diagram of base measurements for location of Levelogger above datum.

3.4.1 Automatic water levels measurements

Levelogger data and Barologger raw data were downloaded onto a laptop computer. Using custom Solinst data converter software in Matlab the files were loaded into a database. All data analysis was carried out using Matlab scripts and functions. To convert raw Levelogger values to water depth (above the sensor) they needed to be “compensated” for barometric pressure changes by subtracting Barologger readings (D) (Figure 3.8).

The data then had errors removed from when data downloads occurred on site and the probe removed from the dipwell. All data from site M9 before 2 February 2016 was removed due to the Levelogger data before this time was out of sequence and considered unreliable.

3.4.2 Peat surface measurements

Peat surface measurements were taken at each site using the metal rod described above and metal tags placed on the peat surface and fixed into place with a galvanised steel nail. Two tags were placed at each site and the results were averaged out. Due to changes in the vegetation at the sites occasionally one tag was unable to be located, when this occurred only one tag measurement was taken. Measurements were taken from the surface tag to the metal rod (measurement A) (Figure 3.7) using a tape measure and a level.

The Barologger was located next to the EC tower sites and data were downloaded at each site visit.

3.5 Water balance

3.5.1 Eddy Covariance evaporation measurements

Flux densities of water vapour (latent heat flux, LE) were measured from 1 September 2015 to 31 August 2018 using an eddy covariance (EC) tower for both sites. The measurement site at Moanatuatua was located 350 m from the western border and 300 m from the eastern border. This Moanatuatua site set-up is fully described in (Ratcliffe et al, 2018). The EC measurements were taken using a sonic anemometer (CSAT3, Campbell Scientific Inc. (CSI), Logan, UT, USA) and an open path infra-red gas analyser (LI-7500, LI-COR Biosciences Inc., Lincoln, NE. USA) The EC sensors were attached to a guyed triangular lattice tower at 3.75 m height at Moanatuatua and 4.25 m height at Kopuatai (Figure 3.9).

Figure 3.9: EC tower sites. Moanatuatua (left) and Kopuatai (right).

Data were collected at 10 Hz using dataloggers: aCR3000 data logger at Kopuatai and a CR1000 datalogger at Moanatuatua (Campbell Scientific Inc.) including additional environmental measurements (Table 3.2)

Table 3.2: Additional environmental data

Variable	**Site**	
	Moanatuatua	**Kopuatai**
Photosynthetic photon flux density, PPFD	BF5, Delta-T, UK	BF5, Delta-T, UK
Net radiation (long and short wave) flux density	NR01, Hukseflux, Netherlands	NR01, Hukseflux, Netherlands
Air temperature	HMP-155, Vaisala Inc., Helsinki, Finland	HMP-155, Vaisala Inc., Helsinki, Finland
Relative humidity	HMP-155, Vaisala Inc., Helsinki, Finland	HMP-155, Vaisala Inc., Helsinki, Finland
Precipitation	TR-525M, Texas Electronics, USA, 0.2 mm tip	TB5, Hydrological Services, Australia, 0.2 mm tip

3.5.2 Data analysis

Latent heat fluxes were calculated using EddyPro with filtering for high quality data including EddyPro quality flags and eliminating data for periods of low turbulence. For more detail of the methods used at both sites, see Ratcliffe et al. (2018).

Missing data in LE flux measurements were gap-filled using Artificial Neural Networks (ANN). The ANN uses a network of multiple processing units and can be 'trained' by providing a set of training examples with input and output values (Papale & Valentini, 2003).

LE during night and day periods were gap-filled separately using photosynthetic photon flux density (PPFD) separated into daytime (PPFD $\geq$ 50 µmol $m^{-2}s^{-1}$) and night time (PPFD < 50 µmol $m^{-2}s^{-1}$). Daytime and night time LE ANN models consisted of drivers including net radiation (Rn), atmospheric vapour pressure deficit (VPD), air temperature (T_{air}) and an antecedent precipitation index (API) which simulates the delay in drying of the vegetation canopy following rainfall (Kohler & Linsley, 1951). During later analysis dry canopy data sets were defined using methodology from Thompson et al., (1999) with a day API threshold to ensure that any periods with a wet canopy were excluded.

Fuzzy datasets for time were generated. The fuzzy time variables included season, morning, evening and afternoon. “Fuzzy datasets” provide time information that can be understood by the neural network.

Water Table Regime

4.1 Introduction

This chapter examines the spatial and temporal variations of the water table at Moanatuatua to describe the water table regime in relation to the border drains and to establish the shape of the water table in relation to the peat surface. The study period was from 1st September 2015 – 31st August 2018. The data sets have been divided into three complete years of data, Year 1(1st September 2015 – 31st August 2016), Year 2 (1st September 2016 – 31st August 2017), and Year 3 (1st September 2017 – 31st August 2018). Final water table data downloads were undertaken on 23rd August 2018, however all other environmental data were recorded and download up until 31st August 2018.

4.2 Temperature and precipitation

Mean annual air temperature for the entire study period was 13.2°C at Moanatuatua (Table 4.1) compared with 30 year mean of 13.8°C from a nearby weather station located at Ruakura, Hamilton, New Zealand which is located midway between the two study sites (NIWA, 2010). Kopuatai was on average 1.2°C warmer than Moanatuatua with a mean of 14.4°C.

Table 4.1: Mean annual mean air temperature (°C) for each study year at Moanatuatua and Kopuatai.

	Moanatuatua	**Kopuatai**
Year 1	13.8	14.5
Year 2	13.2	14.2
Year 3	14.0	14.6
All years	13.2	14.4

Rainfall timings is an important influence on the water table level. Precipitation at Moanatuatua and Kopuatai differed between the two sites (Table 4.2). Moanatuatua had a mean annual rainfall of 1385 mm year^{-1} for the three years of study. The study period had higher than average rainfall for Years 2 and 3 compared with the 30 year mean of 1108 mm year^{-1} from the nearby weather station (NIWA, 2010), although Year 1 was closer to the long term average. Kopuatai had a mean annual rainfall of 1516 mm year^{-1} for the three study years, this resulted in a total of 392 mm more precipitation than Moanatuatua over the entire study period.

Table 4.2: Total yearly rain (mm) for each study year at Moanatuatua and Kopuatai

	Moanatuatua	**Kopuatai**
Year 1	1156	1419
Year 2	1724	1732
Year 3	1277	1398
Mean	1385	1516

Year 1 had less total precipitation, with an overall total of 1156 mm at Moanatuatua and 1419 mm at Kopuatai. Year 2 was considerably wetter with similar rainfall totals at Moanatuatua and Kopuatai, and during Year 3 precipitation totals dropped back again to 1277 mm at Moanatuatua and 1398 mm at Kopuatai (Figure 4.1). The individual sites had considerable differences in rainfall in Years 1 and 3, whereas Year 2 the rainfall total were similar, with both sites receiving high rates of rainfall.

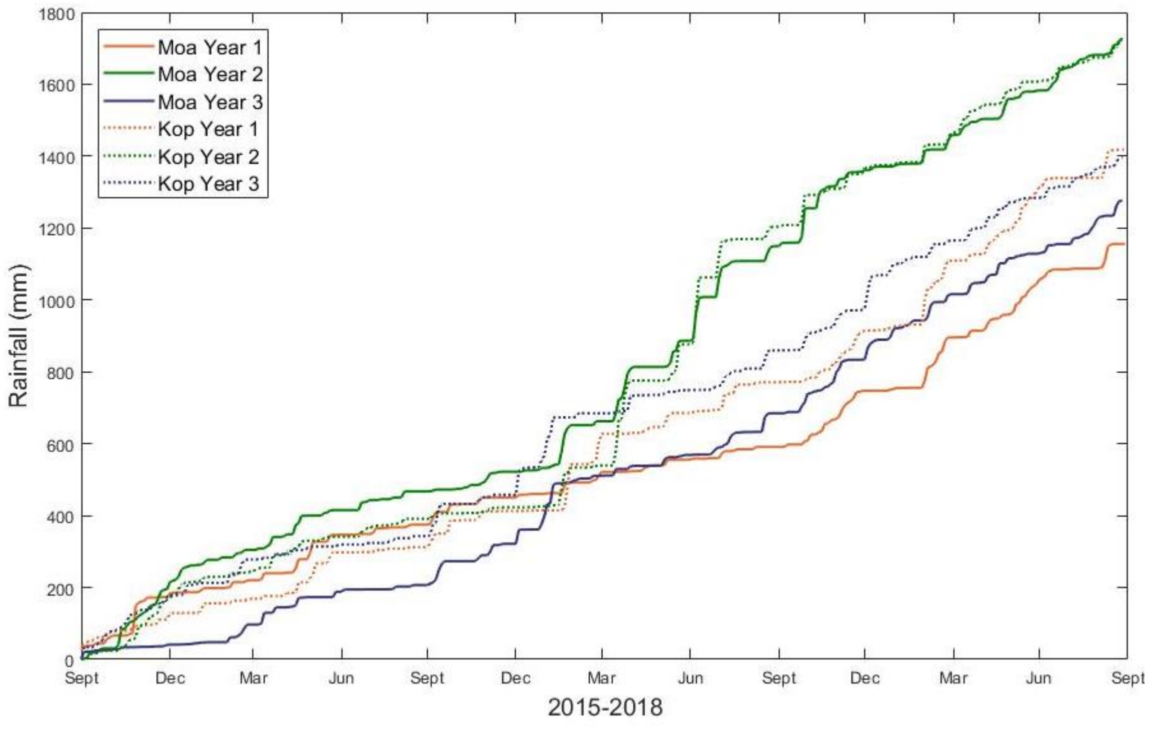


Figure 4.1: Cumulative rainfall for Moanatuatua (solid lines) and Kopuatai (dashed lines).

Seasonal rainfall (autumn (March – May), winter (June – August), spring (September – November) and summer (December – February)) varied at each site which is visually shown in (Figure 4.2). Autumn rainfall for Year 2 was much higher than both other years and higher than any other seasonal total. Moanatuatua rainfall totals show how unevenly distributed precipitation was during the three years of study. Year 2 had the highest rainfall during spring and autumn, with a lower winter total. Year 1 had the lowest autumn and summer rainfall. Total rainfall for Years 1 and 3 were similar even though seasonally the rainfall was distributed differently.

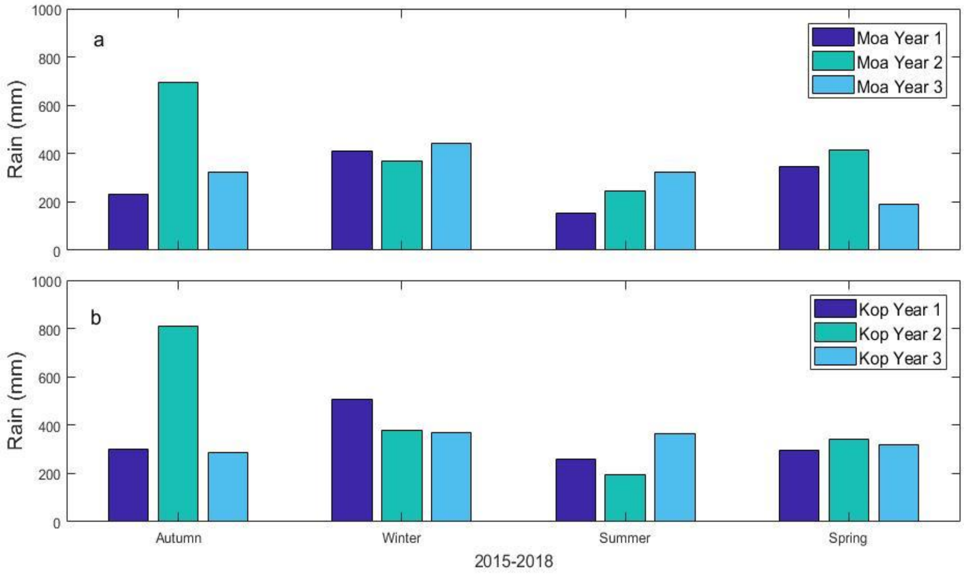


Figure 4.2: Total seasonal rainfall for (a) Moanatuatua and (b) Kopuatai. Autumn (March - May), winter (June – August), spring (September – November) and summer (December – February).

4.3 Kopuatai and Moanatuatua water table comparison

To establish the differences between the hydrologically intact Kopuatai and altered Moanatuatua, site M6 in the center of Moanatuatua was chosen as the comparison site, as water table measurements from Kopuatai were also obtained from the centre of the bog by the EC tower. This ensured that any effects the drain may have on the water table at Moanatuatua were minimised.

The water table at Moanatuatua was consistently lower than at Kopuatai during the study period (Figure 4.3), with no overlap in their ranges. Both bogs showed that during summer the water table was at its deepest below the peat surface, with Moanatuatua reaching a maximum depth of -1080 mm and Kopuatai -170 mm. Mean water table depth at Moanatuatua for the entire study period was -601 mm and at Kopuatai -25 mm.

Winter maximums were also observed with Kopuatai having a water table of 66 mm above the surface of the peat and Moanatuatua -312 mm below the surface. Monthly rainfall totals were generally higher at Kopuatai during the study period compared with Moanatuatua which would lead to higher recharge rates that assist in maintaining the water table height.

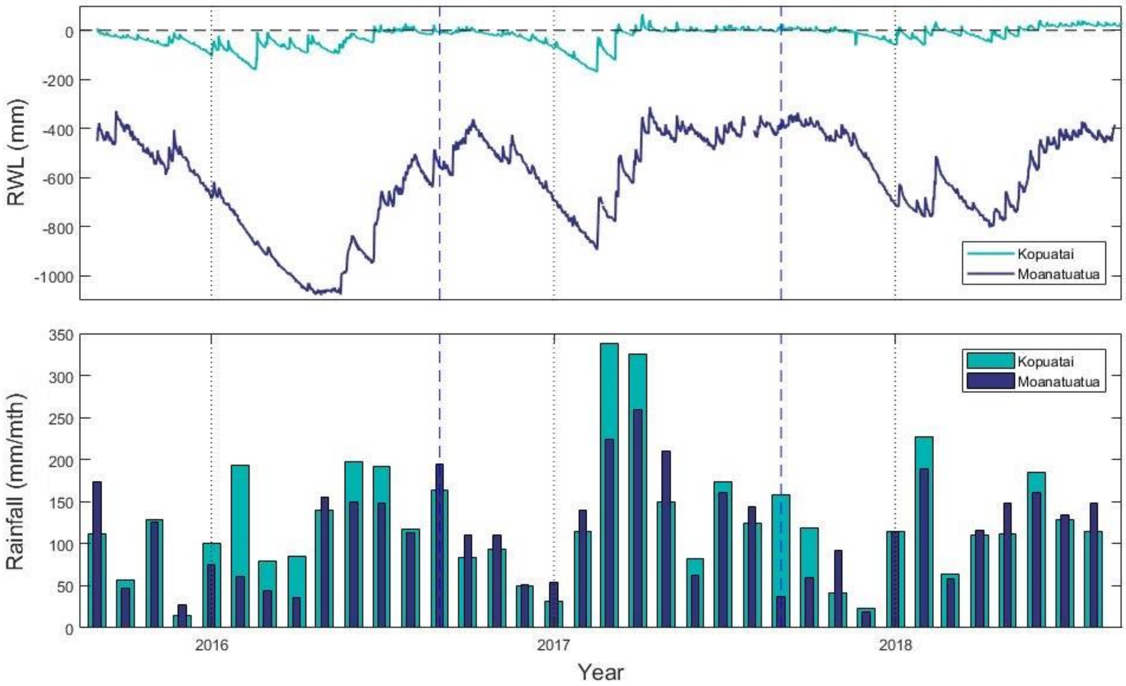


Figure 4.3: Daily mean water table depth and monthly rainfall for Kopuatai and Moanatuatua (site M6). The black vertical lines depict the calendar years and the blue vertical lines show the study Year 1, 2 and 3.

The RWL at Moanatuatua had the largest range of fluctuation from deep (maximum) to shallow (minimum) of -752 mm which occurred during Year 1. Rainfall during this period was also at its lowest, Moanatuatua received 106 mm less rainfall during the Year 1 summer than Kopuatai. During this period the RWL at Kopuatai averaged -47 mm (Table 4.3). The mean water table depth at Moanatuatua fluctuated between -469 mm and -752 mm, whereas Kopuatai fluctuated between -103 mm and -236 mm.

Table 4.3: Moanatuatua and Kopuatai relative water level (mm) maximum, minimum, range and mean for the three years of study.

Moanatuatua (site M6)	Maximum		Minimum		Range (max-min)	Mean
Year 1	Apr-16	-1080	Sep-15	-328	-752	-719
Year 2	Feb-17	-895	Apr-17	-312	-583	-527
Year 3	Apr-18	-804	Sep-17	-335	-469	-553

Kopuatai	Maximum		Minimum		Range (max-min)	Mean
Year 1	Feb-16	-162	Jul-16	29	-190	-47
Year 2	Feb-17	-170	Apr-17	66	-236	-25
Year 3	Jan-18	-60	Jun-18	42	-103	-4

4.4 Moanatuatua water level transect

4.4.1 Absolute water level

The absolute water level at Moanatuatua had a larger range from maximum to minimum during Year 1. In reverse Year 2 had the smallest range in water table depth due to the high precipitation throughout the study period which maintained a high water table (Figure 4.4). During Year 3 the water table remained fairly stable across all sites due to average winter and autumn precipitation for the 3 years, and a relatively wet summer which is reflected in the water table during February 2018, however spring during this period had lower precipitation than Years 1 and 2 the water table did still not drop as low as Year 1. Sites M1 and M9 were deeper than all other sites, Site M9 showed spikes after rainfall events indicating that this site was most sensitive to water input. Site M6 remained higher than all other sites as this was the center of the bog.

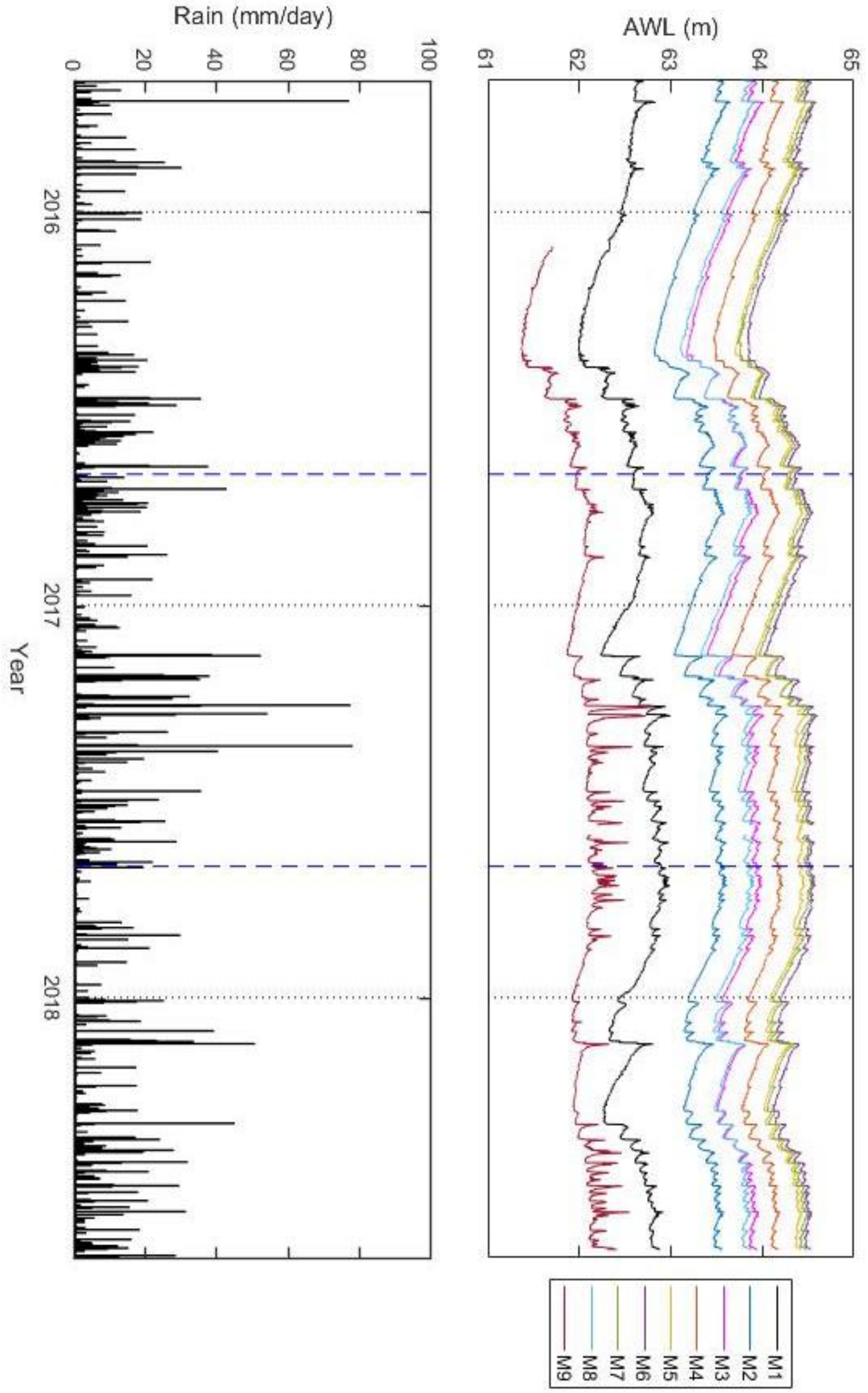


Figure 4.4: (a) Moanatuatua half-hourly absolute water level (AWL) for each site for the entire study period and (b) daily total rainfall. The black vertical dotted lines depict the calendar year and the blue vertical lines show the study Years 1, 2 and 3.

Absolute water level for each year followed the shape of the surface of the bog (Figure 4.5) with the highest AWL located at M6 in the centre of the bog and then decreasing toward the eastern and western borders where the drains are located. The surface of the bog was obtained from manual measurements of the vertical distance of the metal benchmark rods to the peat surface tags. The manual measurements were taken during each site download, then averaged to give a representation of the peat surface. The red outliers show the extreme events that resulted in the water table at M9 spiking after rainfall events where the eastern drain may have flooded.

In Year 1 AWL showed greater range at all sites than the subsequent years as rainfall was lower for two seasons during this period which allowed the water table to drop extremely low. Site M9 on the eastern drain was lowest for all three years with extreme rainfall events causing the water table to rise close to the surface. These can be observed in Figure 4.4 with large fluctuations in the AWL during sustained rainfall events. During Year 2 M9 reached 62.8 m AWL and the peat surface average was 62.73 m above mean sea level. Year 2 had the least fluctuation in the AWL and this year also had the most rainfall with a wet spring and autumn preventing the water table from reaching extreme depths.

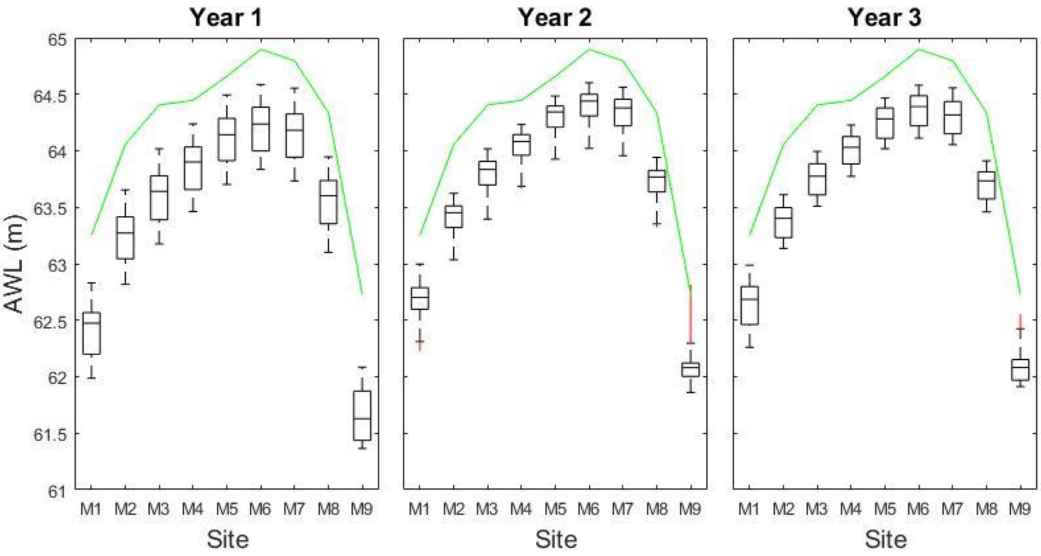


Figure 4.5: Boxplots of Moanatuatua AWL for each of the study years showing the range (upper quartile, median, lower quartile, maximum and minimum) in AWL across Moanatuatua at each site along with the peat surface elevation in green.

Spatial maximum, mean and minimum AWL are represented in Figure 4.6. Maximum was taken as the highest AWL at each site for the entire study period and minimum was the deepest point the AWL reached. The mean AWL is closer to the maximum and shows that the water table remained on the shallower side for most of the study period. This is common in hydrological datasets due to the relatively very large maximum values compared to the majority of values resulting in a skewed response. Distance across the bog shows the shape of the water table, with the water table not reaching the peat surface at most sites although M9 was close after the rainfall event in April-2017 where the drain may have flooded (Figure 4.6). The maximum, mean and minimum AWL all follow the shape of the peat surface giving an overall dome shape for Moanatuatua. This shape is common for domed bogs, with the central part of the bog rising higher than the margins (Ingram, 1982). At sites M1 and M9 both the AWL and peat surface show a steep gradient towards the drains on the borders.

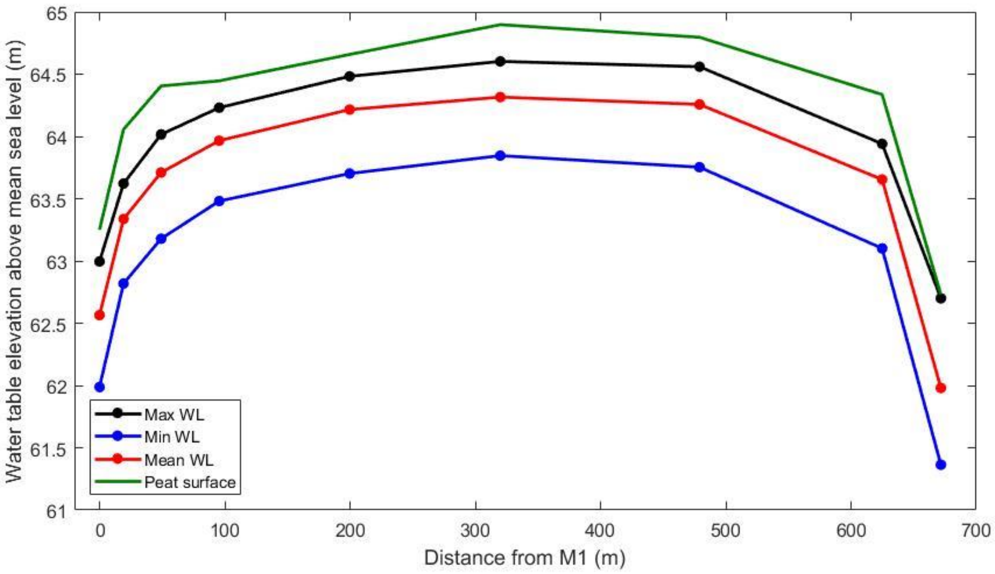


Figure 4.6: Maximum (black), mean (red) and minimum (blue) AWL for each site (represented as dots) across Moanatuatua for the study duration. The peat surface above the water table is shown in green.

4.4.2 Relative water level

Relative water level (RWL) shows the water table depth below the peat surface and is therefore most relevant for describing the hydrological regime relevant to plants. The maximum depth of the RWL represents the thickness of the aerobic acrotelm, or upper layer of peat (Ivanov, 1981). Year 1 had the lowest RWL at all sites due to the low rainfall totals in summer and autumn 2016 that saw a continuous decrease in RWL across all sites from December 2015 to May 2016 (Figure 4.7). The effect of the increased rainfall during Year 2 (autumn 2017) shows large spikes in the RWL especially in M9 although all sites had a high water table during this period. Year 3 spring 2018 had higher precipitation than the previous two years and had a wet February 2018 which helped prevent the post summer water table draw down. RWL is not as uniform as AWL as RWL varied with the thickness of the over lying peat, whereas AWL does not take into account the peat surface.

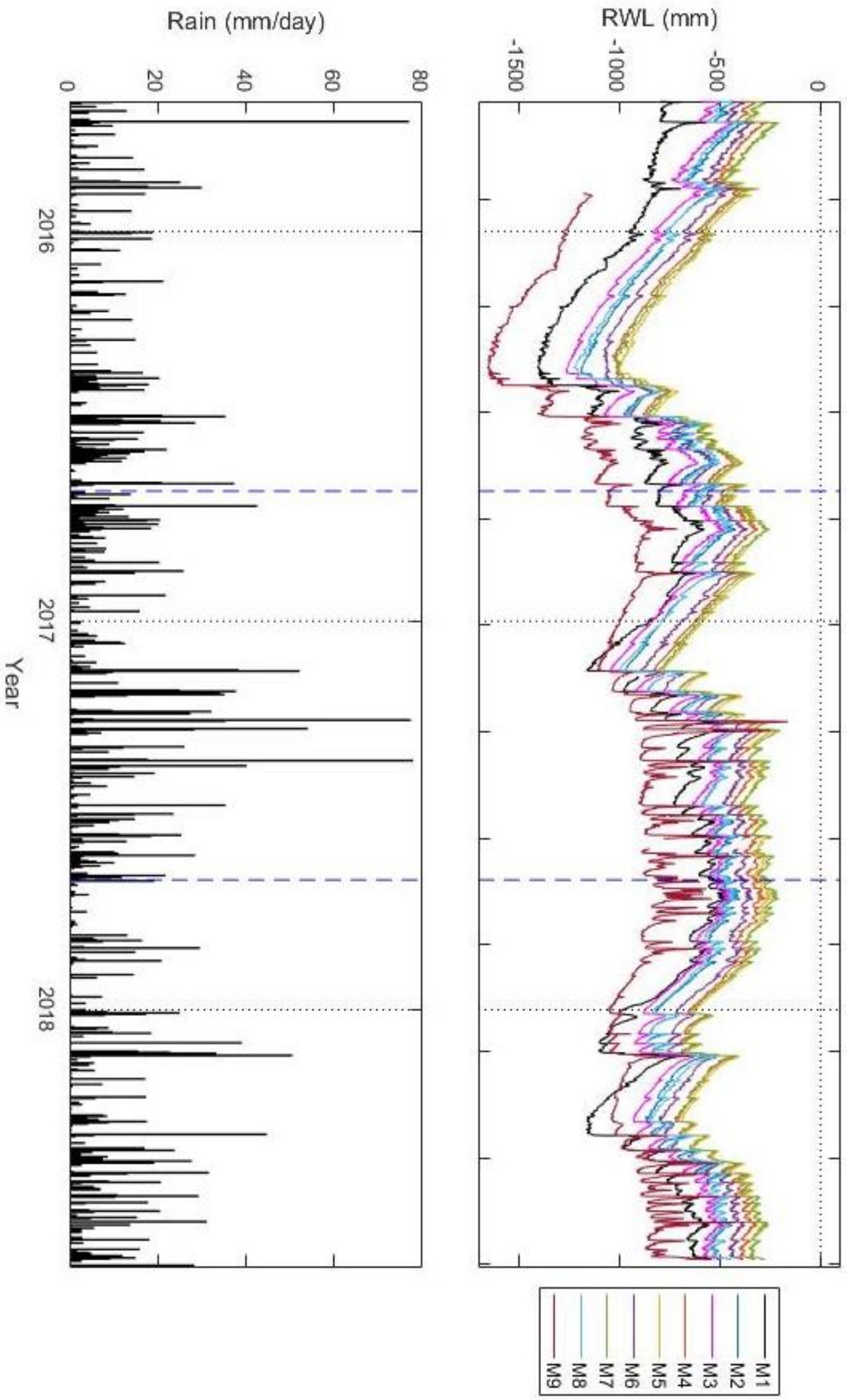


Figure 4.7: Half hourly relative water level for each site for entire study period and daily total rainfall. The black vertical lines depict the calendar year and the blue vertical lines show the study Years 1, 2 and 3.

Figure 4.8 shows how quickly each site reacts to rainfall events. High rainfall in Year 2 resulted in the RWL being close to the surface and therefore reacting rapidly to rainfall events. Figure 4.8 shows 2 – 20 April 2017 when rainfall events caused the water table to rise quickly. Site M9 was most sensitive to rainfall events with the water table increasing from -916 mm on 4 April 2017 to -163 mm on 5 April 2017 after the first rainfall event. Then at site M9 the RWL subsided to -880 mm by 10 April 2017. Another rainfall event occurred on 12 April 2017 showing the same pattern of a sharp rapid rise in RWL of -880 mm -301 mm and then fell rapidly to -735 on the 16 April 2017, and continued to decline back to -880 by 21 April 2016. All sites reacted to rainfall events with the sites located next to border drains showing the highest sensitivity. Relative water level at sites M2 – M8 also increased in response to rainfall although they did not decline as rapidly and tended to maintain the higher water level for a longer duration and then rose more in response to the second rainfall event whereas M9 dropped down again and did not increase as much after the next rainfall event. M9 is right on the border next to the shallow eastern drain and the site receives runoff and seepage from the neighbouring paddocks. The peat at the edges of the bog is likely more degraded than the centre and therefore has a more sensitive water table regime. Site M9 on the eastern border had the strongest reaction to the rainfall events which is a result of the nearby drain flooding, this was not experienced at M1 on the western side due to the drain being much higher than the drain, therefore does not flood over the bog surface.

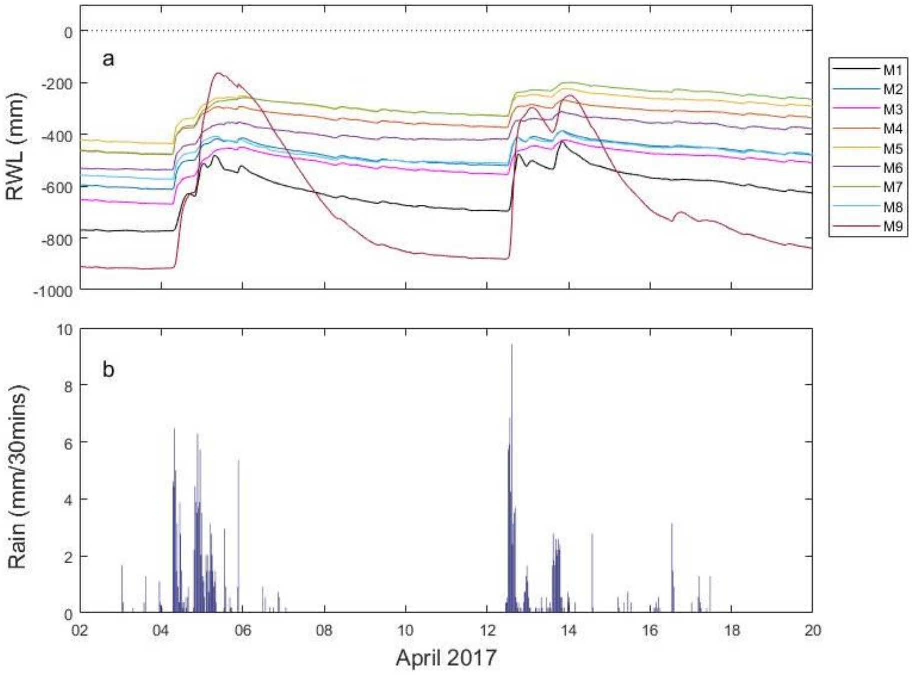


Figure 4.8: Moanatuatua (a) relative water level (RWL) in response to (b) rainfall events during 2 – 20 April 2017.

Annual statistics for RWL across the Moanatuatua transect (Figure 4.9) varied slightly less than AWL as RWL is in relation to the peat surface. Sites M1 and M9 adjacent to the drains had lower RWL than the central drains with M9 lowest for all three time periods. At all sites RWL remained below the peat surface for the duration of the study, in contrast to Kopuatai (Figure 4.3). The high water table levels at M9 during Year 2 are due to the high autumn rainfall in April 2017. Over all, Year 2 had the least range in RWL due to the above average rainfall, and Year 1 had the highest range as a result of the dry summer and autumn.

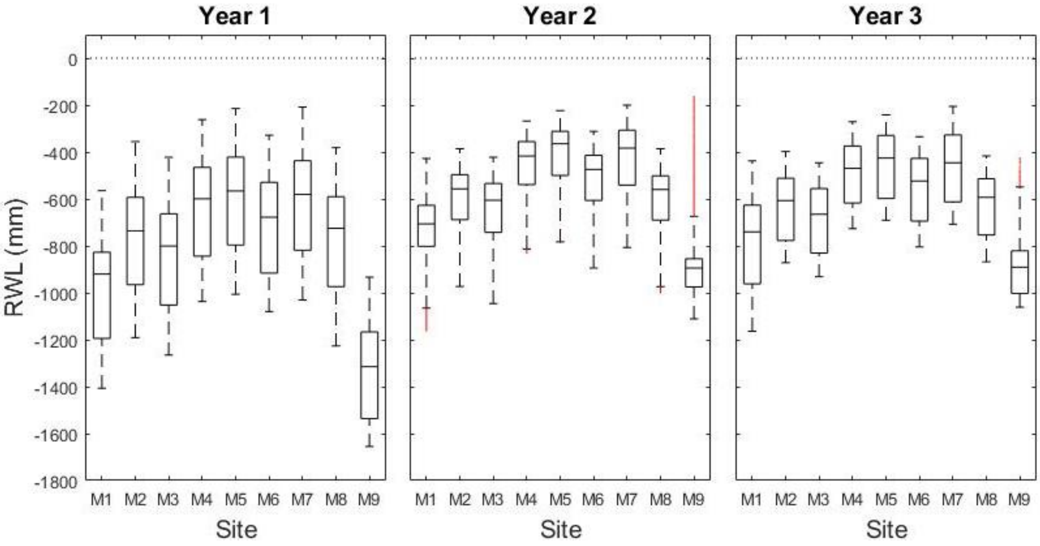


Figure 4.9: Boxplots of relative water level (RWL) statistics for each of the study years (upper quartile, median, lower quartile, maximum and minimum) in RWL at all sites across the bog, extreme values are shown as outliers for M9 and M1.

Spatial analysis of the RWL (Figure 4.10) across Moanatuatua indicates that M9 had the highest range in maximum and minimum water table levels. M9 also had the lowest RWL of all sites indicating how sensitive it is to the eastern border drain resulting in the large differences between maximum and minimum. M1 is close to the western border drain but does not show the same rapid reaction to rainfall events as it is much higher than the drain. The impact of the drawdown of the water table as a result of the border drains is localised as did not extend the width of the bog where the RWL starts to plateau and becomes lower at the centre. The border drains do not appear to impact the entire width of Moanatuatua (Figure 4.10). M6 is located towards the centre of the bog and shows a deeper RWL dropping deeper in the peat profile below the peat surface relative to the adjacent sites (M5, M7). At site M3 the RWL dropped below the surface of the bog relative to M2 and M4.

Figure 4.10 shows that from M4 located 95 m from the western drain of the bog and M7 located 193 m from the eastern drain is where the draw down from the border drains ceases to have an impact on the RWL.

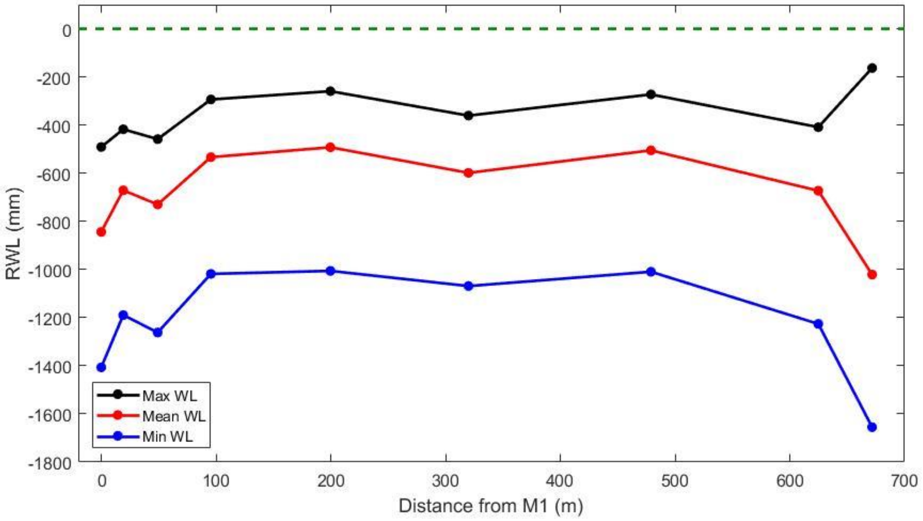


Figure 4.10: Maximum (black), mean (red) and minimum (blue) RWL for each site (represented as dots) across Moanatuatua for study duration. Horizontal dotted green line show the position of the peat surface

Closer investigation of the RWL when it was at its lowest during April 2016 (Figure 4.11), after a drier than average autumn and summer indicates that the water table reached a maximum low at the centre of the bog. Sites M4 – M7 towards the centre of the bog started to plateau on 1 May 2016, whereas sites M2, M3 and M8 continued to drop possibly indicating they were affected by the border drains whereas the central sites were isolated from the drain drawdown affect. Sites and M1 and M9 also plateaued but they may have reached the water table of the surrounding paddocks and therefore could not drop any further.

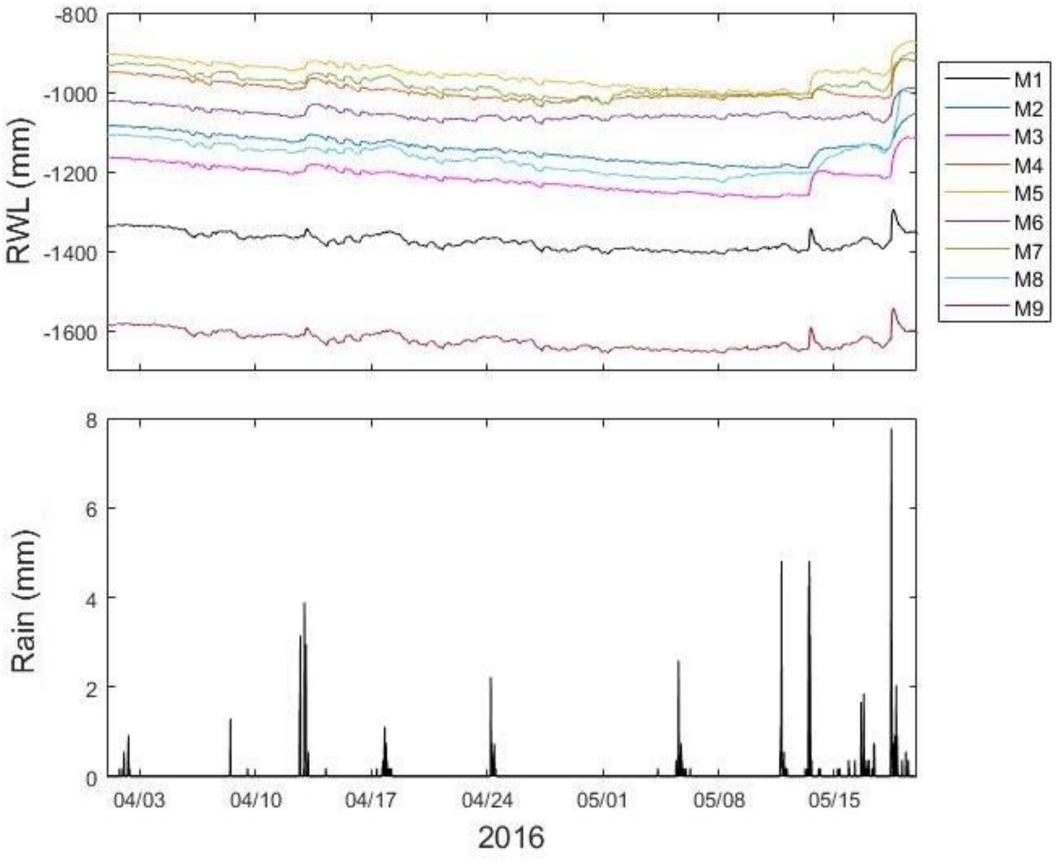


Figure 4.11: Rainfall and RWL depth for M1 – M9 during 1 April 2016 – 15 May 2016.

4.5 Moanatuatua summer water table

The summer (Dec – Feb) water table data were examined separately since this is when the water table can reach its lowest point due to limited recharge from rainfall and continued water loss via evaporation. Summer rainfall totals were 175 mm, 248 mm and 323 mm for Years 1, 2 and 3 respectively. Year 1 had highest variation in water table at all site and due to the low summer rainfall which is shown in both the RWL and AWL (Figure 4.12). In Year 2 summer the AWL range was reduced due to the high rainfall, this is not the same in the RWL for year two which had a larger range from shallow to deep. Year 3 had the smallest range in RWL but a larger range in AWL when compared with Year 2. Site M9 had the lowest AWL and RWL for the entire study period and was located deep below the peat surface especially in Year 1 when rainfall totals were at a minimum. The red outliers seen at site M9 indicate rainfall events during which the site flooded.

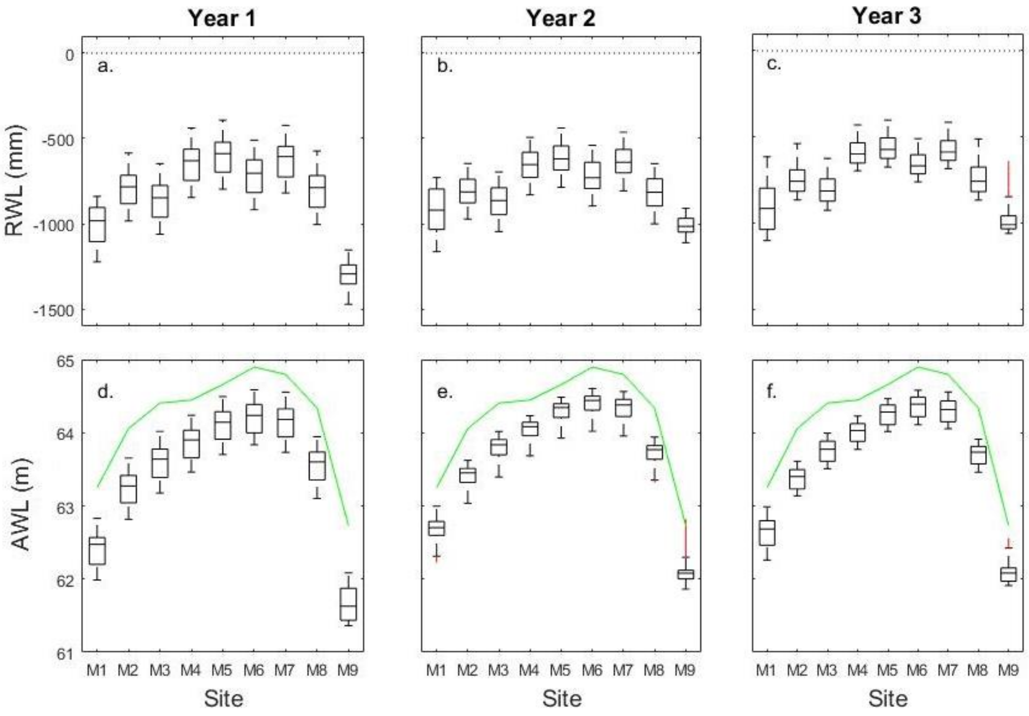


Figure 4.12: Boxplots of relative (a – c) and absolute (d – f) water levels (RWL, AWL) at Moanatuatua during summer (December – February) for each of the study years. Boxplot statistic show (upper quartile, median, lower quartile, minimum and maximum)

4.6 Peat surface oscillation

Using two discrete measurements of peat surface elevation in summer (7th February 2018) close to when the water table was at its seasonal lowest and winter (5th July 2018) when it was at its highest, the PSO was established. Manual measurements of the peat surface showed that the peat surface fluctuated across Moanatuatua from summer to winter, with the largest PSO occurring at sites M6 and M7 (37 mm) and the smallest at M9 (1 mm) (Figure 4.13). Total annual PSO will likely exceed the measurements obtained as the dates of maximum and minimum water table differed to the dates of the manual measurements. Peat surface measurements taken from a separate site located in the centre of Moanatuatua close to M6 indicated that the PSO at that site was 100 mm during 2016 and 50 mm during 2017, the differences in the years consistent with the lower water table experienced during 2016.

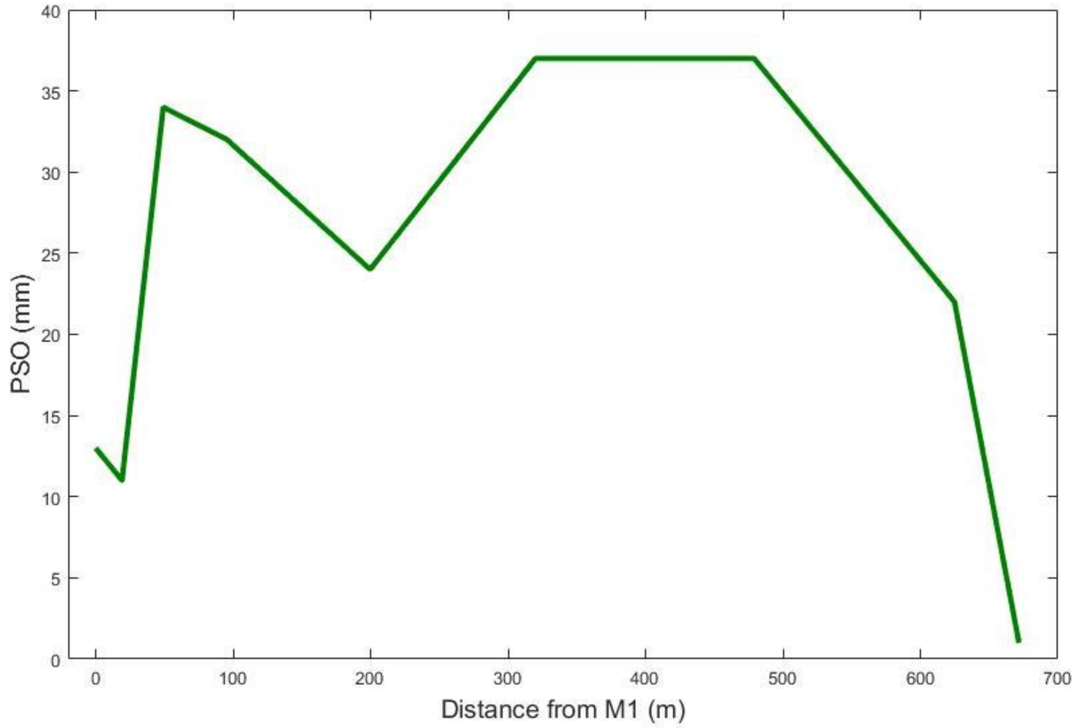


Figure 4.13: Peat surface oscillation measured from metal reference rod to peat surface, using summer peat surface elevation (7th Feb 2018) minus winter peat surface elevation (5th July 2018).

4.7 Discussion on past and current relative water table comparison at Moanatuatua

The mean RWL for the entire study period at M6 in the centre of the bog was -601 mm, this is similar water table at Moanatuatua in 2000 where the mean RWL was -580 mm (Campbell et al., 2014). Previous maximum RWL depths recorded were -747 mm in August 1999 and -813.0 mm in April 2000, and winter water tables were -327 mm in September 1999 and -370 mm in October 2000 (Campbell et al., 2014). During the current study RWL at M6 for Year 1 was deepest at -1080 mm in April 2016 and shallowest -310 mm in September 2016, Year 2 was maximum -895 mm in April 2017 and minimum -361 mm in February 2016 and Year 3 was maximum -80 mm in April 2018 and minimum -335 mm September 2017. Annual rainfall during the previous study was 1037 mm in 1999 and 988 mm in 2000 making this period slightly drier than the current study with rainfall of 1156 mm, 1724 mm and 1277 mm for Years 1, 2 and 3 respectively.

Comparison between the two studies conducted 18 years apart show that the mean water table is similar although the maximum water table depth has increased. The low rainfall totals received during 1999 and 2000 did not result in a low water table as extreme as seen in year one during 2015 – 2016. Rainfall was higher during Year 1 (September 2015 – 16) than 1999 and 2000 yet the water table still dropped down to -1079.8 mm below the peat surface. Years 2 and 3 saw the RWL at an average of 10 mm lower than the previous study. Minimum water table depths were shallower during this study than 18 years earlier which can be attributed to the higher rainfall totals during this study maintaining the higher water table. Both these comparisons are taken from the centre of Moanatuatua and therefore give a temporal concept of how the RWL is behaving.

4.8 Summary

The water table at Moanatuatua remained low for the entire three years relative to Kopuatai. Moanatuatua showed a large fluctuation in water table depth from summer to winter which indicates that the bog is highly modified (Price, 1992; Schouwenaars, 1993). At Kopuatai the water table stayed at or near the surface during this study period, similar to previous studies (Goodrich et al., 2015; Thompson et al., 1999) reconfirming that this bog remains in an unaltered state. Rainfall totals at Kopuatai were higher than at Moanatuatua. Both bogs showed seasonal variations in water table with summer having the deepest water tables and winter the shallowest due to precipitation recharge. Moanatuatua had a much larger variation in minimum and maximum water table levels when compared with Kopuatai.

In the current study the extremely deep water table at Moanatuatua in Year 1 was due to the extended low rainfall during the autumn and summer, Year 3 did not experience the same low water tables even though the overall total rainfall was similar. Year 1 the precipitation was more evenly distributed. Year 2 was the wettest with the highest rainfall of the three years and higher than the 30 year average for the region. The uneven seasonal distribution of precipitation corresponded directly with the water table depth. Climate extremes (droughts, intense rainfalls) impact the level of the water table over short time scales as data from Year 1 indicated that even after a dry spell the water table still recovered when precipitation occurred. Prolonged dry spells may have more impact allowing more time for the peat hydraulic properties to alter to a more degraded condition, and therefore restoration to a more natural hydraulic regime may require artificial management before the system can become self-sufficient (Schouwenaars, 1993).

Absolute water level follows the shape to the surface of Moanatuatua with a sharp gradient towards the border drains. Raised peat bogs have a domed surface that rises above the mineral substrate in a convex shape (Ingram, 1982), low hydraulic conductivity at the edges and in the catotelm allow the bog to rise up above the regional water table (Lapen et al., 2005). However, Moanatuatua has steeper sides than it would have had originally and this may be a result of subsidence of the surrounding drained farmland. The current shape of Moanatuatua would have developed since the surrounding area was drained, which began in the 1950’s (Wallace, 1978), the western drain was last deepened in 1999 (Clarkson et al., 1999).

The spatial analysis of the relative water table suggest that the eastern and western border drains are causing a drawdown in the water table which is localised at the margins and does not affect the central part of Moanatuatua. The water table at site M9 had a lower minimum than M1 even though the drain at M1 is deeper than M9. One hypothesis is that the continuous deepening of the drain on the western side of the bog has degraded the peat, resulting in low hydraulic conductivity and reduced pore spaces therefore created an artificial dam of dense peat which is acting to restrict lateral flow from the bog (Price et al., 2003). The sites located towards the centre of Moanatuatua were not affected by the border drains on the eastern and western sides with RWL at site M6 dropping deeper below the surface than the both M5 and M7. This observation suggests that the drains do not influence the water table along the entire transect of the bog.

Peat surface oscillation varies across the Moanatuatua. Maximum PSO was observed towards the centre of the bog at sites M6 and M7, where both had a PSO of 37 mm based on measurements made in summer and winter. Sites adjacent to the drains had the lowest PSO (M1 = 13 mm, M9 = 13 mm). The differences in PSO are likely an indication of the degree of peat degradation due to consolidation (Price & Schlotzhauer, 1999) with more degraded peat a having a smaller PSO. This is consistent with site M9 at Moanatuatua having the smallest PSO as it is likely to have a higher degree of degradation due to its proximity to the drain, and adjacent pasture. The vegetation at this site consists of weeds and pine trees. *E. robustum* and *S. ferrugineus* do not grow at this site therefore no new peat is being added, allowing the peat to continue to degrade. PSO is an important component of a peatland ecosystem effecting plant species composition (Fritz et al., 2008). At Opuatia peatland, a relatively untouched fen in the North Island, the PSO ranged from 100 – 280 mm at 20 out of 23 which is the upper range recorded for peatlands (Fritz et al., 2008), the PSO at Opuatia was higher than Moanatuatua confirming the assumption that peat at Moanatuatua is more degraded.

Water Balance

5.1 Introduction

This chapter uses eddy covariance measurements of evaporation and measured rainfall to establish the seasonal and annual evaporation regime and water balance (using precipitation and evaporation) at Moanatuatua and Kopuatai. The two sites are compared to see if there is a difference in the water balance, and if the late successional vegetation cover at Moanatuatua has influenced the evaporation rates and therefore contributed to the low water table.

5.1.1 Environmental variables

Rainfall and temperature has been discussed in Chapter 4 (objective one). Kopuatai had more rainfall than Moanatuatua each year during the study period and warmer air temperature.

5.2 Evaporation

Monthly total evaporation at Kopuatai follows a distinctive seasonal pattern with higher evaporation rates occurring during summer and lower evaporation rates during winter (Figure 5.1). Evaporation at Moanatuatua followed a seasonal pattern although during 2016/17 evaporation rates were less seasonally distinctive as evaporation dropped at the beginning of summer. Evaporation was higher at Moanatuatua during all months during the study except during two winter months, June 2016 and June 2017.

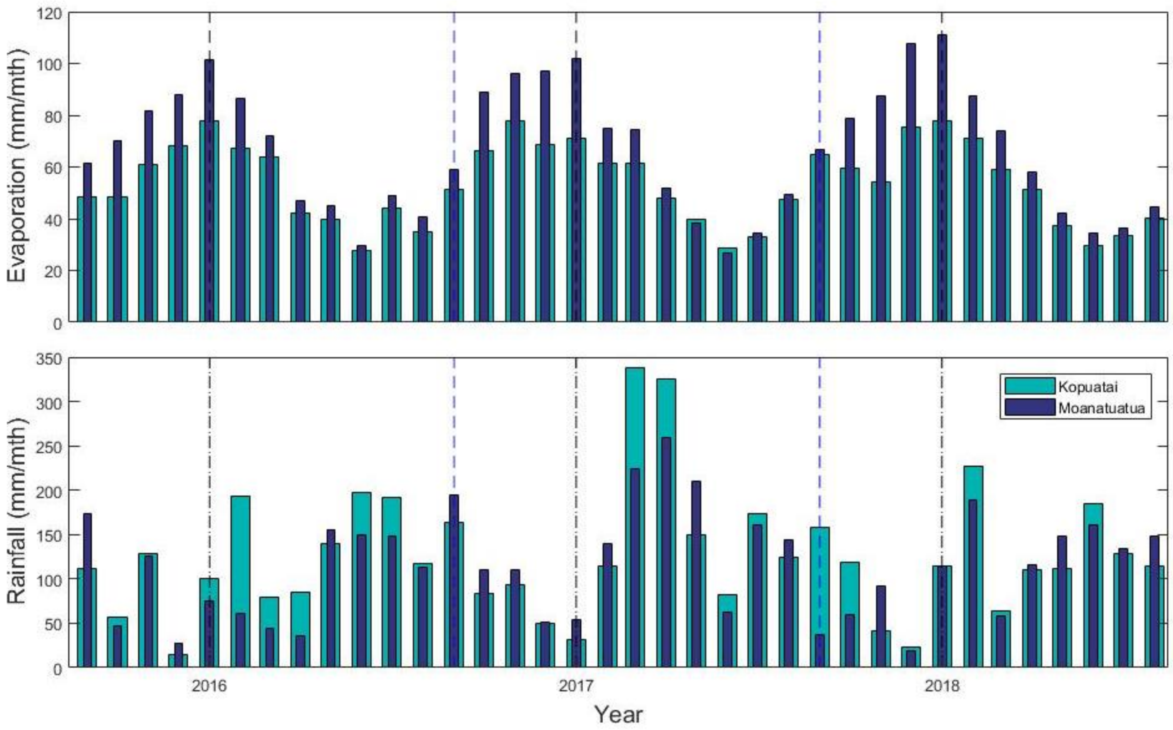


Figure 5.1: Monthly total evaporation and rainfall for Kopuatai and Moanatuatua, vertical dashed black lines indicate the years, blue lines indicate start of study years (1 September)

Total annual evaporation at Moanatuatua was similar for study Years 1 and 3 and slightly lower for Year 2, ranging from 762 mm year^{-1} – 828 mm year^{-1} (Table 5.1). Year 2 had the highest total rainfall but this is not reflected in the evaporation. Year 3 had moderate rainfall, with higher rainfall in summer compared to the other years which may have been what drove the evaporation rate up due to a frequently saturated canopy coinciding with high rates of solar radiation. In contrast, total evaporation from Kopuatai for the three years ranged from 625 mm year^{-1} to 653 mm year^{-1}. Year 3 also had higher evaporation at Kopuatai, although the difference in evaporation between Year 3 and the previous two years was considerably smaller than what was measured at Moanatuatua. This resulted in a difference in evaporation between the two sites, with a range of from 111 mm year^{-1} in Year 2 and 175 mm year^{-1} in Year 3, with an average of 153 mm year^{-1} more evaporation was lost from Moanatuatua than Kopuatai.

Table 5.1: Seasonal evaporation (mm) (autumn (March - May), winter (June – August), spring (September – November) and summer (December – February)) an annual total evaporation (mm) at Moanatuatua and Kopuatai.

Moanatuatua	**Autumn**	**Winter**	**Spring**	**Summer**	**Total**
Year 1	163	120	244	274	801
Year 2	164	111	213	274	762
Year 3	174	115	233	306	828
Mean	167	115	230	285	797

Kopuatai	**Autumn**	**Winter**	**Spring**	**Summer**	**Total**
Year 1	145	111	158	211	625
Year 2	148	107	195	201	651
Year 3	148	103	178	224	653
Mean	147	107	177	212	643

Mean monthly evaporation for the study period was consistently higher at Moanatuatua (Figure 5.2), only in the middle of winter when temperature and solar radiation are limiting are evaporation levels similar at the two sites.

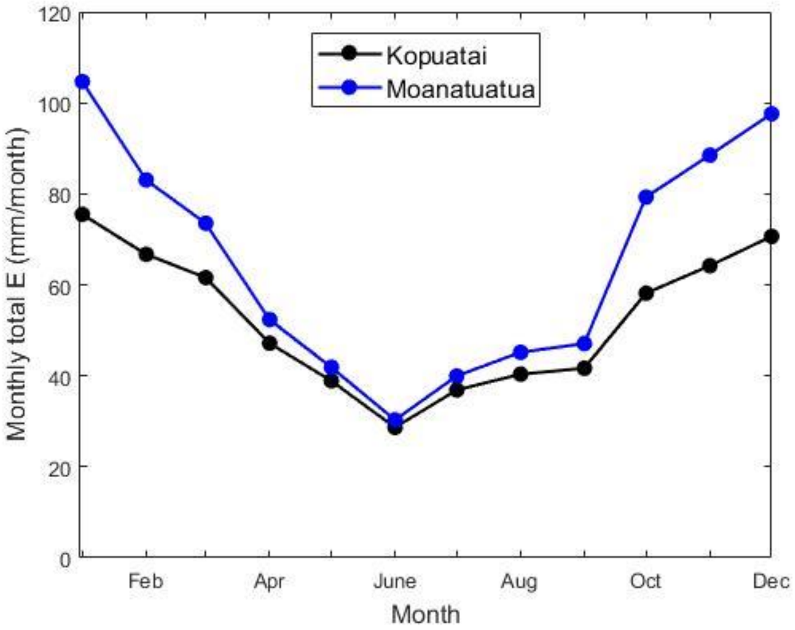


Figure 5.2: Measured mean monthly evaporation rates (1st September 2015 – 31st August 2018)

5.2.1 Seasonal evaporation

Seasonal differences in evaporation rates were greatest in summer (Table 5.2), with Moanatuatua averaging 0.6 mm day^{-1} more evaporation than Kopuatai. Spring and autumn differences were 0.6 mm day^{-1} and 0.2 mm day^{-1} respectively, while in winter there was a negligible 0.1 mm day^{-1} higher evaporation rate at Moanatuatua

Mean seasonal total evaporation was lower at Kopuatai for the entire study period compared with Moanatuatua (Table 5.2). The low water table at Moanatuatua did not appear to be a limiting factor for evaporation. During the dry summer and autumn of Year 1 when the water table was at its deepest, the evaporation was only slightly lower than the following two years. Higher evaporation during Years 2 and 3 may have been a result of more frequent wet canopy evaporation. Mean seasonal evaporation was higher during spring and summer, this was also when the difference in evaporation between Moanatuatua and Kopuatai was most pronounced.

Table 5.2: Seasonal (autumn (March – May), winter (June – August), spring (September – November) and summer (December – February)) mean of daily evaporation (mm day^{-1}) for Moanatuatua and Kopuatai.

Moanatuatua evaporation	**Autumn (mean)**	**Winter (mean)**	**Spring (mean)**	**Summer (mean)**	**Year (mean)**	**Maximum**	**Minimum**
Year 1	1.8	1.3	2.3	3.1	2.1	6.1	0.3
Year 2	1.8	1.2	2.7	3.1	2.2	5.8	0.4
Year 3	1.9	1.3	2.6	3.4	2.3	5.7	0.4
Kopuatai evaporation	**Autumn (mean)**	**Winter (mean)**	**Spring (mean)**	**Summer (mean)**	**Year (mean)**	**Maximum**	**Minimum**
Year 1	1.6	1.2	1.7	2.4	1.7	4.9	0.3
Year 2	1.6	1.2	2.1	2.2	1.8	5.2	0.4
Year 3	1.6	1.1	2.0	2.5	1.8	4.9	0.3

Evaporation during summer was higher than the other seasons due to an increase in solar radiation driving evaporation, with evaporation at Moanatuatua exceeding Kopuatai (Figure 5.3). Year 3 had the highest autumn and summer evaporation at Moanatuatua and Kopuatai. Summer evaporation at Moanatuatua during Year 3 was higher than any other season and can be reflected in the low water table during this period (Figure 5.3).

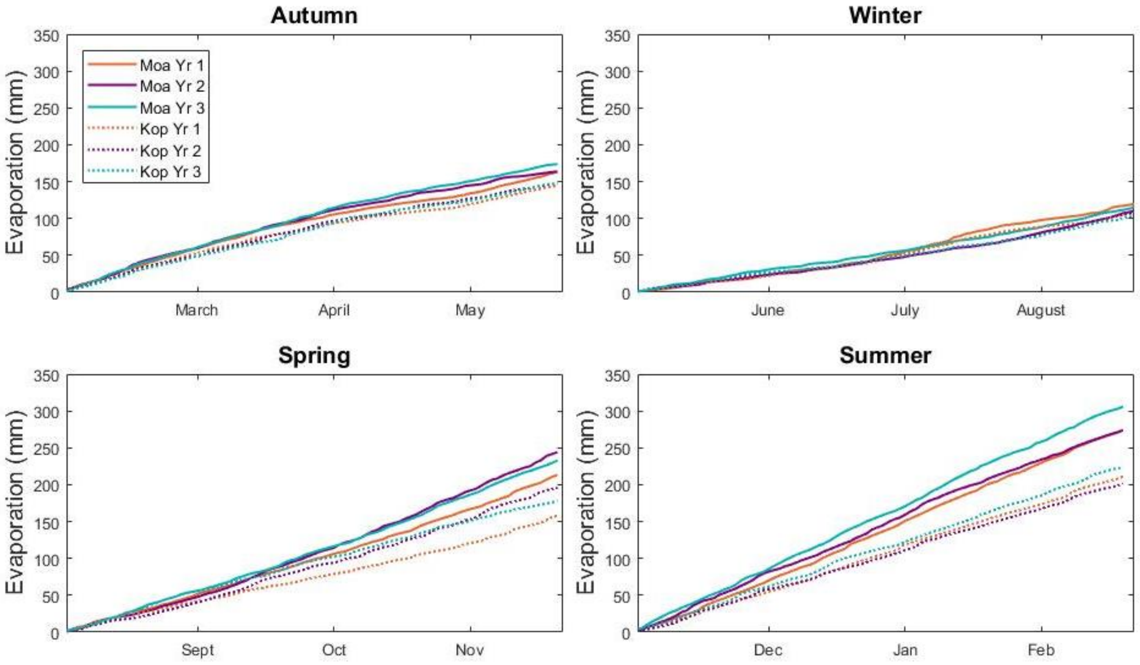


Figure 5.3: Seasonal (autumn (March – May), winter (June – August), spring (September – November) and summer (December – February)) cumulative evaporation for Kopuatai (dashed lines) and Moanatuatua (solid lines) for the individual three individual years of study.

5.3 Dry canopy evaporation

Evaporation rates increase when a vegetation canopy is wetted by rain because stomatal control over transpiration becomes irrelevant. To gain an understanding of the controls on evaporation rates due to vegetation differences and transpiration processes, days where the canopies at each bog were wetted by rain have been separated out in this section. Using an antecedent precipitation index that effectively excluded days where rain has occurred within two days previously, the total number of “dry” days over the three years of study was 386 days at Moanatuatua and 414 dry days at Kopuatai.

Net radiation was higher at Moanatuatua than Kopuatai with a mean of 10.2 MJ m^{-2}day^{-1} and 9.6 MJ m^{-2}day^{-1} respectively (Table 5.3). Higher net radiation will increase potential evaporation, and the higher evaporation is likely because of the taller and rougher Moanatuatua vegetation having lower albedo.

Table 5.3: Mean net radiation (MJ $m^{-2}day^{-1}$) for the three study years at Moanatuatua and Kopuatai.

	Moanatuatua	Kopuatai
Year 1	10.3	9.8
Year 2	10.1	9.5
Year 3	10.1	9.4
All years	10.2	9.6

The equilibrium evaporation rate (E_{EQ}) is the evaporation rate which would occur over moist surfaces in the absence of advective influences (Thompson et al., 1999), i.e. evaporation from open water bodies or well watered vegetation. E_{EQ} was used as an index for comparrison for evaporation from the dry and rain-wetted canopied at Moanatuatua and Kopuatai.. Figure 5.4 shows that when the canopy is dry the evaporation rates at Kopuatai was generally less than Moanatuatua, where at Moanatauatua the dry canopy was more than half of E_{EQ}. Evaporation rates from *Sphagnum* surfaces with a water table depth of 50 – 100 mm below the surface equals or exceeds evaporation rates from open water (Schouwenaars, 1993). Evaporation on dry days during the entire study period resulted in a mean daily evaporation at Moanatuatua of 2.0 mm day^{-1} and Kopuatai of 1.45 mm day^{-1}.

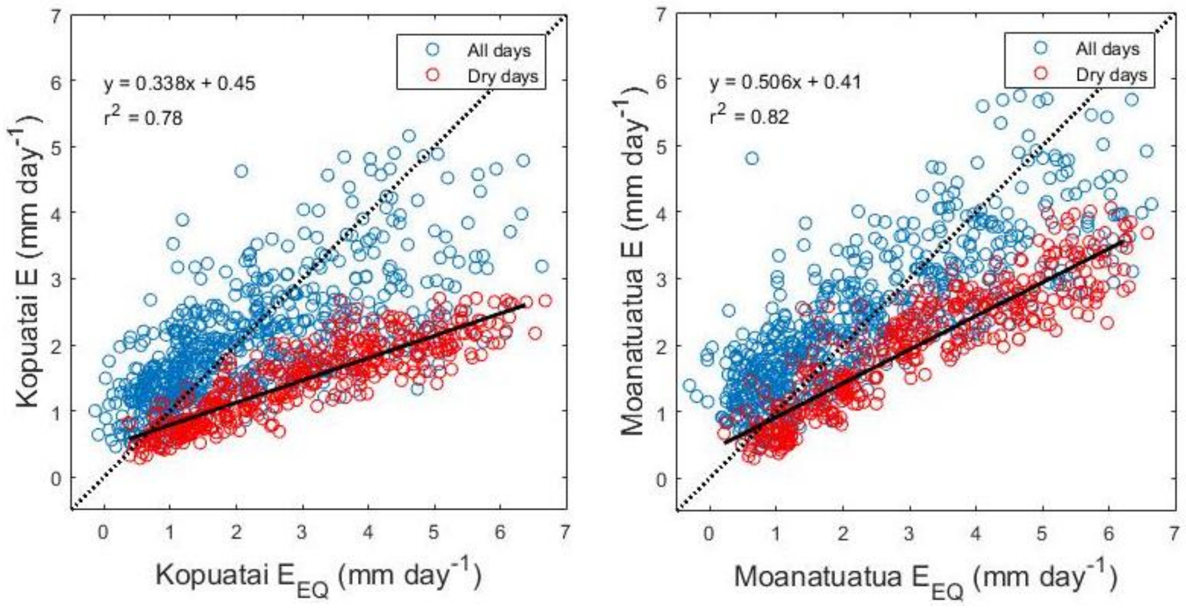


Figure 5.4: Measured evaporation (*E*) versus equilibrium evaporation (E_{EQ}) for the entire study period. All days are shown in blue and days with a dry canopy are in red. (a) Kopuatai and (b) Moanatuatua. The dotted black line shows the 1:1 line and the solid black shows the line of best fit obtained using least squares linear regression.

In previous studies, results from *S. ferrugineus* -dominated sites at Moanatuatua and Kopuatai showed that evaporation rates from a mostly dry canopy to be an average of 2.74 mm day^{-1} at Moanatuatua and 3.01 mm day^{-1} at Kopuatai, the differences between the two site was considered insignificant due to non-overlapping measurement timings (Thompson et al., 1999). In contrast, mean summertime evaporation from an *E. robustum* dominated canopy at Kopuatai was 1.54 mm day^{-1} from a dry canopy and 2.29 mm day^{-1} from a wet canopy (Campbell & Williamson, 1997). *S. ferrugineus* evaporation loss exceeds that of an *E. robustum* dominated canopy (Thompson et al., 1999).

For the current study daily mean evaporation from Moanatuatua for the entire study period was 2.2 mm day^{-1} compared with Kopuatai at 1.8 mm day^{-1}. Dry canopy evaporation for both bogs was 2.0 mm day^{-1} and 1.45 mm day^{-1} at Moanatuatua and Kopuatai respectively. Moanatuatua evaporation rates exceeded Kopuatai even on dry days confirming that the differences in vegetation at the two sites has a noticeable difference. The lower rainfall and increased evaporation at Moanatuatua will contribute to the low water table levels.

The evaporation rates were lower during this study than for the Thompson et al., (1999) study, which can be expected with a longer term study taking into account different seasons and measurement techniques.

5.4 Water balance - evaporation and rainfall variability

To establish if annual rainfall totals affect evaporation at Moanatuatua, cumulative annual rainfall and evaporation were compared (Figure 5.5). This shows that rainfall totals do not have a strong influence on evaporation totals on an annual basis as the cumulative evaporation was similar for all three years of study whereas the rainfall varied significantly. Although rainfall does not affect evaporation it does have a significant effect on the water balance though input into the bog system.

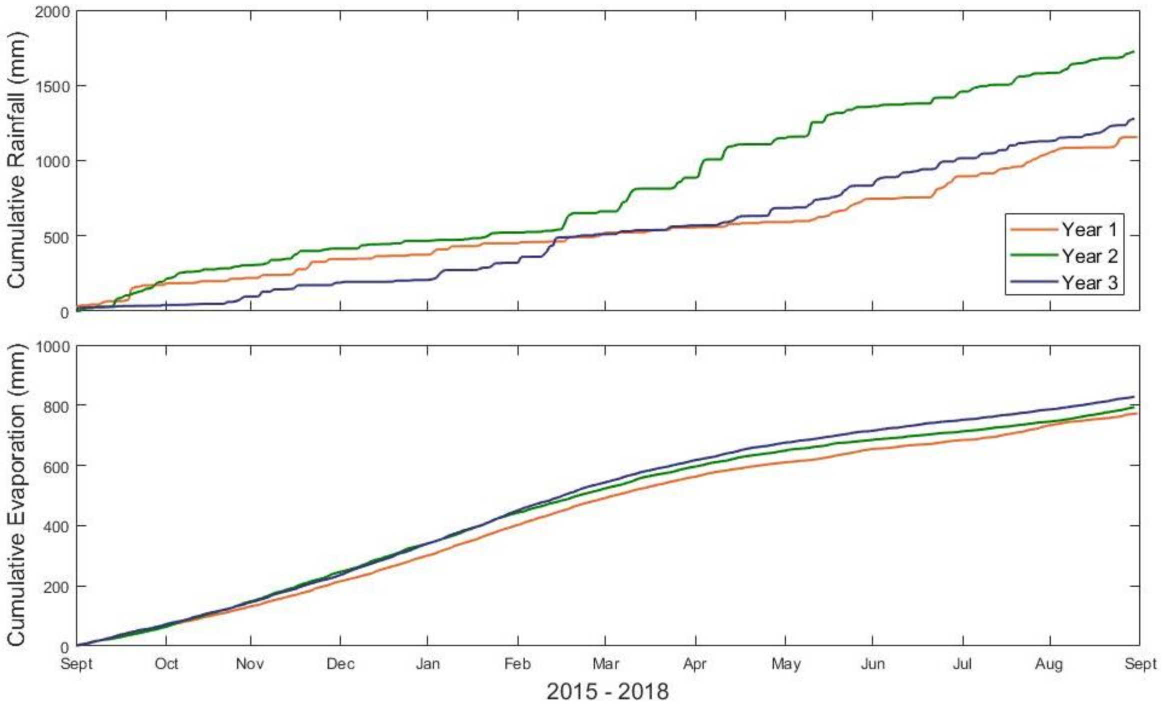


Figure 5.5: Cumulative rainfall and evaporation at Moanatuatua for the three individual years of study.

Precipitation minus evaporation shows the net water flux into the bog that drives changes in stored water, thus being a major driver of the water table regime. For a wetland to exist rainfall must equal or exceed evaporation. During the dry autumn experienced at Moanatuatua in 2016 the water flux was in deficit (negative) (Figure 5.6) since evaporation exceeded rainfall. The negative deficit also occurred at Kopuatai during one or two months of summer (2015 – 2017), whereas at Moanatuatua the deficit lasted for longer periods, from two to four months. Recharge usually occurs during winter when evaporation is lowest and rainfall is usually at its highest. During dry periods water will continue to exit the bogs though evaporation, from the plants further drawing the water table down (Waddington et al., 2015).

During Year 1 the low rainfall totals in autumn and summer at Moanatuatua did not draw the cumulative water balance totals of rainfall – evaporation ($P - E$) into an overall negative deficit (Figure 5.7), even though during the individual summer months this was the case. The winter rainfall totals resulted in enough stored water in the peat profile to ensure that the water flux remained in a positive state helping to maintain the water table level. Year 2 included the wettest season and evaporation totals were similar to Year 1 with resulting in a high water table throughout the year. Year 3 shows a negative water flux during summer as the rainfall was low during spring, Year 3 also had the highest cumulative evaporation as the evaporation during November/December 2017 was higher than the previous two years. The high evaporation and relatively normal rainfall at Moanatuatua in Year 2 resulted in a low $P-E$ of 416 mm (Table 5.4).

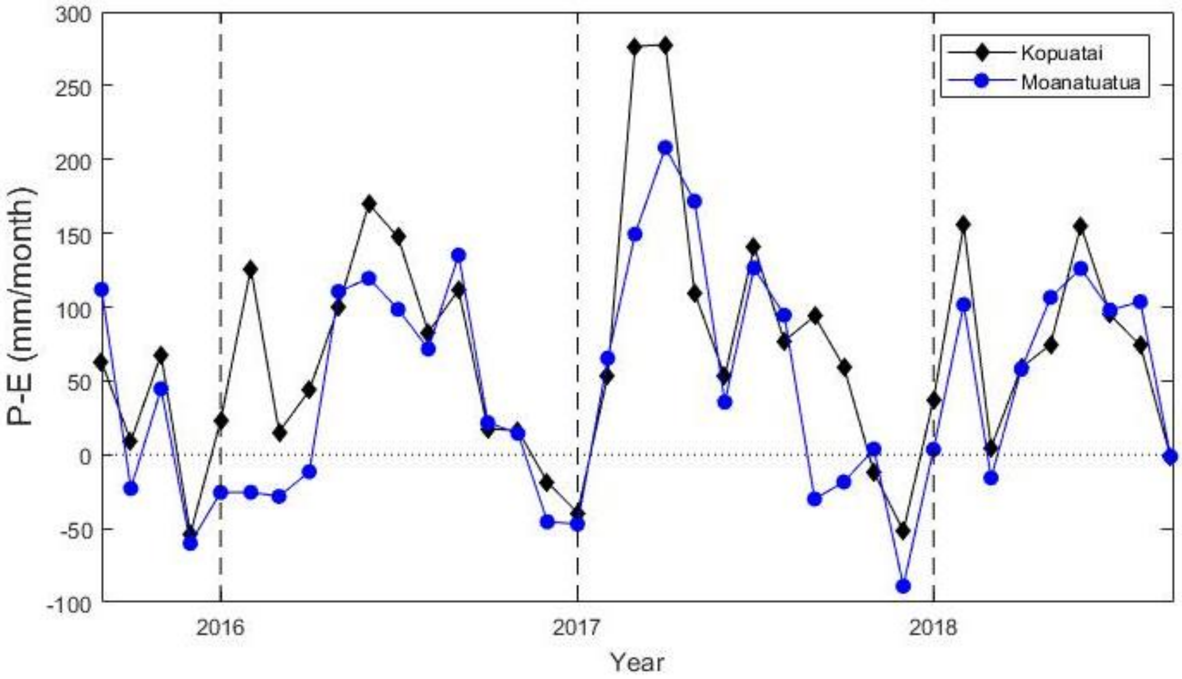


Figure 5.6: Monthly totals of precipitation minus evaporation for Kopuatai and Moanatuatua.

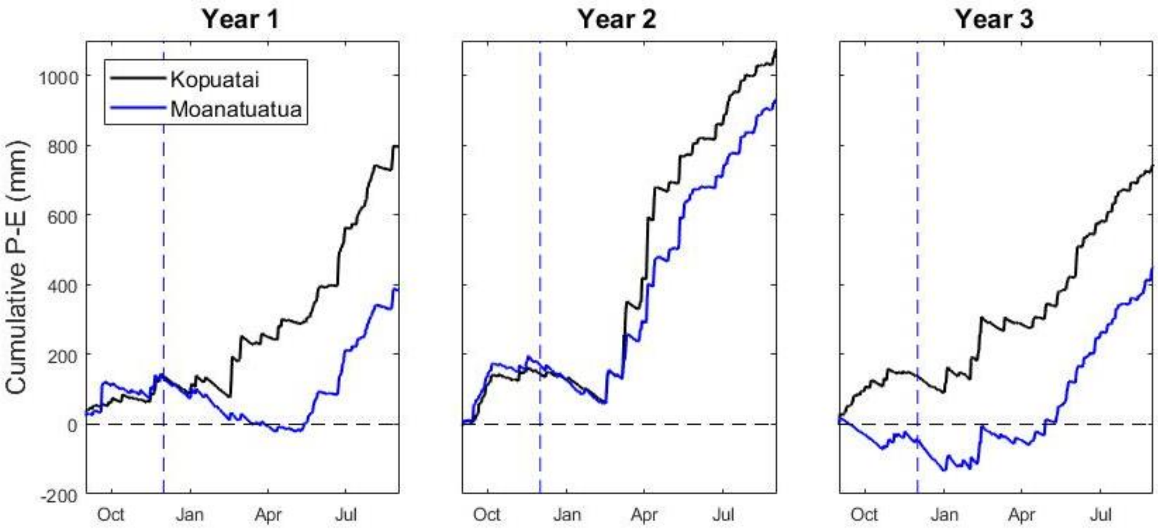


Figure 5.7: Cumulative precipitation minus evaporation for the three individual years of study at Kopuatai (black line) and Moanatuatua (blue line). Vertical line shows the start of summer (1-December).

Table 5.4: Total precipitation minus evaporation (mm) for the three individual years of study at Moanatuatua and Kopuatai.

	Moanatuatua	**Kopuatai**
Year 1	448	795
Year 2	930	1077
Year 3	383	745
Mean	587	872

5.4.1 Seasonal water balance

Seasonal cumulative $P - E$ shows that, in summer at both sites the net flux of water input was already negative at the beginning of summer (Figure 5.8). Summer at Moanatuatua stayed in a negative balance throughout summer for Years 1 and 2. The wet autumn in Year 2 is evident at both sites with a large positive net water flux, this positive trend occurred in spring also. In Year 3 the water balance at Moanatuatua was negative for the entire spring period, then stayed low during summer and autumn. However, by the end of winter the water balance had recovered to the same level as in the previous two years.

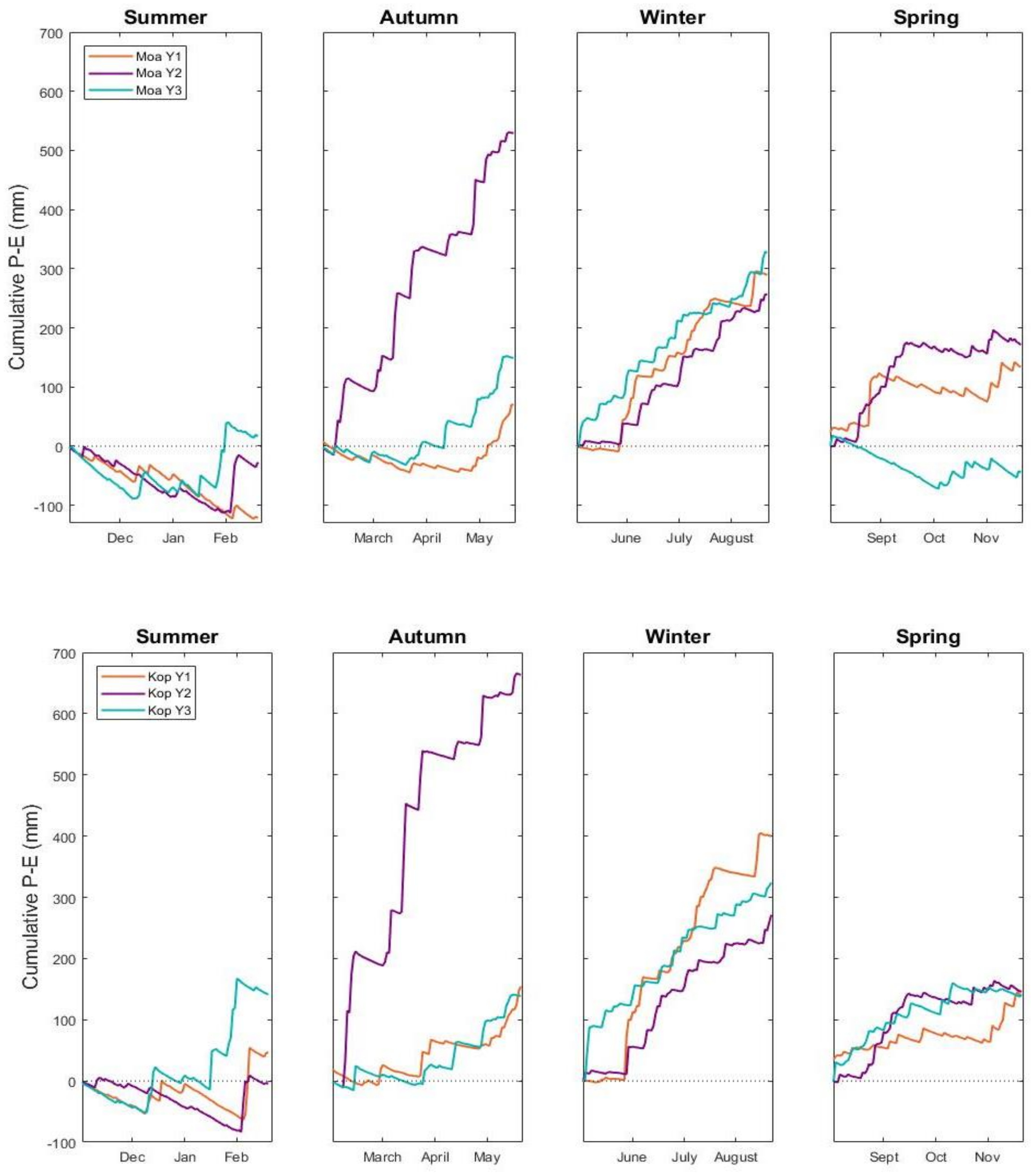


Figure 5.8: Seasonal precipitation minus evaporation for Moanatuatua (top plots) and Kopuatai (bottom plots).

5.4.2 Model water balance Moanatuatua

To predict how the water balance at Moanatuatua would differ under the influence of an *E. robustum* canopy in contrast to a *S. ferruginous* and *E. pauciflora* canopy, a “model” using total measured rainfall from Moanatuatua minus evaporation from Kopuatai was used (Table 5.5). This suggested that, if Moanatuatua had been dominated by an *E. robustum* canopy the mean net water balance input would have been +741 mm of water available for possible water table increase over the three-year study period. On average a total of 154 mm more water is available a year from an *E. robustum* canopy than under a *S. ferruginous* and *E. pauciflora* canopy. This would bring the total potential water balance closer to the more natural system experienced at Kopuatai which had a mean *P* – *E* of 872 mm (Table 5.4).

Table 5.5: Moanatuatua *P* – *E* (mm) calculated using measured *E* and using Kopuatai *E* (model), for the three individual years of study.

	Moanatuatua total *P* – *E*	Model total *P* – *E*
Year 1	448	532
Year 2	930	1069
Year 3	383	623
Mean	587	741

Closer analysis of the model water balance compared with the actual water balance at Moanatuatua indicates that there would be, on average, less deficit over the summer period if Kopuatai *E* rates were imposed on Moanatuatua (Figure 5.9), this is also when the water table is at its lowest and the bog is most sensitive to peat physical changes. There was less observed difference seen over winter when evaporation was at a minimum and rainfall at a maximum. Therefore, summer is more sensitive to increased evaporation from the late successional vegetation at Moanatuatua. The summer water balance (Dec – Feb) would be much closer to the water balance at Kopuatai. The variability in the different water balances seen between the model and Kopuatai is also a function of the generally higher rainfall experienced at Kopuatai.

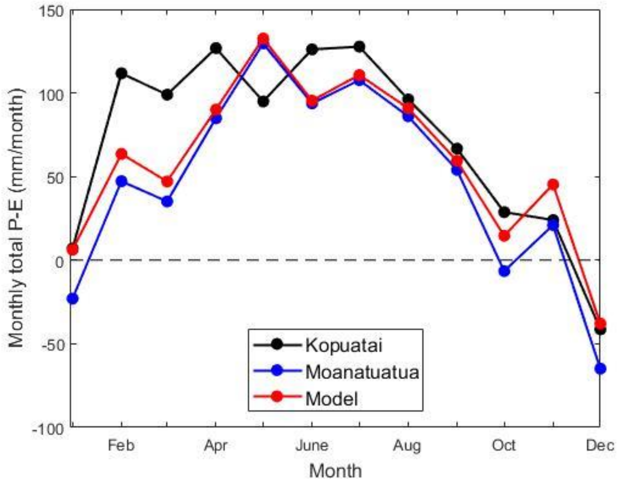


Figure 5.9: Measured mean monthly water balance, averaged for the three study years.

5.5 Water balance relationship with the water table

The water balance can be used as a proxy to predict the depth of the water table. On an annual basis when $P - E$ totals are low the water table is also at its lowest (Table 5.6). Year 1 had the lowest $P - E$ and the deepest water table, the opposite is observed when $P - E$ was at its highest suggesting higher recharge rates into the bog, during this time (Year 2) the water table was at its shallowest.

Table 5.6: Mean water table for each study year, and total evaporation, rainfall and $P - E$. All values are in mm year-^{1}.

Moanatuatua	Water Table (mean)	Rainfall (total)	Evaporation (total)	$P - E$ (total)
Year 1	-719	1156	774	382
Year 2	-527	1724	794	930
Year 3	-553	1277	824	453
Kopuatai	**Water Table (mean)**	**Rainfall (total)**	**Evaporation (total)**	**$P - E$ (total)**
Year 1	-47	1419	624	795
Year 2	-25	1732	655	1077
Year 3	-4	1398	654	745

Investigating the summer water balance, when evaporation is highest and rainfall is at the lowest, can give an insight into the potential recharge rates of the bog systems and effects on the water table. During summer of Year 1, when the water table was at its lowest at Moanatuatua, the $P - E$ or water flux available for recharge was also at its lowest, a total deficit of 121.8 mm during this time (Table 5.7). Summer of Year 3 at Moanatuatua had the highest $P - E$ of 16 mm due to the consistent rainfall that occurred during this period and the water table was shallower than the other two years. Recharge rates were consistently higher at Kopuatai than Moanatuatua during summer in all three years of study, with Kopuatai in deficit of 4 mm in Year 2, due to the lower rainfall observed at this time.

Table 5.7: Summer (Dec – Feb) mean water table depths (mm), total rainfall, total evaporation, and *P – E* (mm year^{-1}).

Moanatuatua	Water Table	Rainfall	Evaporation	*P – E*
Year 1	-715	152	274	-122
Year 2	-721	248	274	-26
Year 3	-656	322	306	16

Kopuatai	Water Table	Rainfall	Evaporation	*P – E*
Year 1	-105	258	211	47
Year 2	-146	197	201	-4
Year 3	-112	365	224	141

5.6 Summary and comparison

Evaporation at Moanatuatua was higher than Kopuatai in all years and seasons, with an average of 153 mm year^{-1} more evaporation was lost from Moanatuatua than Kopuatai. Evaporation from both bogs follows a seasonal cycle, with daily evaporation rates highest in mid-summer and lowest in mid-winter. Evaporation from Moanatuatua which is dominated by *S. ferrugineus* and *E. paucifloru,* averaged 2.2 mm day^{-1}, whereas evaporation from Kopuatai which is dominated by *E. robustum* averaged 1.8 mm day^{-1}, for the entire study period. On days with a dry canopy, when the largest differences in evaporation were observed, average evaporation was 2.0 mm day^{-1} and 1.45 mm day^{-1} for Moanatuatua and Kopuatai respectively. For *E. robustum*-dominated bog vegetation, dry canopy evaporation (transpiration plus diffusion of water vapour from the moist peat surface) is controlled by that plant's water conservative physiology and dense canopy structure (Campbell & Williamson, 1997).

Kopuatai dry canopy evaporation rates were at less than half the equilibrium rate, comparably Moanatuatua dry canopy evaporation rates were at more than half the equilibrium rate.

In earlier studies, bog plant canopies dominated by *S. ferrugineus* have been found to have higher evaporation rates than *E. robustum* (Campbell & Williamson, 1997; Thompson et al., 1999), consistent with the current study. This has resulted in more water loss from Moanatuatua than Kopuatai, however, it is not just *S. ferrugineus* and *E. Robustum* that grows at Moanatuatua, but also *Epacris pauciflora* and little is known about the evaporation from the shrub which could also be driving the high evaporation rates.

Water balance analysis shows Kopuatai received more rainfall and had lower low evaporation rates compared with Moanatuatua which resulted in a positive net water balance input ($P - E$) during all three years. The mean annual $P - E$ for Kopuatai was 872 mm year^{-1} and Moanatuatua 587 mm year^{-1} resulting in an average difference between the sites of 285 mm year^{-1} more available recharge for Kopuatai compared to Moanatuatua. Model $P - E$ for Moanatuatua under an *E. robustum* canopy suggests that removing the late successional plants from Moanatuatua and therefore reducing evaporation rates the water balance would be more positive allowing more water to return to the system and less lost to evaporation. Using these estimates, summer $P - E$ would have been in deficit for two of the three study years at Moanatuatua, however, subsequent rainfall successfully recharged the water table back to a winter minimum depth below the peat surface.

Evaporation does not appear to be limited by increasing water table depth, suggesting the bog vegetation at Moanatuatua is not under extreme stress. However, this was not explored in detail. Ratcliffe et al., (2018) concluded that gross primary production (CO^2 uptake) at Moanatuatua was constrained when the water table reached 775 mm. Little is known about the rooting depths of the vegetation at Moanatuatua and at what level the water table would be the limiting factor for the *E. robustum* and *S. ferruginous*. Past studies suggest that the rooting depth of *S. ferruginous* was 50 – 80 mm below the surface, although during this time (1963) the water table was near the surface (Campbell, 1964). At Mer Bleue bog in Canada Lafleur et al., (2005) found that the surface water availability and the depth of the water table below the surface is the most important factor in controlling evaporation and preventing potential evaporation for being achieved, this was due to transpiration control from vascular plants and evaporation for the moss. They found evaporation was unaffected until the water table was 65 cm below the peat surface, although this also coincided with the end of summer when the air temperature was cooling and daylight hours were becoming shorter, however, these variables were factored out.

Discussion

6.1 Water table

The water table at Moanatuatua is low for a peatland ecosystem when compared with the hydrologically intact Kopuatai bog. The water table formed a domed shape following the peat surface similar to unmodified bogs (Ingram, 1983). The water table remained below the peat surface for the entire study although this does not appear to be causing die off in peatland vegetation. *E. robustum* thrives in an environment where its root zone is not fully saturated (Fritz et al., 2008) and, therefore, may prefer the dry environment at Moanatuatua, as its canopy is generally taller and denser than at Kopuatai. *E. robustum* grows taller as a strategy to access nutrients from rainfall first and therefore to out compete potential competitors (Hodges & Rapson, 2010). However, Ratcliffe et al. (2018) concluded that vegetation at Moanatuatua was likely to be experiencing stress at deep water tables. Therefore, although the vegetation has had an advantage for a period of the year when the water table is at a suitable depth supporting growth, prolonged dry periods may result in natural bog vegetation die off, allowing invasive species to invade. Other factors influencing the growth of vegetation at Moanatuatua could be the increase in nutrient availability from fertiliser application on the surrounding farmland.

The water tables at the centre of Moanatuatua and Kopuatai bogs both show a seasonal pattern with maximum depths in summer and minimum depths in winter as a result of seasonal rainfall availability. The water table depths differed greatly, at Kopuatai the water table stayed at or near the surface, and in winter inundated the surface. Mean water table depths were -25 mm and -601 mm at Kopuatai and Moanatuatua respectively. Moanatuatua water table at site M6, in the centre of the transect reached a maximum summer water table depth of -1080 mm below the peat surface compared to -170 mm at Kopuatai. In winter the minimum water table depth was -312 mm at Moanatuatua and 29 mm above the peat surface at Kopuatai. Water tables were recharged at Moanatuatua even after the low rainfall totals during 2016 when the water table reached its deepest, this has resulted in a relatively stable annual to decadal water table.
Comparing data from 1999 – 2000 (Campbell et al., 2014) and the current study suggests that the water table regime at Moanatuatua has not changed much over the past 18 years, but this is not conclusive due to the inter-annual differences in rainfall totals. Mean water table depth was

-580 mm during 1999 – 2000 (Campbell et al., 2014) and during this study was -601 mm, only 21 mm difference. After the winter period, September water table depths were -327 mm in 1999 and -335 mm in 2017. Rainfall during 1999 (Jan – Dec) was 1037 mm and 1277 mm in 2017 (Aug – Sept). The main change appears to be the summer water table depths which have increased from a maximum depth in 1999 of -813 mm to -1080 mm in 2018. However, this may be the result of the differences in rainfall for the individual periods. Long term changes in the water table can lead to changes in the peat porosity, specific yield and hydraulic conductivity, reducing the water storage abilities of the peat (Schouwenaars, 1993). The water table depth at Moanatuatua was highly sensitive to individual rainfall events along with seasonal totals, this suggests that long-term dry periods will have a considerable impact on the peat, and the ability for the bog to store water. Increased frequency of prolonged dry periods and higher temperatures in New Zealand (Plummer et al., 1999) could result in a permanently lower water table over time, irrespective of the border drains.

The border drains do not appear to impact the water table regime across the entire width of Moanatuatua. The eastern side of the bog had lower water table extremes when compared to the western side, similar to the finding of Grimshaw (2000). One hypothesis to explain the higher water table on the western border is that the very steep water table gradient has led to highly degraded peat constraining lateral water movement creating a “dam” along the border. Prolonged oxidation alters the peat properties, reducing pore spaces and hydraulic conductivity, therefore limiting seepage (Price et al., 2003; Schouwenaars, 1993). Margins of bogs have lower hydraulic conductivity which allows the domed shape to form (Lapen et al., 2005). The mean RWL across the bog transect indicates that the drains have a relatively localised impact adjacent to the western and eastern drains. This suggests that the centre of the bog is less influenced by the drains directly and is more influenced by other factors, e.g. evaporation.

6.2 Evaporation rates

Evaporation rates from the Moanatuatua bog ecosystem were higher than the comparison site at Kopuatai. Previous studies have shown that evaporation rates from *S. ferrugineus* are higher than *E. robustum* (Campbell & Williamson, 1997; Thompson et al., 1999) and Moanatuatua has a larger percentage of *S. ferrugineus* than at the Kopuatai EC site which would result in higher rates of evaporation. Current Moanatuatua vegetation also includes the tall ericoid shrub *E. pauciflora* for which previous studies of their evaporation rates do not exist in New Zealand.

The mean daily evaporation rate at Moanatuatua was 21 mm day^{-1} and Kopuatai 1.8 mm day^{-1} over the entire study period, leading to less available water to recharge the water table at Moanatuatua. Eliminating wet canopy influences the evaporation rate at Moanatuatua averaged 2.0 mm day^{-1} in contrast to 1.45 mm day^{-1} at Kopuatai. On average, 153 mm per year more evaporation was lost from Moanatuatua than Kopuatai.

Campbell & Williamson (1997) showed that mean summertime evaporation from Kopuatai was 1.54 mm day^{-1} from a dry *E. robustum*-dominated canopy and 2.29 mm day^{-1} from a wet canopy. The Thompson et al., (1999) study at Moanatuatua showed that evaporation rates from a mostly dry *S. ferrugineus*-dominated canopy averaged 2.74 mm day^{-1}. The results these historical summer-time only evaporation measurement campaigns agree in general with the summertime maximum differences in evaporation rates described in the present research. Therefore, these studies show that Moanatuatua has had higher evaporation than Kopuatai for at least the last 18 years, suggesting a long-term trend towards less water availability and a lower water table regime.

6.1 Rainfall and the water balance

Rainfall at Kopuatai was consistently higher than at Moanatuatua. Moanatuatua had a mean annual rainfall across the three study years of 1385 mm year^{-1} and Kopuatai had a mean annual rainfall of 1516 mm year^{-1} and, this resulted in a total of 392 mm more precipitation at Kopuatai than Moanatuatua over the three-year study period. The mean annual rainfall at both bogs was higher than normal due to the high rainfall received during Year 2.

Moanatuatua had less rainfall and higher evaporation than Kopuatai resulting in a less positive water flux into the bog, however, by the end of winter all three years the water table level recharged, this suggests that Moanatuatua can maintain the current water table depth. The model $P - E$ used Moanatuatua rainfall and Kopuatai evaporation which suggests that, should the late successional vegetation (*S. ferrugineus and E. pauciflora*) be replaced with the more water conservative *E. robustum* canopy, the water flux would be higher and so potentially result in a higher water table over time. However, the water table appears unable to reach the surface of the bog even after sustained rainfall, therefore it may not be possible to restore the water table to a level similar to Kopuatai. After the prolonged high rainfall during Year 2 the water table at Moanatuatua did not rise above -312 mm, this may be a result of the peat physical properties at this point causing rapid sub-surface lateral flow. The $P-E$ at Moanatuatua showed that, on an annual basis, the water table was fully recharged though adequate rainfall even though it did not reach the surface of the bog, the water balance appears to be in unaltered (non-natural) equilibrium and that the water table is not decreasing.

Conclusion and Recommendations

7.1 Main points

- The water table at Moanatuatua has not dropped markedly in the past 18 years suggesting that the bog's hydrology has reached an equilibrium state. The current domed shape across the bog has developed as a result of the deep drains and shrinkage of the surrounding land.

- Evaporation rates at Moanatuatua were greater than at Kopuatai which resulted in less water available to add to the system although the water flux ($P - E$) still remained positive on an annual basis, with the water table recharging even after a dry summer draw down. Lateral and vertical seepage were not investigated, and these factors would affect the rate of water table recharge.

- The border drains to not cause a drawdown across the entire transect at Moanatuatua, and only have an impact at the edge, this appears to be an estimated 95 m in from the western drain and 193 m in from the eastern drain. Short term seasonal rainfall variability has more influence on the level of the water table than the border drains. The water table across Moanatuatua recharges on an annual basis from winter to winter.

- A change in the dominant vegetation at Moanatuatua from *S. ferrugineus* and *E. pauciflora* to an *E robustum* dominated canopy would result in less water lost to evaporation and potentially bring the water table closer to a more natural state. Other factors are also influencing the water table depth, such as subsurface flows and these were not investigated in the current study.

7.1 Restoration and further research

Previous studies have been conducted in the Northern Hemisphere on *Sphagnum* bogs that have been drained and mined (Chimner et al., 2017; Price et al., 2003; Schouwenaars, 1993), which therefore cannot be directly translated to Moanatuatua which still has native vegetation and does not need the same degree of manipulation to achieve a more natural hydrological regime. However, the ecosystem at Moanatuatua is still threatened by a low water table. Therefore, maintaining a higher water table is important to prevent the upper layer of peat from degrading and subsiding. Moanatuatua has been found to have higher ecosystem respiration (ER) than Kopuatai due to differences in autotrophic respiration and peat decomposition as a result of the lower water table (Ratcliffe et al., 2018). Therefore, increasing the water table and saturating the peat to shallower depths could limit ER. Northern Hemisphere studies have proposed ditch blocking and buffer zones to increase the water table height in restored peatlands, and this may be applicable to Moanatuatua even though the surrounding lands are much lower than the bog. Buffer zones and ditch blocking could aid in preventing the surrounding land from continuing to subside at the current average rate of 2.1 ± 4 mm year-1 (Pronger et al., 2014). To achieve this adjacent farmland would need to be altered (drains filled or buffer zone planting areas).

One possible remediation strategy would be to remove the shrub vegetation from Moanatuatua to allow *E. robustum* to become the dominant vegetation, and therefore reducing the evaporation water loss and increasing peat formation. This is consistent with Clarkson et al., (1999) who already suggested canopy removal or thinning of current shrub vegetation to return the bog to a more natural condition. Seedlings of *E. pauciflora* have not been observed growing on Moanatuatua, suggesting the dense canopy of *E. robustum* is preventing the seeds from sprouting, and the existing cohort may be naturally dying out.

Another approach would be to create buffer zones to prevent lateral seepage and farm overflow to and from the bog. Buffer zones, along with drain blocking and raising the drain water levels could prevent the steep AWL towards the bog margins and could help prevent surrounding farmland subsidence. However, further research is needed on the peat physical properties to determine if the low water has resulted in irreversible physical changes to the peat hydraulic properties, contributing to inability to sustain higher water tables. Other studies understanding how much precipitation actually recharges the water table along with the degree and location of preferential lateral and vertical flow are also needed before manipulation or restoration strategies are proposed.

References

Ausseil., A. G. E., Dymond, J. R., & Weeks, E. S. (2011). Provision of Natural Habitat for Biodiversity: Quantifying Recent Trends in New Zealand. *Biodiversity Loss in a Changing Planet*. https://doi.org/10.5772/24969

Baird, A. J., Eades, P. A., & Surridge, B. W. J. (2008). The hydraulic structure of a raised bog and its implications for ecohydrological modeling of bog development. *Ecohydrology*, *1*(4), 289–298. https://doi.org/10.1002/eco

Belyea, L. R., & Clymo, R. S. (2001). Feedback control of the rate of peat formation. *Proceedings of the Royal Society of Biological Sciences*, *268*(1473), 1315–1321. https://doi.org/10.1098/rspb.2001.1665

Bengtsson, F., Granath, G., & Rydin, H. (2016). Photosynthesis, growth, and decay traits in Sphagnum - a multispecies comparison. *Ecology and Evolution*, *6*(10), 3325–3341. https://doi.org/10.1002/ece3.2119

Bonn, A., & British Ecological Society. (2016). *Peatland restoration and ecosystem services : science, policy, and practice*.

Brown, L. E., Johnston, K., Palmer, S. M., Aspray, K. L., & Holden, J. (2013). River ecosystem response to prescribed vegetation burning on blanket peatland. *PLoS ONE*, *8*(11). https://doi.org/10.1371/journal.pone.0081023

Burba, G. (2013). Eddy covariance method for scientific, industrial, agricultural and regulatory applications: A field book on measuring ecosystem gas exchange and areal emission rates. *LI-Cor Biosciences.*

Campbell, D. I., & Jackson, R. (2004). Hydrology of Wetlands. In J. S. Harding, C. P. Mosley, C. P. Pearson, & B. K. Sorrell (Eds.), *Freshwaters of New Zealand*. Christchurch, New Zealand: New Zealand Hydrological Society Inc. and New Zealand Limnological Society Inc.

Campbell, D. I., Smith, J., Goodrich, J. P., Wall, A. M., & Schipper, L. A. (2014). Year-round growing conditions explains large CO2sink strength in a New Zealand raised peat bog. *Agricultural and Forest Meteorology*, *192–193*, 59–68. https://doi.org/10.1016/j.agrformet.2014.03.003

Campbell, D. I., & Williamson, J. L. (1997). Evaporation from a raised peat bog. *Journal of Hydrology*, *193*(1–4), 142–160. https://doi.org/10.1016/S0022-1694(96)03149-6

Campbell, D. I, Smith, J., Goodrich, J. P., Wall, A. M., & Schipper, L. A. (2014). Year-round growing conditions explains large CO2sink strength in a New Zealand raised peat bog. *Agricultural and Forest Meteorology*, *192–193*, 59–68. https://doi.org/10.1016/j.agrformet.2014.03.003

Campbell, E. O. (1964). The Restiad Peat Bogs at Motumaoho and Moanatuatua. *Translations of the Royal Society of New Zealand: Botany*, *2*, 219–227.

Chappell, P. R. (2014). Chappell, P. R., and National Institute of Water Atmospheric Research , Issuing Body. *The Climate and Weather of Waikato*. 2nd ed. 2014. NIWA Science and Technology Ser. ; Number 61. Web.

Chimner, R. A., Cooper, D. J., Wurster, F. C., & Rochefort, L. (2017). An overview of peatland restoration in North America: where are we after 25 years? *Restoration Ecology*, *25*(2), 283–292. https://doi.org/10.1111/rec.12434

Chimner, R. A., Pypker, T. G., Hribljan, J. A., Moore, P. A., & Waddington, J. M. (2017). Multi-decadal Changes in Water Table Levels Alter Peatland Carbon Cycling. *Ecosystems*. https://doi.org/10.1007/s10021-016-0092-x

Clarkson, B. R., Ausseil, A. E., & Gerbeaux, P. (2013). Wetland ecosystem services. *Dymond JR Ed. Ecosystem Services in New Zealand: Conditions and Trends. Manaaki Whenua Press, Lincoln*, (Table 1), 192–202. https://doi.org/10.1139/f95-059

Clarkson, B. R., Moore, T. R., Fitzgerald, N. B., Thornburrow, D., Watts, C. H., & Miller, S. (2014). Water table regime regulates litter decomposition in restiad peatlands, New Zealand. *Ecosystems*, *17*(2), 317–326. https://doi.org/10.1007/s10021-013-9726-4

Clarkson, B. R., Schipper, L. A., & Clarkson, B. D. (2004). Vegetation and peat characteristics of restiad bogs on Chatham Island (Rekohu), New Zealand. *New Zealand Journal of Botany*, *42*(2), 293–312. https://doi.org/10.1080/0028825X.2004.9512905

Clarkson, B. R., Schipper, L. A., & Lehmann, A. (2004). Vegetation and peat characteristics in the development of lowland restiad peat bogs, North Island, New Zealand. *Wetlands*, *24*(1), 133–151. https://doi.org/10.1672/0277-5212(2004)024[0133:VAPCIT]2.0.CO;2

Clarkson, B. R., Thompson, K., Schipper, L. A., & Mcleod, M. (1999). Moanatuatua Bog-Proposed Restoration of a New Zealand Restiad Peat Bog Ecosystem New Zealand . 20 Department of Biological Sciences , The University.

Clymo, R. S. (1983). Peat. In A. J. P. Gore (Ed.), *Ecosystems of the world 4A. Mires: swamp, bog, fen, and moor.* (pp. 159–224). Amsterdam. The Netherlands.: Elsevier Science.

Clymo, R. S., & Bryant, C. L. (2008). Diffusion and mass flow of dissolved carbon dioxide, methane, and dissolved organic carbon in a 7-m deep raised peat bog. *Geochimica et Cosmochimica Acta*, *72*(8), 2048–2066. https://doi.org/10.1016/j.gca.2008.01.032

Cranwell, L. M. (1939). Soils and Agriculture of part of Waipa Country. In E. V. Paul (Ed.), *Native Vegetation* (pp. 23–29). Wellington: Government Printer.

Davoren, A. (1978). *A survey of New Zealand peat resources*. Hamilton, N.Z. Published by the University of Waikato for the National Water and Soil Conservation Organisation.

de Lange, P. J., Heenan, P. B., Clarkson, B. D., & Clarkson, B. R. (1999). Taxonomy, ecology, and conservation of Sporadanthus (Restionaceae) in New Zealand. *New Zealand Journal of Botany*, *37*(3), 413–431. https://doi.org/10.1080/0028825X.1999.9512645

de Lange, P. J., Rolfe, J. R., Champion, P. D., Courtney, S. P., Heenan, P. B., Barkla, J. W., Hitchmough, R. A. (2013). Conservation status of New Zealand indigenous vascular plants, 2012. *New Zealand Threat Classification Series 3, Department of Conservation, Wellington*, 70. Retrieved from http://www.doc.govt.nz/upload/documents/science-and-technical/nztcs3entire.pdf

Erwin, K. L. (2009). Wetlands and global climate change: The role of wetland restoration in a changing world. *Wetlands Ecology and Management*, *17*(1), 71–84. https://doi.org/10.1007/s11273-008-9119-1

Frankl, R., & Schmeidl, H. (2000). Vegetation change in a South German raised bog: Ecosystem engineering by plant species, vegetation switch or ecosystem level feedback mechanisms? *Flora*, *195*(3), 267–276. https://doi.org/10.1016/S0367-2530(17)30980-5

Fritz, C., Campbell, D. I., & Louis, S. L. (2008). Oscillating peat surface levels in a restiad peatland, New Zealand—magnitude and spatiotemporal variability. *HYDROLOGICAL PROCESSES*, *22*(November 2008), 3264–3274. https://doi.org/10.1002/hyp.6912

Golubev, V., & Whittington, P. (2018). Effects of volume change on the unsaturated hydraulic conductivity of Sphagnum moss. *Journal of Hydrology*, *559*, 884–894. https://doi.org/10.1016/j.jhydrol.2018.02.083

Goodrich, J. P., Campbell, D. I., Clearwater, M. J., Rutledge, S., & Schipper, L. A. (2015). High vapor pressure deficit constrains GPP and the light response of NEE at a Southern Hemisphere bog. *Agricultural and Forest Meteorology*, *203*, 112–123. https://doi.org/10.1016/j.agrformet.2015.01.001

Goodrich, J. P., Campbell, D. I., & Schipper, L. A. (2017). Southern Hemisphere bog persists as a strong carbon sink during droughts. *Biogeosciences*, *14*(20), 4563–4576. https://doi.org/10.5194/bg-14-4563-2017

Grimshaw, D. (2000). *Groundwater dynamics in a restiad peat bog: Moanatuatua Scientific Reserve, Waikato.* University of Waikato, New Zealand.

Haapalehto, T. O., Vasander, H., Jauhiainen, S., Tahvanainen, T., & Kotiaho, J. S. (2011). The effects of peatland restoration on water-table depth, elemental concentrations, and vegetation: 10 years of changes. *Restoration Ecology*, *19*(5), 587–598. https://doi.org/10.1111/j.1526-100X.2010.00704.x

Hewitt, A. E. (2010). *New Zealand Soil Classification* (3rd ed.). Lincoln, Canterbury, New Zealand: Manaahi Whenua - Landcare Research New Zealand Ltd.

Hodges, T. A., & Rapson, G. L. (2010). Is Empodisma minus the ecosystem engineer of the FBT (fen-bog transition zone) in New Zealand? *Journal of the Royal Society of New Zealand*, *40*(3–4), 181–207. https://doi.org/10.1080/03036758.2010.503564

Holden, J., & Burt, T. P. (2003). Hydrological studies on blanket peat: The significance of the acrotelm-catotelm model. *Journal of Ecology*, *91*(1), 86–102. https://doi.org/10.1046/j.1365-2745.2003.00748.x

Holden, J., Wallage, Z. E., Lane, S. N., & McDonald, A. T. (2011). Water table dynamics in undisturbed, drained and restored blanket peat. *Journal of Hydrology*, *402*(1–2), 103–114.

https://doi.org/10.1016/j.jhydrol.2011.03.010

Hooijer, A., Page, S., Jauhiainen, J., Lee, W. A., Lu, X. X., Idris, A., & Anshari, G. (2012). Subsidence and carbon loss in drained tropical peatlands. *Biogeosciences*, *9*(3), 1053–1071. https://doi.org/10.5194/bg-9-1053-2012

Howie, S. A., & Hebda, R. J. (2018). Bog surface oscillation (mire breathing): A useful measure in raised bog restoration. *Hydrological Processes*, *32*(11), 1518–1530. https://doi.org/10.1002/hyp.11622

Howie, S. A., Whitfield, P. H., Hebda, R. J., Munson, T. G., Dakin, R. A., & Jeglum, J. K. (2009). Water Table and Vegetation Response to Ditch Blocking: Restoration of a Raised Bog in Southwestern British Columbia. *Canadian Water Resources Journal*, *34*(4), 381–392.

Ingram, H. A. P. (1978). Soil Layers in Mires: Function and Terminology. *Journal of Soil Science*, *29*(2), 224–227. https://doi.org/10.1111/j.1365-2389.1978.tb02053.x

Ingram, H. A. P. (1982). Size and shape in raised mire ecosystems: A geophysical model. *Nature*, *297*(5864), 300–303. https://doi.org/10.1038/297300a0

Ingram, H. A. P. (1983). Hydrology. In A. J. P. Gore (Ed.), *Ecosystems of the world 4A. Mires: swamp, bog, fen, and moor.* (pp. 67–158). Amsterdam. The Netherlands.: Elsevier Science.

Ivanov, K. E. (1981). *Water Movements in Mirelands*. London: Academic Press Inc.

Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y., & Fawcett, P. J. (2013). Terrestrial water fluxes dominated by transpiration. *Nature*, *496*(7445), 347–350. https://doi.org/10.1038/nature11983

Johnson, P., & Gerbeaux, P. (2004). *Wetland Types in New Zealand*. Department of Conservation, Wellington.

Kohler, M. A., & Linsley, R. K. (1951). *Predicting the runoff from storm rainfall*. Government Printing Office, Washington 25, D. C.

Labadz, J., Allott, T., Evans, M., Butcher, D., Billett, M., Yallop, A., & Hart, R. (2010). Peatland Hydrology October 2010. *Information Systems*, (October), 4–6.

Lafleur, P. M., Hember, R. A., Admiral, S. W., & Roulet, N. T. (2005). Annual and seasonal variability in evapotranspiration and water table at a shrub-covered bog in southern Ontario, Canada. *Hydrological Processes*, *19*(18), 3533–3550. https://doi.org/10.1002/hyp.5842

Lafleur, P. M., Moore, T. R., Roulet, N. T., & Frolking, S. (2005). Ecosystem respiration in a cool temperate bog depends on peat temperature but not water table. *Ecosystems*, *8*(6), 619–629. https://doi.org/10.1007/s10021-003-0131-2

Laiho, R., Vasander, H., Penttilä, T., & Laine, J. (2003). Dynamics of plant-mediated organic matter and nutrient cycling following water-level drawdown in boreal peatlands. *Global Biogeochemical Cycles*, *17*(2), n/a-n/a. https://doi.org/10.1029/2002GB002015

Laine, J., Vasander, H., & Sallantaus, T. (1995). Ecological effects of peatland drainage for forestry. *Environmental Reviews*, *3*(3–4), 286–303. https://doi.org/10.1139/a95-015

Lapen, D. R., Price, J. S., & Gilbert, R. (2005). Modelling two-dimensional steady-state groundwater flow and flow sensitivity to boundary conditions in blanket peat complexes. *Hydrological Processes*, *19*(2), 371–386. https://doi.org/10.1002/hyp.1507

Limpens, J., Berendse, F., Blodau, C., Canadell, J. G., Freeman, C., Holden, J., & Schaepman-Strub, G. (2008). Peatlands and the carbon cycle: from local processes to global implications - a synthesis. *Biogeosciences*, *5*, 1475–1491. https://doi.org/10.5194/bgd-5-1379-2008

Littlewood, N., Anderson, P., Artz, R., Bragg, O., Lunt, P., & Land, M. (2010). Peatland Biodiversity. *Scientific Review*, (December), 1–35.

Logsdon, S. D., Schilling, K. E., Hernandez-Ramirez, G., Prueger, J. H., Hatfield, J. L., & Sauer, T. J. (2010). Field estimation of specific yield in a central Iowa crop field. *Hydrological Processes*, *24*(10), 1369–1377. https://doi.org/10.1002/hyp.7600

MacKay, J. (1912). *Parlimentary Debates. Legistative Council and House of Representitives* (160th ed.). Wellington: Government Printer.

Matheson, K. S. (1979). *Moanatuatua - an ecological study of an oligotrophic, restiad bog, Waikato, New Zealand*. University of Waikato, New Zealand.

McCraw, J., & Geoscience Society of New Zealand. (2011). *The wandering river : Landforms and geological history of the Hamilton Basin.* (16th ed.). (Guidebook (Geoscience Society of New Zealand).

McGlone, M. S. (2009). Postglacial history of New Zealand wetlands and implications for their conservation New Zealand wetland nomenclature. *New Zealand Journal of Ecology*, *33*(1), 1–23.

Mckenzie, S. (2004). Subsidence Rates Of Peat Since 1925 In The Moanatuatua Swamp Area, (June 2002).

Miettinen, J., Hooijer, A., Wang, J., Shi, C., & Liew, S. C. (2012). Peatland degradation and conversion sequences and interrelations in Sumatra. *Regional Environmental Change*, *12*(4), 729–737. https://doi.org/10.1007/s10113-012-0290-9

Molini, A., Lanza, L. G., & La Barbera, P. (2005). The impact of tipping-bucket raingauge measurement errors on design rainfall for urban-scale applications. *Hydrological Processes*, *19*(5), 1073–1088. https://doi.org/10.1002/hyp.5646

Newnham, R. M., de Lange, P. J., & Lowe, D. J. (1995). Holocene vegetation, climate and history of a raised bog complex, northern New Zealand based on palynology, plant macrofossils and tephrochronology. *Holocene*, *5*(3), 267–282. https://doi.org/10.1177/095968369500500302

NIWA. (2010). *National Climate Database*. https://www.niwa.co.nz/education-and-training/schools/resources/climate

Papale, D., & Valentini, R. (2003). A new assessment of European forests carbon exchanges by eddy flux and artificial neural network spatialization. *Global Change Biology*, *9*, 525–535.

Plummer, N., Salinger, M. J., Nicholls, N., Suppiah, R., Hennessy, K. J., Leighton, R. M., & Lough, J. M. (1999). Changes in Climate Extremes Over the Australian Region and New Zealand During the Twentieth Century BT - Weather and Climate Extremes: Changes, Variations and a Perspective from the Insurance Industry, 183–202. https://doi.org/10.1007/978-94-015-9265-9_12

Potvin, L. R., Kane, E. S., Chimner, R. A., Kolka, R. K., & Lilleskov, E. A. (2014). Effects of water table position and plant functional group on plant community, aboveground production, and peat properties in a peatland mesocosm experiment (PEATcosm). *Plant and Soil*, *387*(1–2), 277–294. https://doi.org/10.1007/s11104-014-2301-8

Price, J., Evans, C., Evans, M., Allott, T., & Shuttleworth, E. (2016). Peatland restoration and hydrology. In A. Bonn, T. Allott, M. Evans, H. Joosten, & R. Stoneman (Eds.), *Peatland Restoration and Ecosystem Services* (pp. 77–94). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781139177788.006

Price, J. S. (1992). Blanket bog in Newfoundland. Part 2. Hydrological processes. *Journal of Hydrology*, *135*(1–4), 103–119. https://doi.org/10.1016/0022-1694(92)90083-8

Price, J. S. (1996). Hydrology and microclimate of a partly restored cutover bog, Quebec. *Hydrological Processes*, *10*(10), 1263–1272. https://doi.org/10.1002/(SICI)1099-1085(199610)10:10<1263::AID-HYP458>3.0.CO;2-1

Price, J. S., Heathwaite, A. L., & Baird, A. J. (2003). Hydrological processes in abandoned and restored peatlands:an overview of management approaches. *Wetlands Ecology and Management*, *11*, 65–83. https://doi.org/10.1023/A:1022046409485

Price, J. S., & Schlotzhauer, S. M. (1999). Importance of shrinkage and compression in determining water storage changes in peat: The case of a mined peatland. *Hydrological Processes*, *13*(16 SPEC. ISS.), 2591–2601. https://doi.org/10.1002/(SICI)1099-1085(199911)13:16<2591::AID-HYP933>3.0.CO;2-E

Pronger, J., Schipper, L. A., Hill, R. B., Campbell, D. I., & McLeod, M. (2014). Subsidence Rates of Drained Agricultural Peatlands in New Zealand and the Relationship with Time since Drainage. *Journal of Environment Quality*, *43*(4), 1442. https://doi.org/10.2134/jeq2013.12.0505

Ramsar. (2016). The List of Wetlands of International Importance. *Ramsar*, (14), 1–48. https://doi.org/http://www.ramsar.org/pdf/sitelist.pdf

Ratcliffe, J., Campbell, D. I., Clarkson, B. R., & Schipper, L. A. (2018). Water table fluctuations control CO2 exchange in wet and dry bogs through different mechanisms. *Science of the Total Environment*, *inpress*, 1037–1046. https://doi.org/10.1016/j.scitotenv.2018.11.151

Rycroft, W. D., Williams, J. A. D., & Ingram, H. A. P. (1975). The Transmission of Water Through Peat: II. Field Experiments. *The Journal of Ecology*, *63*, 557.

Rydin, H., Jeglum, J. K., & Hooijer, A. (2013). The biology of peatlands, (January 2013), 343.

Schipper, L. A., & McLeod, M. (2002). Subsidence rates and carbon loss in peat soils following conversion to pasture in the Waikato Region, New Zealand. *Soil Use and Management*, *18*(2), 91–93. https://doi.org/10.1111/j.1475-2743.2002.tb00225.x

Schouwenaars, J. M. (1993). Hydrological differences between bogs and bog-relicts and consequences for bog restoration. In E. P. H. Best & J. P. Bakker (Eds.), *Developements in Hydrobiology, Netherlands-Wetlands* (Vol. 265, pp. 217–224). Springer, Dordrecht.

Smallfield, P. W. (1939). Soils and Argiculture of part of the Waipa Country. In E. V. Paul (Ed.), *Agriculture of Waipa Country* (pp. 65–85). Wellington: Government Printer.

Smith, J. (2003). *Fluxes of carbon dioxide and water vapour at a Waikato peat bog*. University of Waikato, New Zealand.

Strack, M., Kellner, E., & Waddington, J. M. (2005). Dynamics of biogenic gas bubbles in peat and their effects on peatland biogeochemistry. *Global Biogeochemical Cycles*, *19*(1), 1–9. https://doi.org/10.1029/2004GB002330

Strack, M., Waddington, J. M., Lucchese, M. C., & Cagampan, J. P. (2009). Moisture controls on CO2 exchange in a Sphagnum-dominated peatland: Results from an extreme drought field experiment. *Ecohydrology*, *2*(February), 454–461. https://doi.org/10.1002/eco.68

Thompson, M. A., Campbell, D. I., & Spronken-Smith, R. A. (1999). Evaporation from natural and modified raised peat bogs in New Zealand. *Agricultural and Forest Meteorology*, *95*(2), 85–98. https://doi.org/10.1016/S0168-1923(99)00027-1

Tuatua-Moana Swamp - Report on Drainage. (1915, May 26). *The New Zealand Herald*.

Verry, E. S., & Boelter, D. H. (1978). Peatland hydrology. In P. Greeson (Ed.), *Wetland Functions and Values: the State of Our Understanding. Proceedings of the National Symposium on Wetlands. Lake Buena Vista, Florida, November 7–10* (pp. 389–402). Minneapolis: American Water Research Association.

Waddington, J. M., Morris, P. J., Kettridge, N., Granath, G., Thompson, D. K., & Moore, P. A. (2015). Hydrological feedbacks in northern peatlands. *Ecohydrology*, *8*(1), 113–127. https://doi.org/10.1002/eco.1493

Wagstaff, S., & Clarkson, B. (2012). Systematics and ecology of the Australasian genus Empodisma (Restionaceae) and description of a new species from peatlands in northern New Zealand. *PhytoKeys*, *13*(0), 39–79. https://doi.org/10.3897/phytokeys.13.3259

Waikato Regional Council. (1999). *For Peat's Sake* (First edit). Environment Waikato Regional Council.

Wallace, D. (1978). Experiences of farming peatlands. In L. S. Hamilton & A. P. W. Hodder (Eds.), *Proceedings of a symposium on New Zealand Peatlands, Hamilton.* (pp. 62–70). Hamilton, New Zealand: University of Waikato.

Xu, J., Morris, P. J., Liu, J., & Holden, J. (2018). PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *Catena*, *160*(April 2017), 134–140.

https://doi.org/10.1016/j.catena.2017.09.010

Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W., & Hunt, S. J. (2010). Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, *37*(13), 1–5. https://doi.org/10.1029/2010GL043584

Appendix

Most of the data analysis was done in Matlab and these scripts are located on the University of Waikato computer in the Environmental Research Institute. However, some manual measurements needed to be obtained and these are listed below.

Site visits

During each site visit manual measurements were obtained during the time of downloads. How these were done is describe in the methods section (Figure 3.7). Some data is missing as some of the tags were buried in the peat and unable to be located at the time of site visits. Table 7.1 is a list of all the manual measurements taken.

Table 7.1: Manual measurements of peat surface, water table depth and height of the PVC pipe (mm) taken at the time of download

13-Aug-15

Site	Time	Tag_1 (mm)	Tag_2 (mm)	A(mm)	C (mm water table from surface)
M1	12:30			465	1252
M2	10:00			710	610
M3	10:35			655	630
M4	10:50			644	499
M5	11:05			1135	368
M6				973	550
M7	13:35			772	499
M8				774	619
M9					

30-Sep-15

Site	Time	Tag_1 (mm)	Tag_2 (mm)	A(mm)	C (mm water table from surface)
M1				760	464
M2				708	576
M3				570	656
M4				446	640
M5				320	1035
M6				501	990
M7				430	766
M8				604	777
M9					

26-Nov-15

Site	Time	Tag_1 (mm)	Tag_2 (mm)	A(mm)	C (mm water table from surface)
M1	9:00			468	840
M2	9:40			710	670
M3	9:56			655	678
M4	10:12			644	510
M5	10:26			1135	396
M6				971	560
M7	11:30			774	530
M8	11:40			776	658
M9	12:30			555	973

13-Jan-16

Site	Time	Tag_1 (mm)	Tag_2 (mm)	A(mm)	C (mm water table from surface)
M1	10:00			482	740
M2	10:20			722	862
M3	10:35			670	866
M4	10:50			665	694
M5	11:05			1156	568
M6	11:20			1000	748
M7	12:10			797	700
M8	12:20			791	836
M9				555	958

2-Feb-16

Site	Time	Tag_1 (mm)	Tag_2 (mm)	A(mm)	C (mm water table from surface)
M1		616	565	491	1146
M2		800	800	730	942
M3		725	701	679	954
M4		798	745	677	782
M5		1219	1142	1167	640
M6		1052	1088	1016	838
M7		840	857	808	802
M8		836	866	796	950
M9		702	719	558	992

4-Oct-16

Site	Time	Tag_1 (mn	Tag_2 (mn	A(mm)	C (mm water table from surface)
M1			565	578	645
M2		794	556	723	556
M3	9:50		686	660	552
M4	10:00	787	730	650	442
M5	10:07	1203	1130	1137	320
M6			1065	980	496
M7	11:45	814	832	776	430
M8		831	860	785	580
M9		711	728	564	784

22-Feb-17

Site	Time	Tag_1 (mn	Tag_2 (mn	A(mm)	C (mm water table from surface)
M1	9:30		600	598	986
M2	9:45	844		752	859
M3	9:54		723	686	834
M4	10:45	836	779	693	680
M5	10:17	1241	1167	1182	580
M6	11:14		1125	1133	750
M7	11:27	864	875	826	706
M8	11:40	863	893	818	884
M9	11:57	720		565	962

7-Feb-18

Site	Time	Tag_1 (mm)	Tag_2 (mm)	A(mm)	C (mm water table from
M1	10:30		630	606	1100
M2	10:44	845		757	899
M3	11:18		736	679	902
M4	11:05	840	776	694	739
M5	11:30	1240	1157	1180	624
M6	11:46		1115	1027	802
M7	12:16	862	872	822	750
M8	12:25	864	892	815	892
M9	12:43	722	750	563	963

3-Jul-17

Site	Time	Tag_1 (mn	Tag_2 (mn	A(mm)	C (mm water table from surface)
M1	11:27		598	582	610
M2	11:42	807		723	566
M3	11:56		696	656	550
M4	12:09	795	732	653	450
M5	12:24	1198	1126	1140	320
24-Jul-17					
M6	10:00		1063	980	478
M7	10:20	805	822	770	339
M8	10:34	833	855	756	563
M9	10:43	704	742	559	715

5-Jul-18

Site	Time	Tag_1 (mn	Tag_2 (mn	A(mm)	C (mm water table from surface)
M1	11:16		617	588	670
M2	11:27	834		730	586
M3	11:41		702	663	581
M4	11:53	806	746	668	466
M5	12:09	1202	1147	1147	340
M6	12:22		1078	990	506
M7	14:32	822	838	785	444
M8	14:43	837	875	798	596
M9	14:59	750	720	565	746