“Keeping the wet in wetlands”

A case study of wetland response to projected changes in climate

at

Mathews Lagoon, Boggy Pond and Wairio Wetlands

BY

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Abstract

Wetlands are some of the most biodiverse ecosystems on the planet. They are critical for global, regional and local ecosystems, and provide considerable social and economic value for human populations (Findlayson, *et. al.*, 2011). Wetlands have been extensively destroyed in many developed countries, establishing a growing concern and greater awareness of the importance of wetlands in the global hydrological cycle - for climate regulation, and for ecological migration (Pfadenhauer & Grootjans, 1999). Changes in climate, driven by increases in atmospheric concentrations of greenhouse gasses are predicted to cause significant changes to the spatial and temporal distributions in rainfall. Since water is the dominant forcing component in the structural development of wetland systems, they are particularly susceptible to changes in climate. While considerable work is now being conducted globally to better understand how wetlands will respond to changes in climate, little work has been conducted in New Zealand to identify the vulnerability of New Zealand wetland systems.

Recent projection by NIWA (2016a) on regional changes in climate have been used to assess how three wetland systems (Wairio Stage 1, Boggy Pond, and Mathews Lagoon), located in the Lower Wairarapa Valley may respond to changes in climate. This study identifies relationships between ground and surface water, examines the interactions and connections between the three wetlands, and explores the sensitivity of the wetlands to climate-induced changes in evapotranspiration, temperature, humidity, wind speed, and rainfall. Wairio stage 1 has been identified as the most susceptible wetland of the three due to a lack of recharge source, while Boggy Pond is the least susceptible due to its interaction/connection with the local groundwater system.

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May the force be with you – always!

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1 Introduction

Wetlands are highly productive ecosystems that exhibit significant variability in their type, size, operation and ecological complexity. Wetlands are found over most of the world, covering 6-7 % of the earth's surface (over 10 million km^2) (RAMSAR, 2015). Wetland functions are critical for global, regional and local ecosystems, and provide services that have considerable social and economic value for human populations (Findlayson, *et. al.,* 2011, Mitsch & Gosselink, 2000). Wetlands have been extensively destroyed in many developed countries, with over 50% lost in Europe, North America, Australia and New Zealand in the 20^{th} century (RAMSAR, 2008), and are now being removed throughout emerging economies as demand for arable land rapidly increases.

An increased concern over wetland loss has generated a greater awareness of the importance of wetlands in the global hydrological cycle - for climate regulation, and for ecological migration (Pfadenhauer & Grootjans, 1999). This heightened awareness has driven global, regional, and local action to protect, preserve and restore wetlands all over the world (Butchart, *et al.,* 2010). Subsequently, wetland restoration science has developed significantly over the past 40 years, and has allowed for better protection and management of wetland systems from perverse land use practices (Erwin, 2009).

However, changes in climate, a product of global warming, has presented a new set of challenges (Erwin, 2009). Climate change[1] is predicted to significantly affect many global wetland ecosystems (Findlayson *et. al.,* 2011, and IPCC, 2016). Increases in greenhouse gasses, driven by anthropogenic activity, have already increased atmospheric and oceanic temperature (NOAA(b), 2016). These increases

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[1] References to climate change in this thesis refer to the changes in earth's climate that are either directly or indirectly attributed to anthropogenic activities which have led to the intensification of greenhouse gasses in the earth atmosphere. This differs from climate variability, which is the natural fluctuation observed in the earth's temperature record (UNFCCC, 2007).

in temperature are predicted to intensify the global hydrological cycle, creating spatial and temporal changes in the distribution of rainfall, increasing the frequency and magnitude of droughts and floods, and raising sea levels (Milly, *et al.,* 2002 and Dahl *et. al.*, 2017). These changes will have both direct and indirect effects on wetlands, where ecosystems have developed in response to relatively stable (over annual timescales) hydraulic regimes.

Water acts as the dominant forcing component in the structural development of wetland systems, making them neither terrestrial nor aquatic in nature, but ecosystems that sit (and over time, move) along a continuum between the two, (Dawson, *et. al.,* 2003). Over time, stable hydro periods form, dictating the presence and turnover of wetland-specific biotic communities (Shafroth, *et. al.,* 2002). For this reason, a clear understanding of both historic and contemporary hydrology both at and around a wetland is crucial to ensure desired conservation and restoration outcomes. Understanding the historic and contemporary fluctuations in intensity, seasonal timing, and frequency of inundation is vital, yet often missing from wetland management plans (Fennessy & Mitsch, 2001).

Wetland hydrology is often the most poorly understood component of a wetland ecosystem as hydrological assessments are time-consuming and can be technically challenging (Cole, 1997, and Jackson, 2006). Subsequently, efforts to assess, restore and protect these systems becomes difficult (Erwin, 2009). While predictions can be made on the vulnerability of wetland types to changes in climate, the limited understanding of how individual wetlands operate, inhibit the determination of the effect a changing climate may have on a wetland performance (Clair, *et al.,* 1997). The ability of a wetland to adapt to climatic stresses will depend on the rate and extent to which these changes play out in wetland's hydrology (Bergkamp & Orlando, 1999). Predictions of how individual wetlands will cope must therefore be conducted on a case by case basis, and must take a catchment-wide approach when considering hydrologic responses.

Currently, research is being conducted by the Convention on Biological Diversity (CBD) to better identify the threats changes in climate pose to wetlands. The Ramsar Convention has also developed a method for assessing wetland climate change vulnerability (Gitay *et. al.,* 2011). However, no national assessment of the effects that climate change will have on New Zealand wetlands has been conducted, despite their importance to the nation's biodiversity, and the acknowledgement that they are at significant risk (MfE, 2014 and DOC, 2016). This lack of assessment has been attributed in part to the uncertainties associated with regional climate change projections and a gap in the understanding of the sensitivity of many wetland ecosystems, due to their high level of endemism and the restriction in their geographic and climatic ranges (IPCC, 2007 and NIWA, 2015).

New Zealand has experienced a more substantial loss in wetland extent than any other region of the world (Myers *et. al.,* 2013). Prior to colonisation, an estimated 9% of New Zealand was covered in wetlands, now less than 10% (~250,000ha) remain (Johnson and Gerbeaux, 2004). Many of New Zealand's remaining wetlands are already in states of stress and therefore likely to be more susceptible to changes in climate.

A complex of wetlands on the eastern margins of Lake Wairarapa at the southern end of the North Island of New Zealand are examples of a remnant wetland system that has survived extensive regional anthropogenic changes to their hydrology, and localised stresses from land intensification. In conjunction with Lakes Wairarapa and Onoke, these wetlands are part of Wairarapa Moana, the largest wetland complex in the lower North Island (GWRC, 2013). Historically a strong hydrological relationship existed between Lake Wairarapa and the surrounding wetlands, driven primarily by the flooding of the lake and the Ruamahanga River. However, since the construction of the Lower Wairarapa Development Scheme (LWVDS) in the 1970's the artificial manipulation of lake levels, lowering of the groundwater table, and clearances and drainage of marginal land around these lakes for farming has resulted in significant changes to the size and nature of these wetlands and consequently the ecological and cultural services they provide (GWRC, 2013).

Despite these changes, Wairarapa Moana offers a diversity of habitat types including mudflats, lagoons, sand flats, marshlands, saltmarshes and back waters, which provide seasonal and migratory habitat to over 100 bird species, 40 species of native aquatic turf plant and 10 nationally critical, endangered and vulnerable fish species (DOC, 2010 and GWRC, 2013). Currently, efforts are underway by Greater Wellington Regional Council (GWRC) to gain this system Ramsar status as wetlands of international importance. The Ramsar convention, signed in 1971, is an international treaty that provides a framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. Subsequently, a range of partnerships and community-driven restoration projects are currently underway to preserve and restore this system (GWRC, Application for Ramsar status, Wairarapa Moana Wetlands , 2013).

Two wetland have been singled out as being particularly important to regional biodiversity, Mathews Lagoon and Boggy Pond. Situated on the eastern shoreline of Lake Wairarapa, these two wetlands operate under different hydrological regimes, Mathews Lagoon is artificially fed via a pump drainage schemes while Boggy Pond is left to operate naturally. A further set of man-made wetlands have been constructed between these wetlands and Lake Wairarapa (Wairio). The regional setting, with a climate, especially during the summer, not conducive to wetlands, provides an ideal systems for the analysis of possible climate change effects on three different lowland wetlands types.

1.1 Thesis Objectives

The purpose of this research is to identify the responsiveness (and subsequently the risk) of three wetlands (Mathews Lagoon, Boggy Pond, and Wairio Stage 1) to predicted changes in regional climate. To achieve this, this study must first identify the dominant hydrological components operating in these wetlands, and secondly; identify how significantly NIWAS downscaled, regional changes in climate, are likely to influence these hydrological components. The following gaps in knowledge must therefore be addressed.

- What relationships do these wetlands have with local groundwater and surface water environments, and what is the level of connectivity between each wetland?
- How sensitive to changes in precipitation and evapotranspiration is each wetland?
- How sensitive is evapotranspiration to predicted changes in temperature humidity, and wind speed out to 2040 and 2090? and
- How is rainfall, both locally and across each wetland system, likely to change with predicted changes in climate?

2 Wetlands

Wetlands are found all over the world (Figure 2.1); situated in transitional zones between aquatic and terrestrial ecosystems, where the seasonal or permanent presence of water lies at or near the ground surface. The spatial and temporal distribution of this water influences biogeochemical cycles and develops hydric soil, stimulating the development of diverse plant communities and subsequently habitat for fish and bird species (Casanova & Brock, 2000).

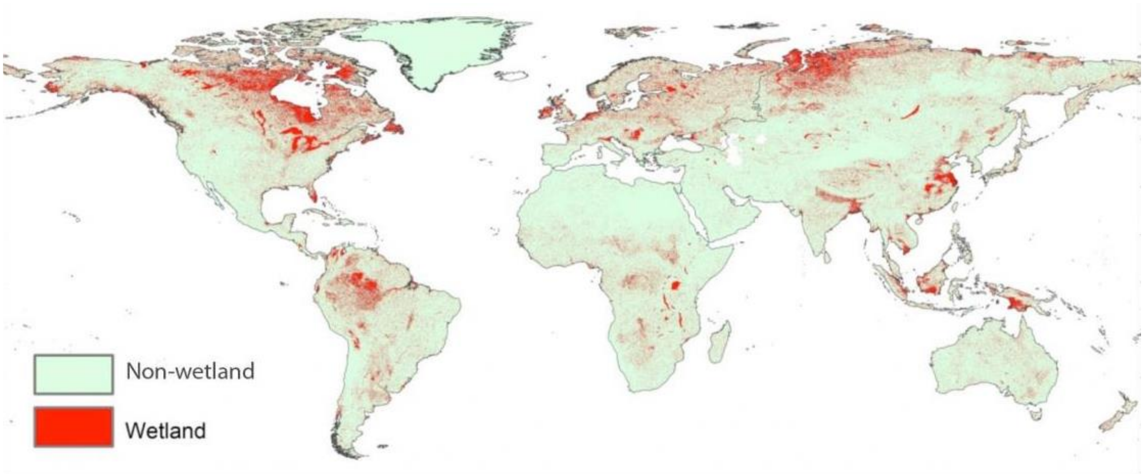


Figure 2.1: A global map of wetland distribution (Zhu and Gong, 2012)

2.1 Wetland classifications

2.1.1 Ecological classification

Due to considerable international variability among wetland habitats, and the transitional nature of their boundaries, wetlands do not fit neatly into aquatic/terrestrial classifications (Cowardin, *et. al.*, 1979 and Shine & de Klemm, 1999). However, standardisation of wetland types is required to allow for information to be collected into the conceptual frameworks, required for effective national, and international wetland management (Pressey & Adam, 1995 and Wardrop, *et al.,* 2013). Early wetland classification systems gave emphasis to ecology and vegetation, leading to habitat-based classification systems, the most notable being the Cowardin system, developed for the U.S Fish and game service in 1979. This system, covered in depth by Cowardin & Golet (1995), uses a hierarchal approach to delineate wetlands based on their position in the landscape, and further refines them into subsystems based on predominant cover type (open water, emergent vegetation i.e. shrubs or forests). Classes are then defined based on substrate types, and subclasses based on vegetation types and soils. It also allows further specification based on flood frequency and salinity levels and/or disturbance activities (Cowardin *et. al.*, 1979, Ernst *et. al.,* 1995, Schot, 1999). The highest tier of the Cowardin system comprise of five wetland systems;

- Marine
- Estuarine
- Riverine
- Lacustrine
- Palustrine

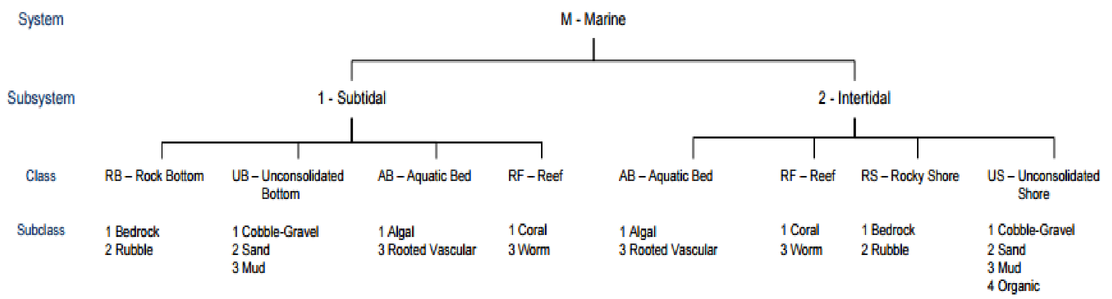


Figure 2.2 An example of the hierarchal structure of the Cowardin system for wetland classification (marine), Cowardin *et. al.,* 1979

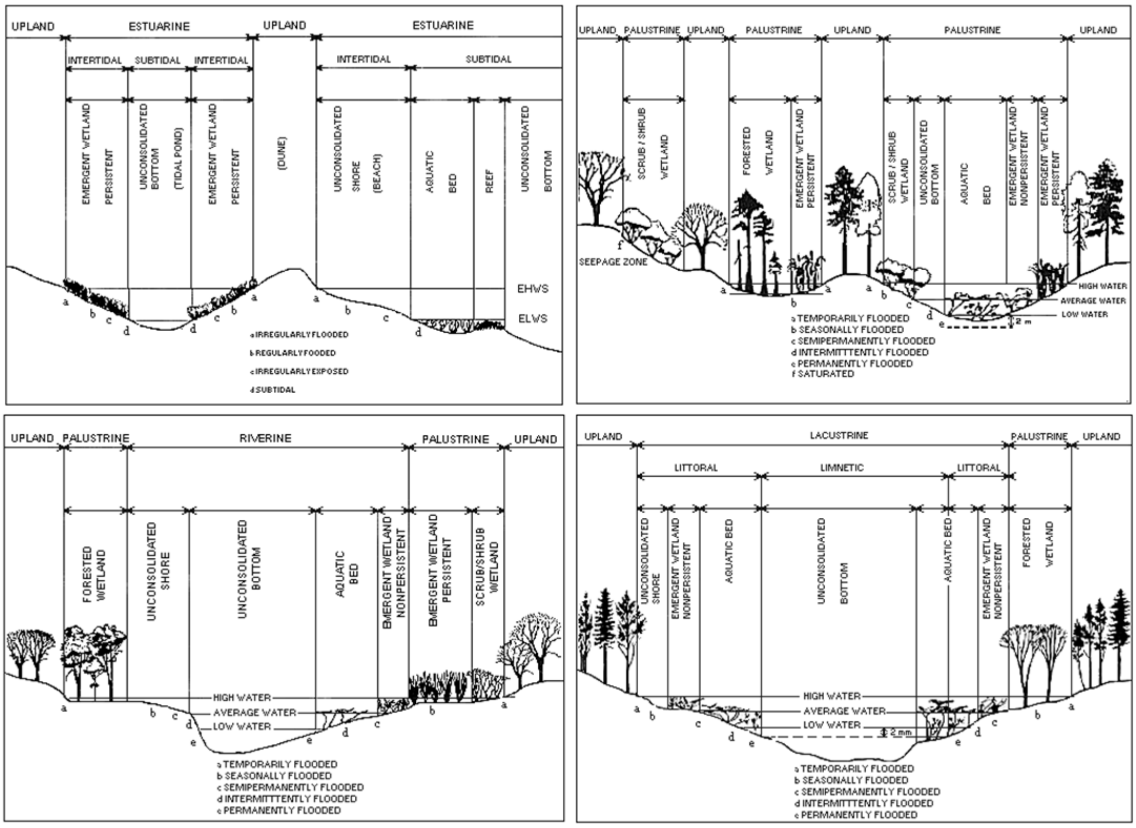


Figure 2.3 Distinguishing features and examples of habitats in Esturine, Palustrine, Riverine, and Lucustrine systems (Cowardin *et. al.*, 1979)

2.1.2 Hydrological classification

Brinson (1993) deviated from the Cowardin classification and suggested that emergent features of wetlands, (i.e. vegetation) were products of hydrogeological conditions. By placing emphasis on geomorphology, regional hydrology and dominant hydrodynamics, Brinson developed a hydrogeomorphic classification system (HGM) which provides a method of identifying how wetlands function, therefore providing a greater understanding of the changes wetland ecosystems may undergo due to external stresses (Brinson *et. al.*. 1993, and U.S. EPA, 2002). This method was further refined by Smith *et. al.* (1995) to better recognise biotic characteristics (e.g., vegetation, soil texture, soil pH) that also have influence on wetland functions.

This classification system separates wetlands into classes based on landscape position (Table 2.1 and Figure 2.4). Geomorphology is the main control over where a wetland sources its water, and therefore influences water level fluctuations, flow rates, and chemistry (USDA, 2008). These factors are responsible for maintaining most wetland functions and therefor act as primary controls. Landscape positions are:

- Depression
- Riverine
- Mineral Flats
- Organic Flats
- Tidal Fringe
- Lacustrine Fringe
- Slopes

Subclasses are then created to reflect primary hydrologic influences i.e. landforms and micro-features such as mounds, hummocks, swales or pools. Both class and subclass are based on three components:

- Geomorphic setting—topographic location within the surrounding landscape
- Water source and its transport—precipitation, surface/near surface flow, and ground water discharge
- Hydrodynamics—direction and strength (hydrologic head) of flow.

Both of these classification methodologies are useful for wetland scientists as they reflect the components of wetland ecosystems that are used to describe wetland environments; water, soil and organisms (Charman 2002). Subsequently wetland definitions derived from these classification methods are comprehensive, examples include Keddy (2000):

"an ecosystem that arises when inundation by water produces soils dominated by anaerobic processes and forces the biota, particularly rooted plants, to exhibit adaptations to tolerate flooding".

and Cowardin (1979):

"Land where an excess of water is the dominant factor determining the nature of soil development and the types of animals and plant communities living at the soil surface. It spans a continuum of environments where terrestrial and aquatic systems intergrade."

Table 2.1: Brinson's hydrogeomorphic classes for wetlands, recognised at a national level in the U.S. (Smith *et. al.*, 1995)

Hydrogeomorphic Class	Dominant Water Source	Water Flow Direction
Riverine	Channel flow and flooding from channel	Unidirectional (channels, and bidirectional (floodplain)
Depressional	Inflow, groundwater discharge	Vertical (seepage)
Mineral Soil Flats	Direct precipitation	Vertical (seepage)
Organic Soil Flats	Direct precipitation	Vertical (seepage)
Slope	Groundwater discharge	Unidirectional, horizontal
Lacustrine Fringe	Inflow and surges from lake	Bidirectional, horizontal
Estuarine Fringe	Inflow and tidal surges	Bidirectional, horizontal

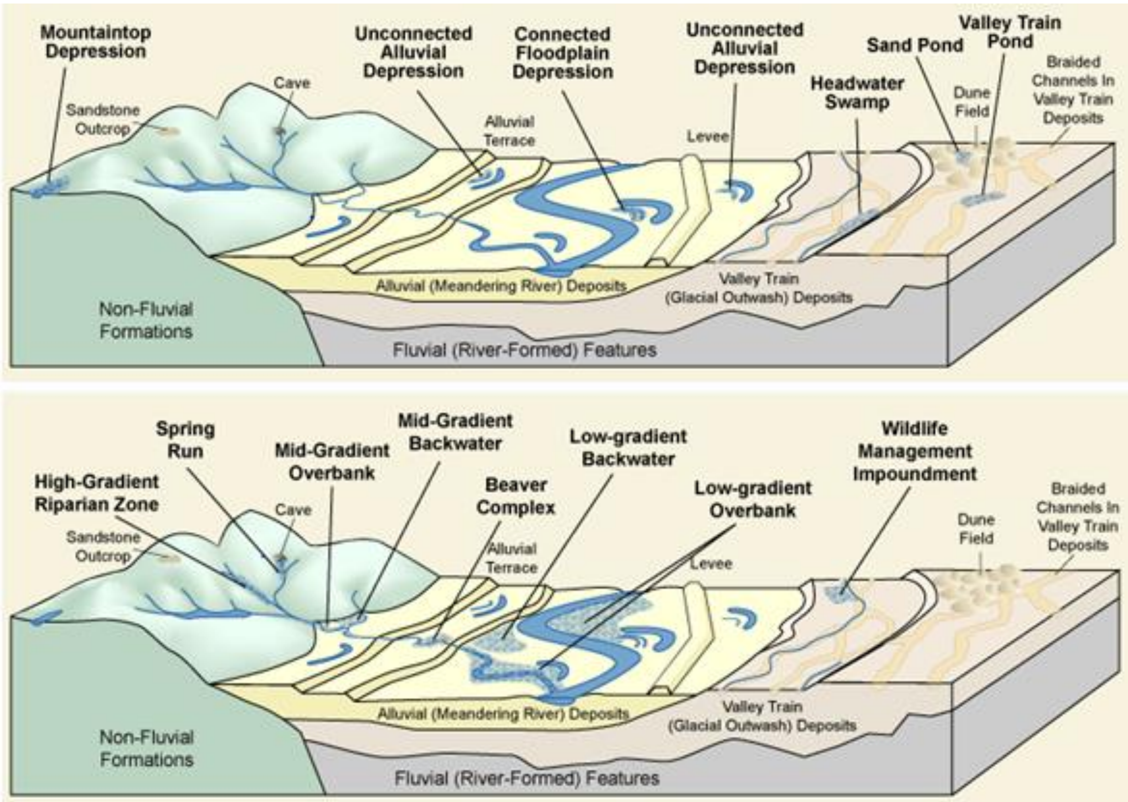


Figure 2.4 Examples of hydro geomorphic classification and characterisation of depression and riverine wetland 2 types, adapted for Arkansas wetlands (ANRC, 2016)

2.1.3 Classification System Used in New Zealand

In New Zealand a need to develop a classification system for inventory and regional State of the Environment monitoring of wetlands saw the development of a classification system based on wetland function (Gerbeaux & Richmond 1999, and Partridge et al. 1999). This classification system merges the Cowardin system and HGM by beginning with the top order of a wetlands hydrosystems based on landform setting, before dividing wetlands into subsystems based on water source, movement, drainage, fluctuation, and periodicity of wetness. Classes are then based on substrate, water regime and chemistry, with further subclasses based on structural classes of vegetation and dominant plants (Ward & Lambie, 1999). This system is semi hierarchal, and does not delineate specific boundaries for groupings within or between classification levels (Partridge *et. al.,* 1999) but instead acknowledges overlap between units (Figure 2.5).

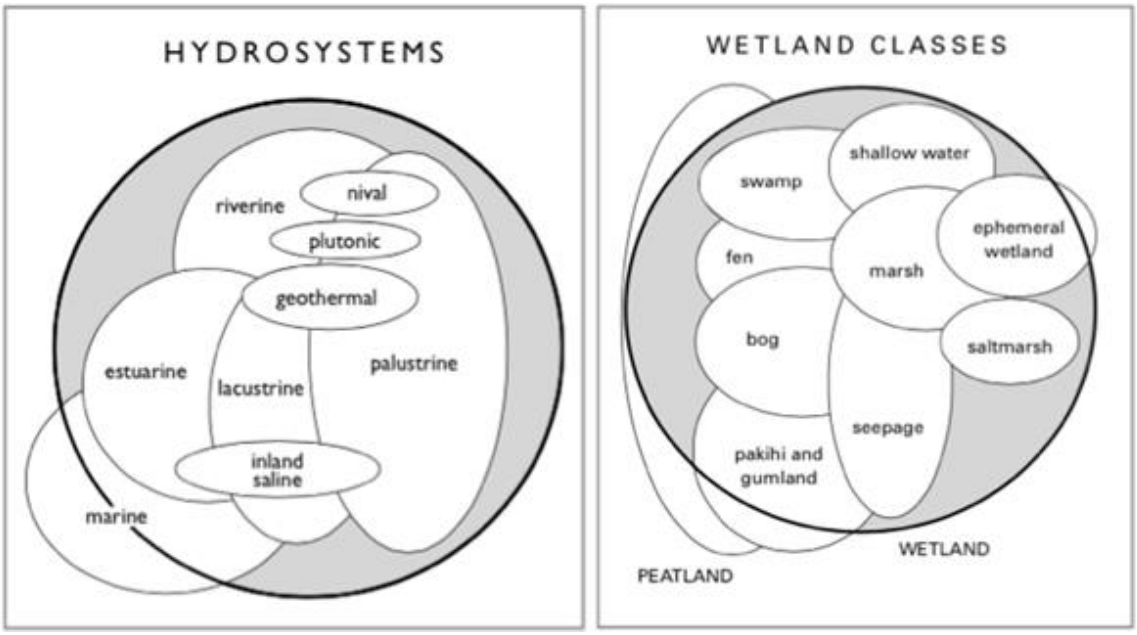


Figure 2.5 Overlapping of wetland hydrosystems and classes based on regional setting and chemistry (Johnson and Gerbeaux, 2004)

Nine hydrosystems are recognised at the highest level of this classification method. These reflect broad hydrological and landform settings, salinity and temperature. The four major systems found in New Zealand are based off wetlands associated with land, rivers, lakes, and coasts, and five minor hydro systems are used to accommodate specialised habitats like coastal wetlands, inlets and deltas, groundwater specific wetlands and frozen habitats. A detailed description of each hydrosystem can be found in Johnson and Gerbeaux, (2004) and Peters & Clarkson, (2012). The four main hydrosystems systems in New Zealand are summarised below:

Palustrine	This hydrosystem encompasses all freshwater wetlands fed by rain, groundwater, or surface water, that are not directly associated with estuaries, lakes, or rivers. This hydrosystem encompasses the greatest variety in wetland classes.
Riverine	Wetlands are connected to functioning natural or artificial rivers or stream systems on either a permanent or intermittent basis. This also includes wetlands along open flowing waters and the riparian zones of channels.
Lacustrine	Wetlands are associated with the beds, and immediate margins of lakes and other freshwater bodies large enough to be influenced by characteristic lake features and processes such as fluctuating water level, and wave actions.
Estuarine	Wetlands are found at the mouth of river systems where salinity reaches a concentration of 0.5%. Coastal lagoons, and wet habitats of open coasts where soil water is affected by sea salts. The estuarine hydro system includes all areas of sub tidal and intertidal zones in estuaries, and also wet ground where surface water and groundwater receive saline contributions from wave splash, or airborne salt in sea spray.

An informal set of subsystems is then used to identify hydrological features that influence the classes that follow. These characteristics include water sources, flow regimes, hydro periods and water residence time. Wetland classes are then defined based on substrate, nutrient status and pH. These factors are not neatly definable and often share characteristics with each other (Figure 2.6). Nine wetland classes are recognized: bog, fen, swamp, marsh, seepage, shallow water, ephemeral wetland, pakihi and gumland, and saltmarsh. Again a detailed description of each class can be found in Johnson and Gerbeaux, (2004). The five main classes found in New Zealand are summarised from their work below:

Wetland Type	BOG / FEN / SWAMP / MARSH — SHALLOW WATER*
Water Source	Rainfall → Groundwater → Surface water
Water flow & fluctuation	Low → Medium → High
Nutrient availability	Low → Medium → High
pH	Low/acidic → Medium → High/neutral
Peat Content	High → Medium → Low/none

Figure 2.6 Environmental Characteristics of wetlands types, (Clarkson & Peters, 2012)

Bog Bogs occur in flat areas and are supplied mainly by precipitation. This makes them oligotrophic and poorly aerated, leading to a low pH (Johnson, 2004). The water table in bog systems is generally seasonally stable, and close to the ground surface. Bogs accumulate peat through the slow decomposition of vegetation and are the most efficient carbon sink on the planet.

Fen Fens are located on shallow slopes and are fed by both rainfall and groundwater which results in the accumulation of some nutrients, making them oligotrophic to mesotrophic. Like bogs, fens have an accumulation of peat but this is often not as thick and more decomposed. Water levels remain predominantly below the surface of fens but ponding above the ground surface can occur.

Swamp	Swamps are usually located in lower energy environments, at the base of valleys and on flood plains. They are supplied via a range of freshwater sources, with overland flow from rainfall and water from flooded rivers providing nutrients while minerals are present from groundwater. Swamps tend to be highly productive environments and subsequently a range of larger flora can be present than that found in bogs and fens. Swamps have substrates dominated by a mix of mineral soils and peat. Fluctuations in water level can be large and frequent and open water is often a feature of swamps; however some areas within the system may appear dry.
Marsh	Marshes are located along rivers, lakes, and on valley floors and margins. Marshes are similar to swamps but are characterised by large fluctuations in water level that may even fall below the ground surface. In most situations substrates will remain moist. Marshes are the most nutrient rich wetlands, and accumulate sediment via surface runoff and groundwater from adjacent land.
Shallow water	Shallow water wetlands are areas of standing water, usually only a few metres deep that are too small to be considered lakes. Shallow water wetlands are often found around lakes, rivers and estuaries. One significant difference between shallow water wetlands and marshes is that nutrient levels and water chemistry reflect the water source, not the wetlands substrate.

2.2 Wetland functions

Since the 1970's a growing concern over wetland loss saw a rapid rise in scientific and social awareness about the roles and functions of wetlands and the inherent value they provide (Kusler & Montanari, 1978). The functions of wetlands are critical to both local and global ecosystems, including flood mitigation, water purification, pollution, and sediment retention and decomposition. They also provide localised climate regulation and carbon storage while also acting as fish nurseries, tourist attractions and recreational areas. The functions of wetlands can be divided into three categories; hydrology, water quality and ecology. In all cases developments in the understanding of the importance of wetland systems and the functions they provide has seen a rapid rise in the development, construction and restoration of wetlands to provide natural, low cost, 'soft engineering" solutions for development-associated problems.

2.2.1 Hydraulic functions

Wetlands can play a critical role in the regulation of river flows by reducing flood levels during flooding events, absorbing water during precipitation events and releasing it back into the system slowly. The removal of wetlands along river systems increases the response times of rivers to rainfall events, making systems more 'flashy' and exacerbating flooding events. In many countries wetlands are now being restored or created along rivers to reduce flood flows (Fengling *et. al.,* 2006 and Ming *et. al.,* 2007). The Whangamarino Wetland in Waikato, New Zealand has been preserved purely for the role it plays in mitigating flood events in the Waikato River, saving the region an estimated $180 million in flood protection works. In preserving the system for the purpose of flood mitigation other functional characteristics are also preserved including; the provision of recreational habitat for hunting, habitat for Inanga, tuna, birdwatching tourism, carbon sequestration, and water storage for irrigation of farmland during dry periods (Roberts, *et al.*, 2015).

2.2.2 Water Quality

Wetlands slow water movement, reducing its ability to suspend sediments, and therefore act to retain sediments from decomposition. Additionally wetland ecosystems filter out pollutants and purify water. Wetlands have become a popular tool for developers to settle heavy metals and Polycyclic Aromatic Hydrocarbon (PAH's) resulting from urban developments and motorways, and are used in the final stage of effluent systems to polish water prior to discharge back into aquatic environments (Mitsch & Gosselink, 2007; and Nabulo *et. al.,* 2008)

2.2.3 Habitat

Wetlands are considered as some of the world's most biologically productive habitats, accounting for an estimated 20% of taxa and genetic resources (Navid, 1989; Gibbs, 1993; Mitsch & Gosslink, 2007). In New Zealand wetlands are the natural habitat to a disproportionate number of threatened and endangered species, and are internationally significant habitat for migratory bird species (Cromarty, 1995). They also act as nurseries for many fish species. The use of wetlands by recreationally hunted waterfowl has led to an increase in the restoration and development of open water wetlands for hunting around New Zealand by NZ Fish and Game. In conjunction with DOC, this also involves the preservation and restoration of other wetland types in the local area.

2.2.4 Valuing wetland functions

Despite the invaluable functions of wetlands, development and planning decisions surrounding land use change are primarily governed by their economic feasibility and free market principles (Barbier, Acreman, & Knowler, 1997). This requires quantifying an anthropocentric value to the functions and services wetlands provide to assist planners and policy makers in making informed assessments of the economic consequences and environmental externalities associated with removing a wetland system. This is exceptionally hard to do for wetland ecosystems, as the benefits they provide are extensive, dynamic, often poorly understood, and occur at different hierarchal levels.

The Total Economic Value method (TEV) (Figure 2.7), seeks to identify the total amount of resources that individuals would be willing to forego for increased amount of wetland services (Mitsch & Gosselink, 2007). The method divides services into use, non-use, social, optional and existence values. Use values are divided into two types: direct use (material goods an ecosystem provides i.e. recreational hunting, fishing, peat harvesting) and indirect use (ecosystem services that wetlands provide i.e. water retention, purification, nutrient recycling). These are assigned values by assessing relocation, restoration and replacement costs (Lambert, 2003). Non-use values of wetlands refer to values which are derived from wetlands operating as they are and include aesthetic qualities and ecological functions essential to nature but not humans. There is no market proxy for these values and therefore they are valued through estimates of the replacement cost of the services they provide (Woodward and Wui, 2001). Optional values are benefits derived to communities or individuals through ensuring the resource will be available in the future. Pricing optional values has to take into account individual preferences, perceptions and values (de Groot *et. al.,* 2003).

Like most types of ecological evaluation, the application of the TEV method fails to address a number of key issues associated with wetland ecosystems. These include:

- Assessing the costs of a degraded wetland, or the loss of some wetland functionality due to stress is difficult as each ecosystem's resilience is not known

- Characteristics of wetlands are lost when removed and many may be irreversible
- Wetlands develop over time and so do the services they provide, and therefore short term, high economic yielding projects tend to win out over the short term

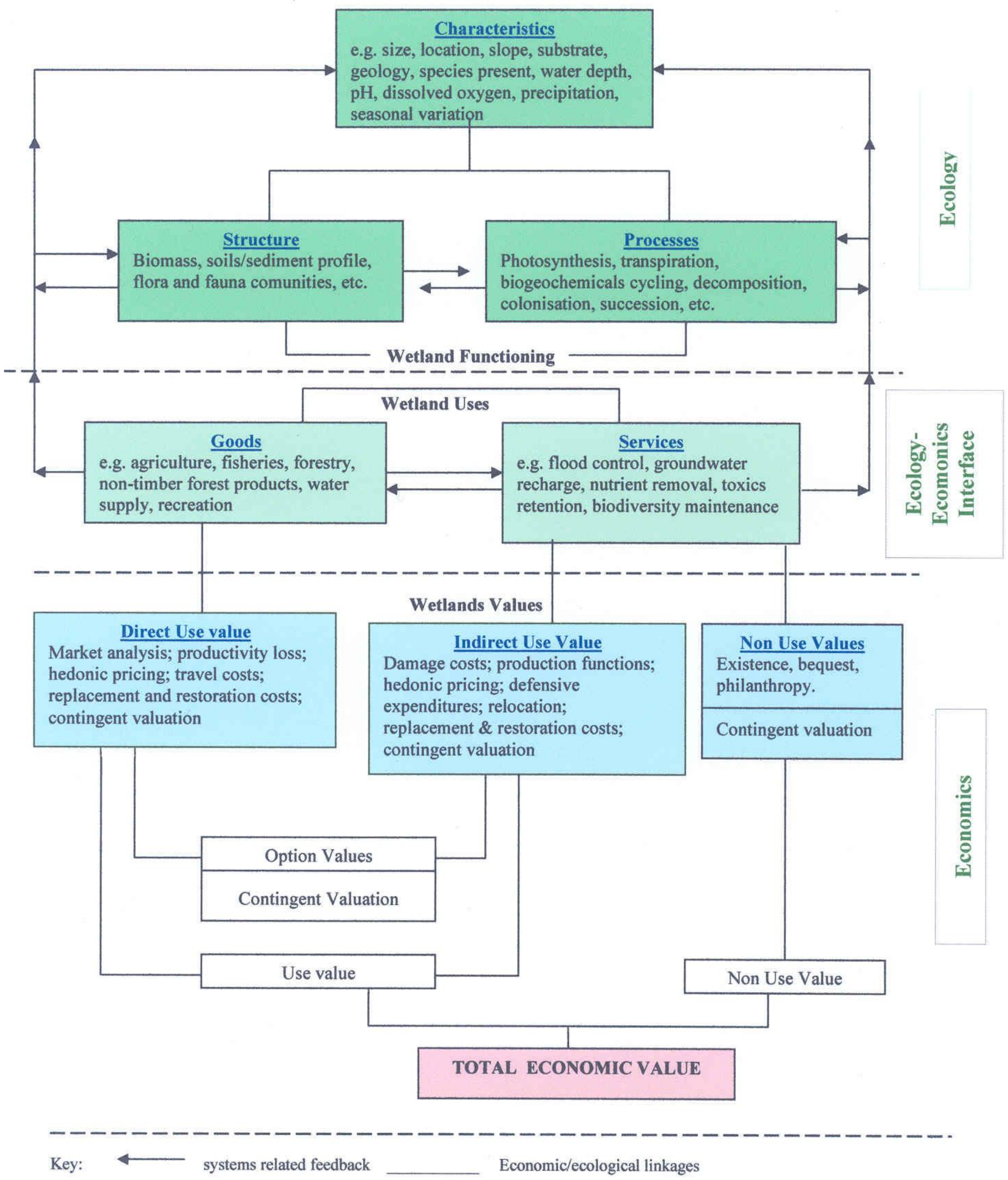


Figure 2.7 Total Economic Value (TEV) method for wetlands, adapted from Lambert, 2003

2.3 Wetland Loss

Despite the many functions of a wetland and the associated values of these functions, wetlands are the most degraded natural ecosystems in the world (Fog & Lampio, 1982, and MEA, 2005). Until recently a large majority of the world's wetlands were protected by their size, remoteness and marginal worth for economic development (Mitsch & Gosselink, 2000). However, rapid demand in arable land, and market, and intervention failure has seen an accelerated rate of wetland loss internationally (Turner 1991). While developed countries are now more aware of the advantages of protecting remaining wetlands, issues over quality degradation and climate change are outstripping restoration and conservation attempts (Dahl & Stedman, 2013). The U.S, for example, lost approximately 145,686ha of coastal wetlands between 2004 and 2009 and 25,211ha of inland wetlands due to hydraulic changes, an increase of 25% on the previous six years (Dahl & Stedman, 2013). Developing countries continue to face on-going economic pressures to convert wetlands for industrial, agricultural and residential developments (Zedler & Kercher, 2005). China for example is home to 10% of the world's remaining wetland resources, and saw a 30% loss between 1990 and 2000 (Cyranoski, 2009).

Estimating the global extent of wetland loss is difficult, as many developing countries still do not have comprehensive wetland inventories. This prevents and estimation of the current extent of wetlands, and the ability to reconstruct the extent of pre-agricultural-wetlands (Kuzila *et. al.,* 1991). The most comprehensive work on calculating the extent of wetland loss has been conducted by Davidson (2014) who concluded that the loss of global wetland area (since 1900AD) is between 50-60%, with rates of loss 3.7 times higher in the 21st century than what was occurring 19th - 20th century (Davidson, 2014).

2.3.1 Wetlands in New Zealand

New Zealand's young and dynamic geological environment, coupled with relatively high rainfall provides perfect conditions for wetland development. New Zealand wetlands have been identified as the primary habitat for 20% of native bird species and are crucial to the survival of eight native fish species (DOC, 2007).

2.3.2 Wetland Loss in New Zealand

The loss and state of New Zealand's wetlands is well documented by Ausseil *et. al.*, (2008) and Myers *et. al.*, (2013), and in a review article in Wetland Protection by Robertson (2015). New Zealand has experienced more loss in wetland extent than any other region of the world (Johnson and Gerbeaux, 2004, and Myers *et al.* 2013). Prior to colonisation an estimated 9% (2,471,080ha) of New Zealand was covered in wetlands, and now less than 10% of this (249,776ha) remains (Figure 2.8) (Robertson H. A., 2015). The greatest reduction in wetland extent has occurred in the past 150 years where two-thirds of New Zealand was converted for farming, industry and settlement (Taylor and Smith, 1997). In the late 1920's government tax incentives to convert marginal land into farmland (considered necessary steps for national prosperity) saw a further 263,999 ha of wetland drainage until the 1980's where the Resource Management Act (1991) identified the protection of wetlands as a matter of national importance (Simpson, 1985, Taylor and Smith, 1997).

Spatial and temporal variation exists in wetland loss around New Zealand. Nationally 5% of inland freshwater wetlands remain in the North Island and 16% in the South Island (Ausseil *et. al.,* 2008). Regional extremes are the Hawkes Bay, with only 1.9% of its original wetland extent left and Otago, where 24.4% remain (Ausseil *et. al.,* 2008). These variations can be attributed to the nature of wetlands found in each region, with fertile lowland swamps drained faster than wetlands at higher altitudes. Ongoing pressures are still driving wetland loss in many regions. Recent demand for dairy products has driven a boom in conversion of low land and marginal land for dairy production.

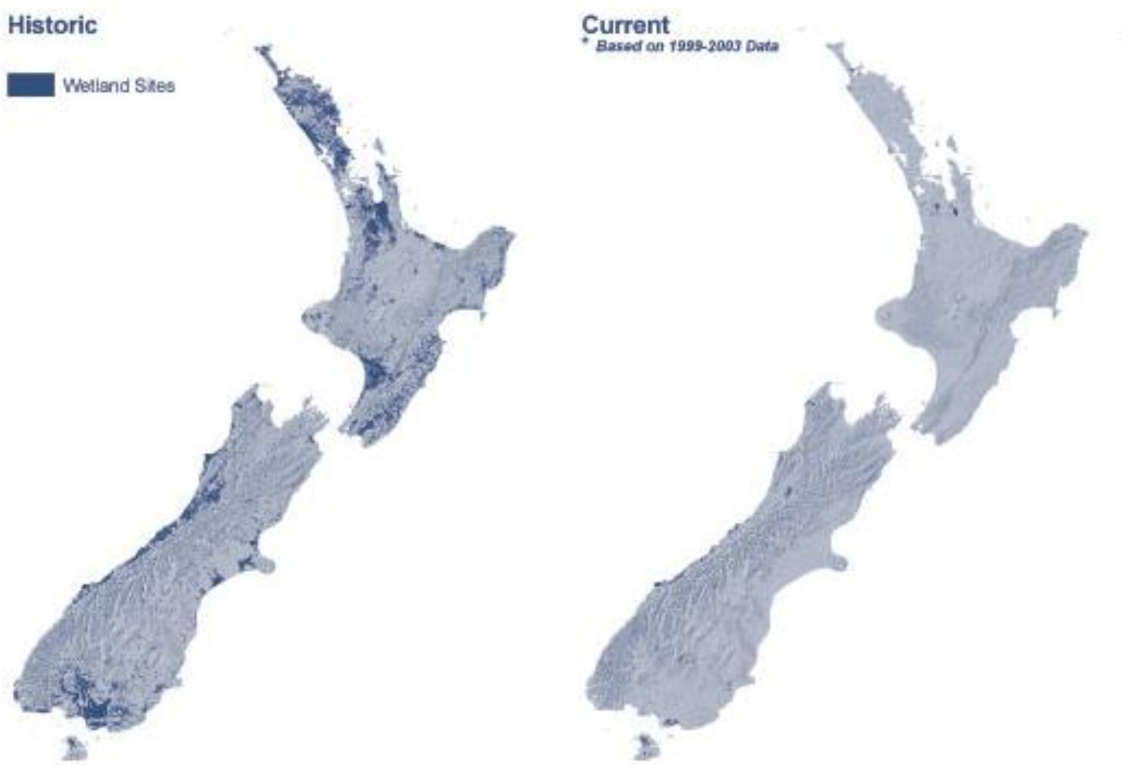


Figure 2.8 Wetland loss in New Zealand (Aussel, 2011)

Wetlands that remain are often small, fragmented and separated from their natural hydraulic sources. Furthermore due to their location within the landscape wetlands act as 'receivers' and are particularly susceptible to the chronic effects of contamination by land-use based effluents. This leaves them stressed, susceptible and less resilient to invasion from introduced species, pollution and hydraulic disturbances that occur outside their visual extent. While direct wetland loss in New Zealand has been partially managed through legislation, systems are so complex that wetland functions are often poorly understood, let-alone the effects of local or regional changes to peripheral hydraulic components (Rokosch *et. al.*, 2001, and Campbell, 2010).

These factors are all likely to be further amplified through changes in climate. Additional stresses on freshwater in lowland areas, especially on the East Coast, will increase stresses. Furthermore changes in invasive species, a critical factor when discussing climate change on ecosystems will further provide challenges.

2.4 Wetland Management in New Zealand

In 1976 New Zealand became a signatory to the 1971 Ramsar Convention of Wetland of International importance, and in so doing attempted a more meaningful push to preserve wetlands. Under this treaty New Zealand was required to identify wetlands of national and international importance, construct a wetland inventory, and actively preserve and protect wetlands. Between 1976 and 2005 New Zealand identified six wetlands of international importance, covering a total of 55,112ha (DOC, 2008) for inclusion into the international list of 2000 wetlands. Currently three more wetlands are being considered for inclusion, one of which is the Wairarapa Moana wetland complex. Inclusion however does not guarantee protection; as has been observed in the declining state of the Whangamarino Wetland Complex in the Waikato Region, which is suffering from declining water quality associated with catchment-wide dairy intensification (Robertson & Funnel, 2012).

Despite New Zealand being a signatory to the Ramsar Convention, wetland loss throughout the eighties continued at an alarming rate (Robertson H. A., 2015). Government agencies were increasingly tasked with protection however failed due to fragmented agencies and policies. In 1986 The New Zealand Wetland Management Policy was signed to centralise wetland protection with the Department of Conservation (DOC), giving the department rights to claim areas of wetlands for protection. However, of the 7000 wetlands mapped nationally only 63% are protected on land administered by DOC, the remainder are located on private land (DOC, 2008).

In 1991 the Resource Management Act (RMA) replaced all government agencies tasked with environmental protection. Currently it is the principal act governing wetland protection in New Zealand by defining roles and responsibilities for the three levels of government in New Zealand—central, regional and local. Central government, in particular Ministry for the Environment (MfE) is required to provide national policy statements and standards to be implemented by DOC, and by regional and local councils (Figure 2.9). Regional and local councils are then tasked with managing wetlands on private land. This is achieved through a combination of regulatory mechanisms based off MfE national policy statements and standards (tailored by each regional council to the specific challenges and wetland types found in their regions), and voluntary incentives to encourage protection and restoration of wetlands (Myers *et. al.*. 2013). Regulatory mechanisms include regional policy statements, regional and district plans, water conservation orders and Heritage orders. While this creates a more standardised approach to wetland protection by setting national, variation does exist between council's rules restricting damaging activities in wetlands. Only 60% of plans restrict damaging activities to wetlands that do not meet criteria for ecological significance, while less than 50% have strong regulations surrounding drainage of wetland areas (Myers *et. al.*. 2013).

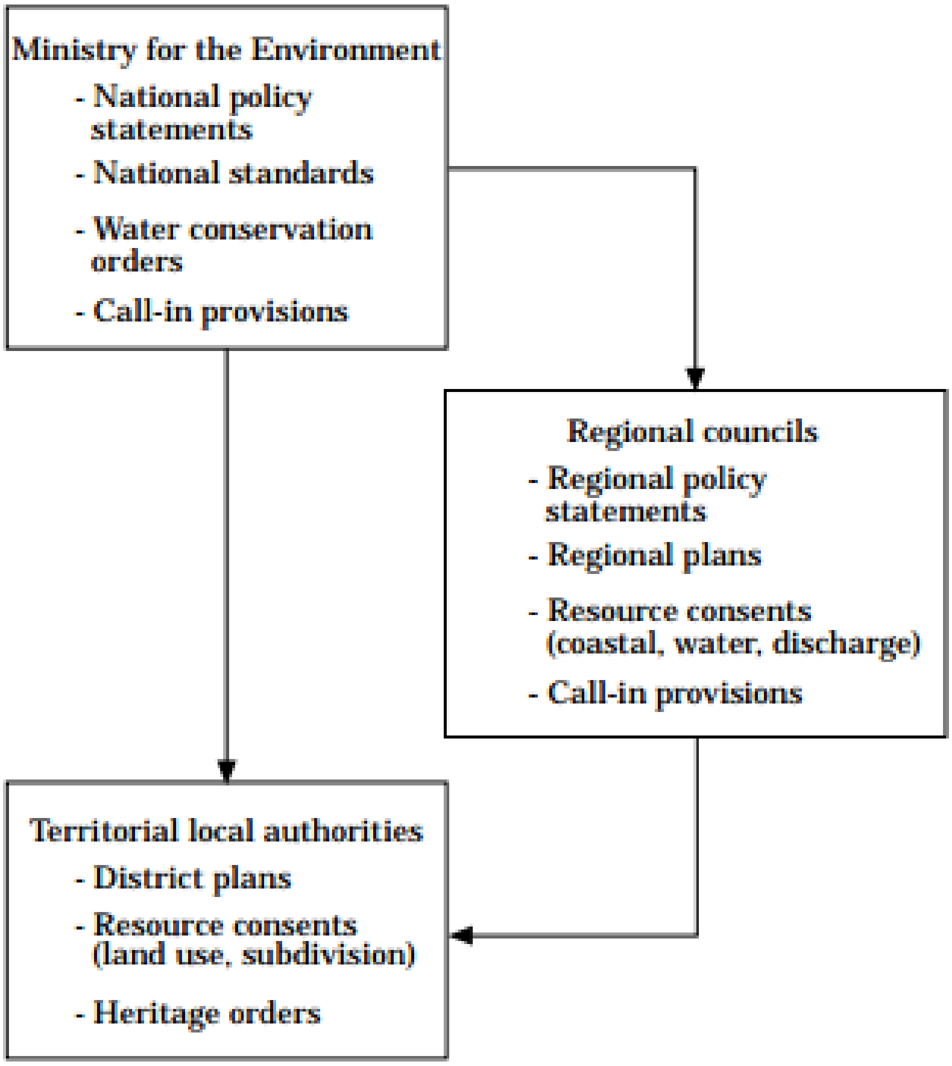


Figure 2.9 The roles of territorial authorities in NZ for wetland Management (Myers *et. al.,* 2013)

Joint management ventures are a popular tool used by DOC to manage and restore wetland systems. An example of this is the Wairio wetland system. While the wetlands are owned by DOC, the management of Wairio Wetlands is undertaken by Ducks Unlimited, a group of recreational hunters, which convenes and chairs a restoration committee comprising of members from GWRC, South Wairarapa District Council (SWDC), DOC, Fish and Game, Forest and Bird, the Queen Elizabeth Trust, local Iwi groups Kahungunu ki Wairarapa and Rangitāne o Wairarapa, resident farmers and Dairy NZ.

2.5 Wetland Hydrology

There are two general components to studying a wetland's hydrology. The first is the study of the source of water in a wetland. This is achieved through the use of a mass balance equation (wetland water balance) which identifies the relative importance of inputs (precipitation, surface and groundwater inflow, and in coastal areas tides), and outflows (evapotranspiration, surface flow, losses to groundwater, and tides) of water in a wetland. A detailed breakdown of each of these components can be found in Carter, 1997; Brinson 1993; Owen 1995; and Mitsch and Gosselink, 2007). The culmination of these inputs and outputs leads to a wetland water balance equation, (Mitsch & Gosselink, Wetlands, 2007) i.e:

$$\Delta S = P + Si + Gi - AET - I - So - Go \pm T$$

Where:

- ΔS = change in storage volume
- P = precipitation
- S_i = surface water inflow
- G_i = ground water inflow
- AET = actual evapotranspiration
- I = infiltration
- S_o = surface water outflow
- G_o = ground water outflow
- T = tidal flow

The relative importance of each input or outflow of water from a wetland varies depending on a wetland's physical location and underlying geology. Similarities between dominant water sources are useful in identify wetland type and functional processes (Figure 2.10) (Bradley, 2002). Isolated wetlands in upper catchment areas will receive a dominant component of their water balance from rainfall, or overland flow, and lose this water through a combination of evapotranspiration, groundwater seepage or overland flow depending on typography and geology. These wetlands will be highly responsive to rainfall and can exhibit significant changes in water storage from very wet to dry depending on seasonal climate cycles. These wetlands will therefore be particularly susceptible to future changes in precipitation patterns brought on by climate change. Lowland swamp or open water wetlands receive a greater proportion of their water balance through ground or surface water interactions. These wetlands are often influenced by flooding events from fluctuations in lake and river levels. Future changes in flood frequency, or catchment based flood protection works may significantly influence these systems, however, wetlands with a strong reliance on groundwater will be affected by increases in abstraction of groundwater from associated aquifers, as demands for freshwater increase with land use intensification and climate change adaptation.

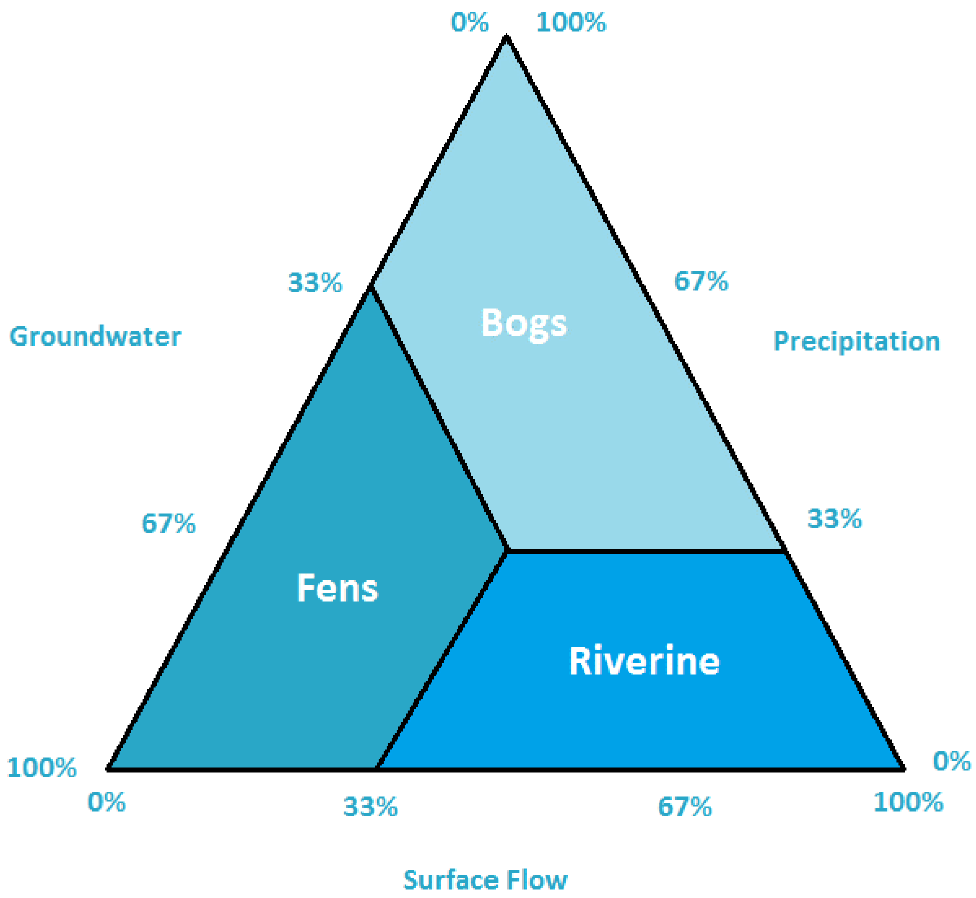


Figure 2.10 Wetland types based on distribution of inflow types

Accurate assessments of a wetland's water balance can be extremely hard to achieve due to the complex nature wetlands interact within a watershed (Maltby, 2009). As each component is studied, errors associated with estimate of water volume in the water budget accumulate and often assumptions are required to fill in calculated discrepancies (Winter, 1981 and Carter, 1986). As a result, detailed water balances are time consuming, and require considerable understanding of individual components and specialised equipment (Favero *et. al.,* 2007). Furthermore, hydrological inputs and outputs of wetlands change over a range of temporal scales. As a result of climate or surrounding conditions, a water balance will only provide a snap shot, and either needs to span a long period in time, or must be placed within a climatic context.

Water balance equations are not useful in identifying how the presence of water influences the ecosystem processes which set wetlands apart from other terrestrial and aquatic ecosystems (Brinson, 1993). Fluxes in the inputs and output of wetlands become evident in changes in water level, flood durations and the flow of water through a wetland. These physical hydrological features are what drive the productivity of wetlands, and the adaptations of plants. Changes in these hydrological features will subsequently influence the stress and productivity of wetlands. Figure 2.11, (adapted from Odum *et. al.,* 1995.) shows that an increase in productivity of a wetland will increase with hydrological turnover to a point, until extensive hydrological turnover will lead to stress within a system.

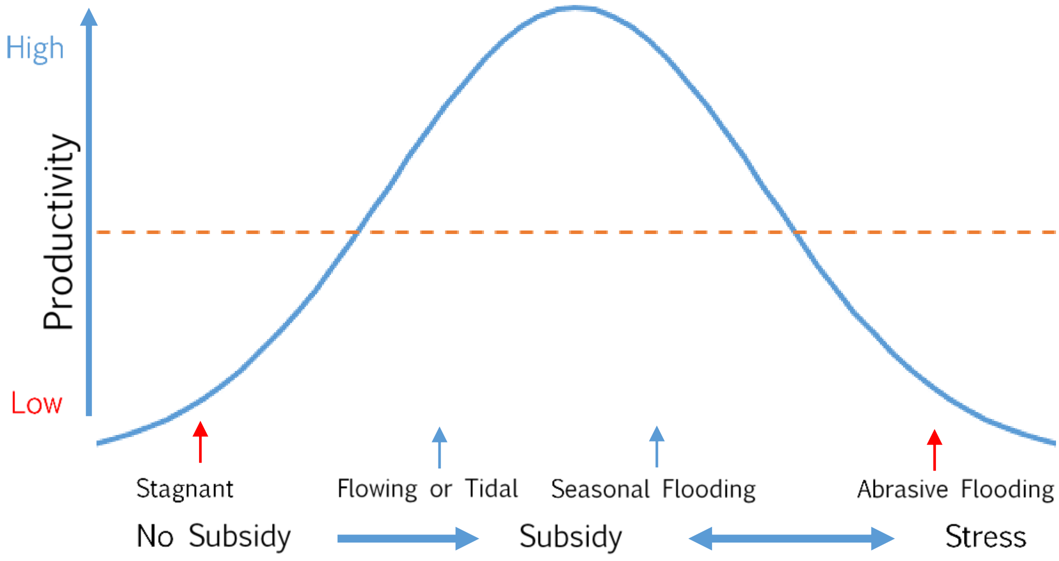


Figure 2.11: Subsidy-stress model illustrating the relationship between ecosystem productivity and wetland hydrology along a flooding gradient. Reproduced from Odum *et. al.,* 1995

2.5.1 Hydro periods

A wetland's hydro period is the seasonal fluctuation of water level that results from changes in the gains and losses of water relative to the soil surface. The hydro period is largely determined by its hydrogeological setting in the landscape and regional climate (Winter 1992). Hydroperiods can be studied through long term recording of water level relative to changes in inflows. Three main classes of hydro-periods are used to define wetlands,-short,-intermediate,-or; long.

Short hydro-periods	Wetlands with short-hydro periods will have surface water for between a few weeks to four months a year and may even stay dry for some years depending on climate shifts in rainfall or snowmelt. Wetlands that exhibit short hydro-periods tend to be found in upper catchment areas and can be very hydrologically responsive to isolated precipitation events.
Intermediate hydro-periods	Wetlands with intermediate hydro-periods hold water for over four months a year but dry out in response to low

	precipitation. Wetlands with intermediate hydro-periods can exhibit dynamic extremes in visible water and can dry out over summer.
Long/ permanent hydro-periods	These may be lake or pond type wetland systems that typically have permanent surface water. These wetlands are often located in the lower reaches of a catchment where hydrological changes are not as dramatic as upper catchment areas.

2.5.2 Water level

Changes in wetland water level have pronounced effects on wetland plant communities and are therefore important considerations. Some (Brinson, 1993) argue that prioritising wetlands based on their extent is short sighted, as wetlands that are smaller, but with variable water levels often have more diverse plant communities and are therefore more ecologically significant. The main component of this is the saturation of soils. Anaerobic conditions affect vegetation by creating adverse conditions for plants, thereby creating diverse assemblages.

The availability of water strongly determines the wetland plants and animals through the cycles between flooding and drying periods (Mendelssohn and Batzer, 2006). Therefore, water level has a profound influence on the structure of a wetland ecosystem. In general, a stable water level favours one or a few plant species while a fluctuating water level can support more complex and diverse plant communities (GWRG, 2005).

2.5.3 Residence time

The hydraulic residence time is the duration of time it takes for water to pass through a wetland system. Calculating the length of time water stays in a wetland for can be difficult as preferential flow paths and patterns can change depending on the volume of water in the system. Many larger wetlands often occur in areas of low topographic relief, a greater volume of water present as a result of a flood or higher seasonal rainfall may spill over areas of the wetland decreasing flow times or pooling water in adjacent topographical depressions. Additionally, during summer, increased macrophyte and plant cover in a wetland may slow down movement or inhibit it all together, altering preferential flow paths. For this reason, residence time is often estimated based on the following assumptions:

- The water exits the wetland in the same “order” it enters
- Water flows at a steady rate through the wetland
- There is a single surface water inflow and outflow
- There are no losses or gains from groundwater or the atmosphere during the period of calculation (usually over an annual time scale).

3 Climate Change

The evidence in support of anthropogenic climate change is now unequivocal, with consensus among the scientific community (Oreskes, 2004, NOAAb, 2016, MfE, 2016a, IPCC, 2016, NASA, 2016a). Global temperatures have risen approximately 1.0^{0}C since 1880 (Figure 3.1) (NASA, 2016b). These increases are driven by the increased concentration of greenhouse gasses (GG) (carbon dioxide, methane, and nitrous oxide) emitted as a result of anthropogenic activity. Concentrations of carbon dioxide are currently exceeding 400ppm (± hemispherical fluctuations in season), up from 280ppm since the 1750s (an increase of 40%). Concentrations of GG are believed to have not been this high for at least 800,000 years (NASAb, 2016).

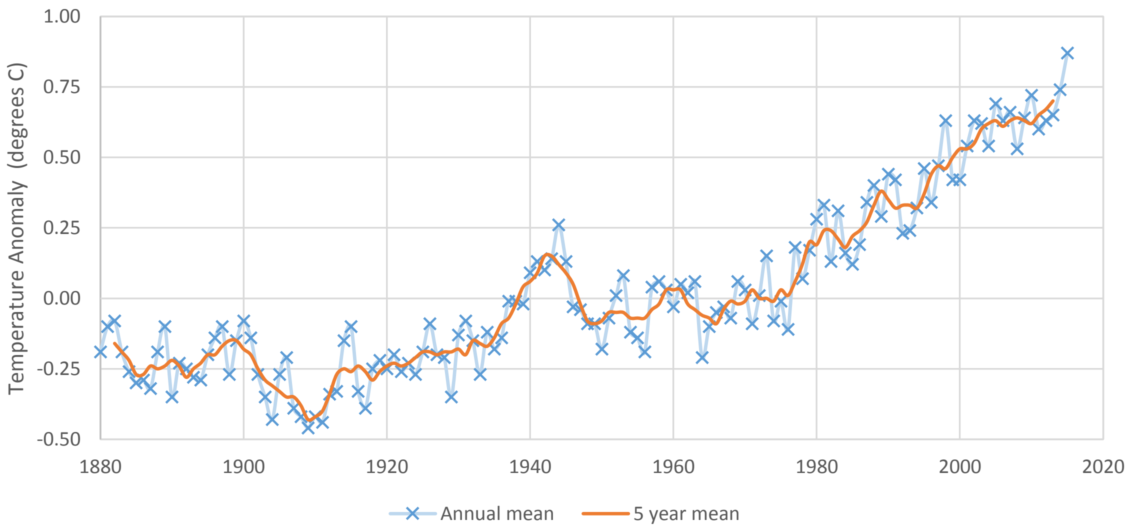


Figure 3.1: Global temperature anomalies from the land ocean temperature index (Data sourced from NASAb, 2016)

In 2014 the Intergovernmental Panel on Climate Change (IPCC), released its 5th assessment report (AR5). 40 emission scenarios have been used to project future changes in climate. Each scenario is derived through the estimations of future rates of emissions and land-use change by predicting rates of population and economic growth, and the invention and adoption of new technologies (WMO, 2016). While this means they incorporate subjective elements, open to various interpretations, they are currently considered to be the most appropriate tool with which to analyse how social and economic driving forces may influence future emission scenarios.

The 5th assessment report concludes:

- Human activity is extremely likely (>95% certainty) to be the dominant cause of the global increase in temperature since the 1950's;
- Warming will continue, with many scenarios suggesting it is likely (>66%) to exceed 2.0^{0}C (relative to the 1850-1900 period);
- Increases in the temporal and spatial distribution of rainfall will occur;
- Global loss of ice sheets will continue. Coupled with a warming ocean, sea levels are very likely (>90%) to rise faster than they have done in the last 40 years.

Details on climate change science, analysis and projections can be found in the IPCC 5th asessment report, *"Climate Change 2014, Impacts, Adaptation, and Vulnerability".*

3.1 Drivers of change

Global warming is a response to global changes in radiative forcing (Collins *et. al.*, 2007). Changes in the concentration of greenhouse gasses, solar radiation, and natural and anthropogenic changes to terrestrial systems all have an influence on the balance of energy in the climate system (IPCC, 2013).

Records of past climate demonstrate natural changes in radioactive forcing as a result of changes in solar output, wobbles and tilts in the earth's orbit, natural changes in GG concentrations and volcanic eruptions. The most recent large scale eruptions of Mt Agung and Mt Pinatubo, in 1963 and 1991, respectively, have a distinct cooling imprint on terrestrial temperature (MfEb, 2016). However, more recent warming cannot be accounted for by these 'natural changes'. The strong historic relationship observed between carbon emissions and temperature identify that GG emissions play a pivotal role in the temperature of the planet. Subsequently, the rapid increase in these concentrations over the past 200 years is now of substantial concern.

It is estimated that approximately 750 gigatonnes of CO_2 is cycled through the climate system each year, and currently an estimated 40 gigatonnes is emitted per year by anthropogenic activity (Figure 3.2 and Figure 3.3 detail types and sources of emissions). While this is a small proportion, a net 60% cannot be absorbed by natural systems and therefore accumulates in the atmosphere. Natural increases in concentrations of Co_2 of 100ppm historically took between 5 and 20 thousand years, however, the current rate is 120 years (NASA, 2016).

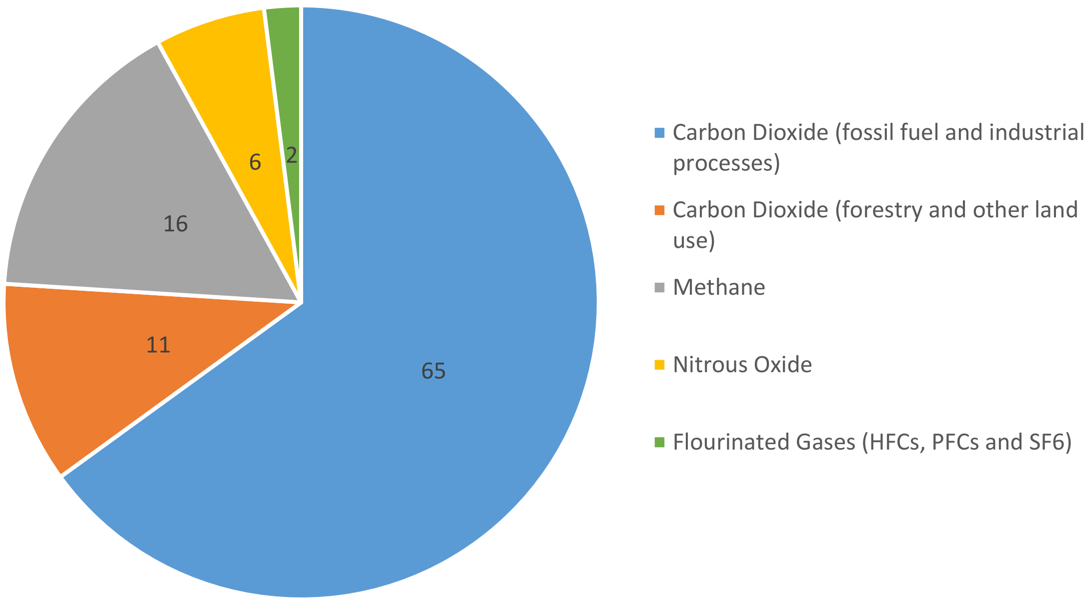


Figure 3.2: Breakdown of fossil fuels by source (IPCC, 2016)

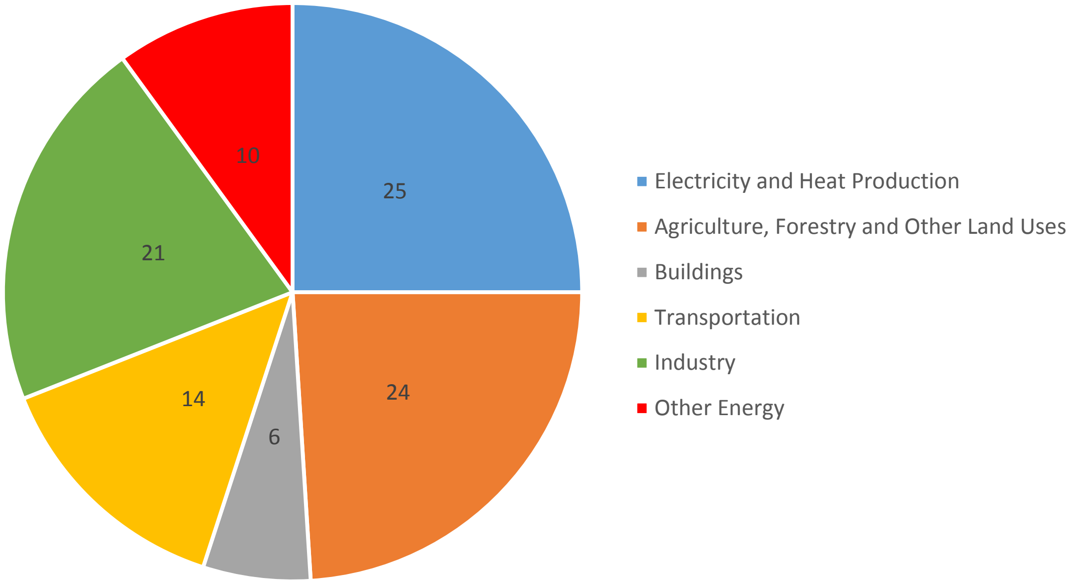


Figure 3.3: Breakdown of fossil fuel by Economic Sector (IPCC, 2016)

3.2 Climate Change and Wetlands

Climate change is projected to have significant effects on wetlands (MEA, 2005). Wetland ecosystems are formed and maintained by the sustained presence of water at or near the earth's surface (Carter, 1997). Wetlands in many developed countries are already prone to stress as a result of perverse land use practices. Climate change will not only increase the cause of these stresses (i.e demands for irrigation) but create a range of new stresses that will negatively impact wetland performance.

Rising sea levels will affect coastal wetland systems while changes in precipitation, including the increase in frequency and magnitude of droughts will reduce water availability. Increases in temperature will warm stagnant water bodies (to the detriment of wetland biota), create new pathways for invasive species, and increase evaporation. (RAMSAR, 2015). The degree to which these stressors will affect wetlands will depend on their geographical location, the rate of regional climate change, the frequency of disturbance events, and the type of wetland (Ross, 2013 and IPCC, 2016).

Changes in temperature are not occurring evenly over the planet, with warming of the Arctic and higher elevations occurring faster than the global average (NASA, 2011). This is already having profound effects, notably the thawing of arctic tundra. Withey & Van Kooten (2011) predict a reduction in the “effective” wetland extent 47-56% in the Canadian prairie pothole region by 2100. In more temperate regions, higher temperatures will warm wetlands, where water can often be stagnant or slow flowing.

Wetlands in tropical regions will be affected by increases in the duration of dry seasons, and subsequently disturbance through increased fire may be the principal driver of change (Hogenbirk & Wein, 1991).

Coastal and intertidal wetlands are likely to be the most adversely affected wetland type. Increases in sea level, driven at present by thermal expansion, and in the near future, by the melting of land based ice sheets is going to force coastal wetlands inland (Ross & Adam, 2013). The rate at which this occurs, especially in the latter half of the century is likely to be too fast for coastal wetland systems to adapt. Furthermore, the increase in storm events, ocean acidification reductions in sediment supply, and increased salinity in upper estuarine systems will further stress coastal wetlands (Michiener *et. al.,* (1995) & Parry *et. al.*, (2007).

Inland wetlands are predicted to reduce in size and number as the climate dries (Batzer & Sharitz, 2014). Wetlands reliant on groundwater are likely to be less susceptible to abrupt climate stresses like storms or droughts as groundwater systems are likely to buffer intense climatic episodes (Winter, 2000). However, over long periods, changes in precipitation volumes and the seasonality of event may alter aquifer recharge rates and volumes. Increased demands on freshwater, especially in low-lying areas used for agriculture production, may stress aquifers (Fredrick and Gleick, 1999). Management of this is often difficult to prove as direct connections between systems are not always apparent and responses often lagged.

Wetlands that are reliant on either rainfall or surface water interactions will be affected by changes in the spatial and temporal distribution of rainfall, as no buffering of the climate will occur and so disturbance events will increase in both frequency and magnitude.

3.2.1 Downscaling of climate scenarios and models to New Zealand

Four climate forcing scenarios, referred to as representative concentration pathways (RCP's), have been downscaled by NIWA (2016) to a 5km grid over New Zealand centred around the 20-year averages over 2031-2050, 2081-2100, and 2101-2120 (relative to the 20 year average 1986-2005) (Table 3.1). Based off a range of emission scenarios, these concentration pathways allow for the assessment of potential changes to New Zealand's climate under a mitigation scenario (RCP2.6), two stabilisation scenarios (RCP4.5 and 6.0), and one runaway emission scenario (RCP8.5). These pathways are defined by the level of radiative forcing predicted at 2100 (Table 3.1).

Table 3.1: Representative concentration pathways used by NIWA (2016)

RCP	Radiative forcing at 2100 relative to 1750 (W m^{-2})	CO_2 concentration reaching (ppm)
RCP2.6	2.6	421
RCP4.5	4.5	538
RCP6.0	6.0	670
RCP8.5	8.5	936

Note these data have been taken from page 21 of MfEa 2016.

A detailed description of the selection of pathways used, models, and downscaling methodology can be found in *"Climate change predictions for New Zealand – atmospheric projections based on simulations undertaken for the IPCC 5th Assessment (2016)"*. While projections are made for three time periods, (2040 –

2120) only projections centred around 2040 and 2090 have been used in this study.

Primary projections for New Zealand's climate from MfEa, (2016) are

Temperature	Temperature increases of 0.7^{0}C to 1^{0}C (centred 2040), 0.7^{0}C to 3^{0}C (centred 2090) and 0.7^{0}C to 3.0^{0}C (centred 2110) are expected. Warming will occur faster, and be greater at higher elevations. Seasonally, summer and autumn will experience greater increases in temperature than winter and spring. Daily maximum temperatures will increase faster than daily minimums. The frequency of frost is expected to decrease by between 30-50% (2040) and 30-90% by 2090.
Precipitation	A net increase in rainfall is expected over New Zealand, and the spatial variation of rainfall will also increase. Increases in rainfall are likely to occur in the south and west of the country while a decrease will occur in the north and east. An increase (10%) in the number of dry days (rainfall less than 1mm) will occur, most markedly in the north and east of the North Island.
Snow	The number of days that snow occurs over the county are projected to decrease by 30-days or more by 2090 (RCP 8.5)
Drought	Drought will increase both in its frequency and intensity. By 2090 the national drought deficit will increase by up to 50mm or more, predominantly in areas already prone to drought.

Storms	A likely poleward shift of mid latitude storms is expected, however these may reduce in frequency. Extreme winds are likely to increase by up to 10% in most parts of the country.

Note: these data have been adapted from Table 1, MfEa, 2016 p15

3.2.2 New Zealand's climate

The increase in New Zealand's mean annual air temperature has been approximately 1^{0}C over the past century (Mullan, Dean, & Stuart, 2013). This is slower than the global average (1.2^{0}C) IPCC (2013), and can be attributed to New Zealand geographical location, where the ocean (warming much slower than terrestrial systems) is acting as a buffer (MfEb, 2016).

3.2.3 Cyclic behaviour and trends

Some of the warming experienced in New Zealand can be partially attributed to cyclic behaviours in the New Zealand climate (Mullan *et. al.,* 2010, MfEa, 2016, NIWA, 2016). Cyclic trends have been proven to create significant fluctuations in New Zealand's climate and are therefore important to identify when conducting any long term climate analysis. These cyclic behaviours include the Interdecadal Pacific Oscillation, and El Niño–Southern Oscillation (ENSO).

The Interdecadal Pacific Oscillation (IPO) refers to decadal fluctuations in ocean and air temperatures between the central equatorial Pacific and the Northwest and Southwest Pacific. Positive (active) IPO phases lead to heavy rainfall and flooding in many parts of New Zealand. Positive phases in the IPO occurred between 1922-1945 and 1977-1999 (Figure 3.4). Currently the IPO is in a negative phase, and subsequently heavy rainfalls are not as high as those observed in long term record (McKerchar & Henderson, 2003).

Shifts in the phases of the IPO can therefore produce noticeable differences in rainfalls around the country. This must be considered when analysing long term rainfall records. Assuming that data are drawn from a static record has been proven to not be valid in New Zealand's climate (Mullan *et. al.,* 2010). For example, rainfalls in the east of the North Island were consistently ~8% less over the period 1978-1999 (a positive IPO phase) when compared with 1947-1977 (Edwards, *et. al.,* 2012).

IPO phases have amplified effects on the frequency and intensity of El Niño and La Niña phases. Positive phases increase the frequency and intensity of El Nino events – leading to higher intensity rainfall in the south and west coast, and drier conditions on the east coast, the opposite occurs during La Niña phases.

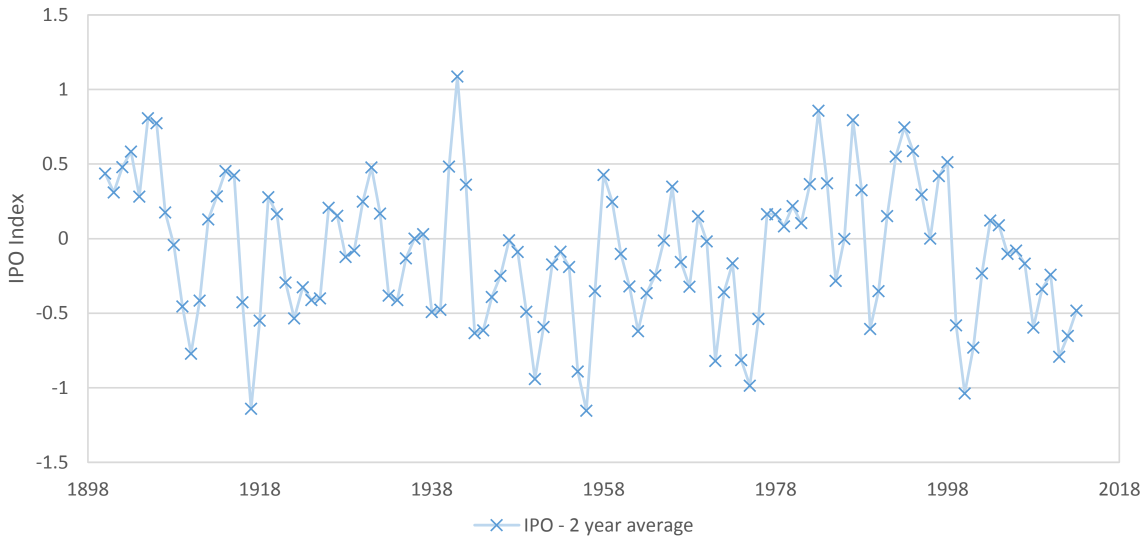


Figure 3.4: Variation in the IPO phase which has been related to changes in rainfall (Henley, et al., 2015)

3.2.4 El Niño–Southern Oscillation (ENSO)

The Southern Oscillation Index (SOI) is an index of fluctuations in air pressure difference between Tahiti and Darwin. It is used as a means of tracking El Nino or La Nina events in the Pacific Ocean. Negative values, below 7, are representative of sustained warming in the central Pacific Ocean and indicative of El Nino events. Values greater than 7 are indicative of La Nina events.

El and La Nina events oscillate between each other every 2-7 years and can lead to more than a degree of cooling or warming over large areas in the Tropical Pacific Ocean (BoM, 2014). Warming of the Pacific Ocean, caused by a reduction in up welling of cold Antarctic waters off the coast of Chilli. This then becomes a self-perpetuating cycle, warmer waters lead to a disruption of the Walker circulation, reducing rainfall in the western Pacific. A reduction in the strength of the westerly trade winds then occurs, which under normal conditions assists in the up welling of colder waters of the coast of Chile.

El Niño conditions have a significant influence on New Zealand's climate. During El Nino events, stronger westerly winds, and higher than average rainfall occurs in the south west, with drought occurring in the east. These conditions also bring more benign weather in the north and east of the North Island. Over autumn and winter period El Niño perpetuates the development of strong southerlies, up from the Antarctic, lowering temperatures in the North Island (Kidson and Renwick, 2002).

El Niño events account for less than 25% of the annual variance in rainfall and temperature in NZ (NIWA, 2016). While droughts may be more common during El Niño periods, they also occur in non El Niño years (i.e. the 1988-89 drought). It has been estimated that the conditions brought on by El Nino events are likely to become more extreme and last longer (Figure 3.5) (Wenju *et. al.,* 2014).

In contrast, La Niña brings colder temperatures in the east pacific, strengthen trade winds and in the eastern Pacific. La Niña tends to have a weaker effect on the climate of New Zealand; with a greater prevalence of moist, north easterly winds bringing higher than average rainfall throughout the year to the north-east of the North Island, and reduced rainfall to the south and south-west of the South Island (Kidson and Renwick, 2002).

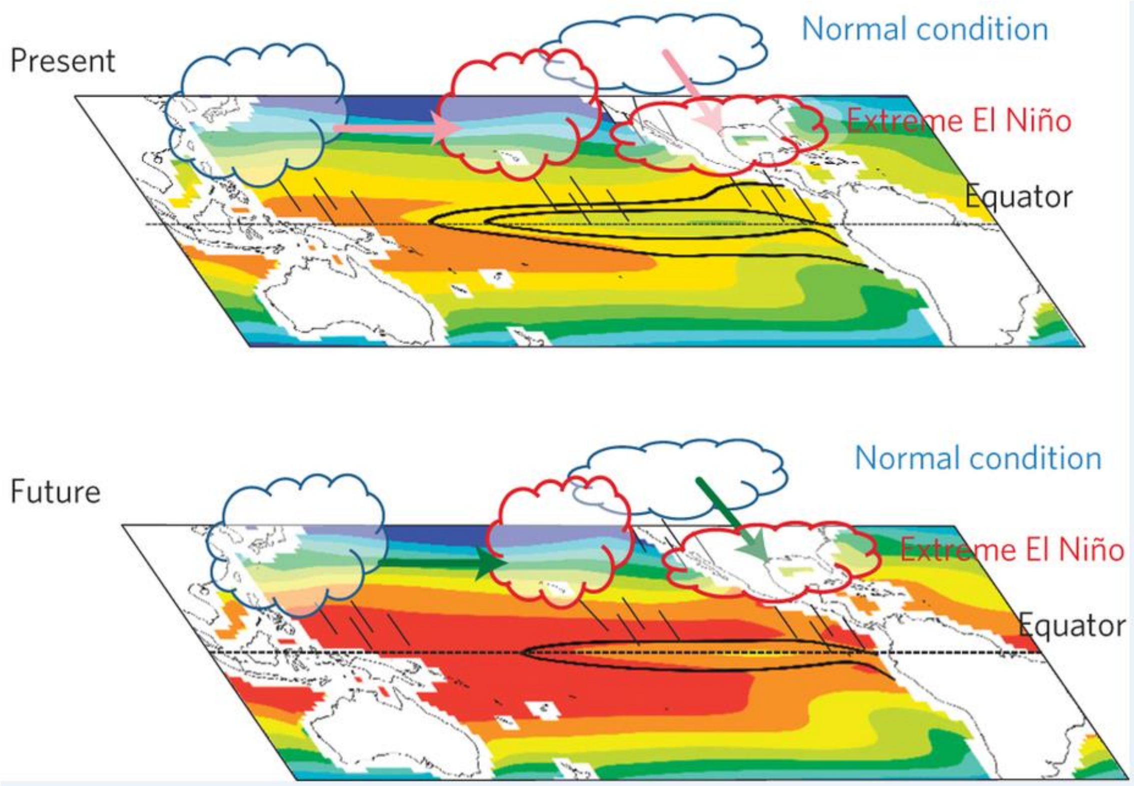


Figure 3.5: Changes in ocean temperature and rainfall patterns in the Pacific under current and projected future changes in climate, specifically, El Nino events (taken from (Wenju *et. al.,* 2014)

3.2.5 Southern Annular Mode (SAM)

The Antarctic Oscillation (AAO), commonly referred to as the Southern Annual Mode (SAM) also influences New Zealand's climate, however unlike the IPO it operates at an annual scale. The AAO is highly variable, shifting between positive and negative phases. Negative phases lead to the strengthening of westerly winds at lower latitudes, while positive phases intensify winds closer to the poles. While the AAO is highly variable, work by Thompson and Solomon (2002) has identified that the AAO is trending towards stronger positive phases, potentially caused by both warming of the atmosphere and as a result of Ozone depletion (Christensen *et. al.,* 2013). The AAO is accounted for in many of the models used to predict potential changes in climate (Gong & Wang, 1999).

4 Regional setting

Wetlands only exist where geology, topography and regional climate provide water and landscape settings conducive to the sustained presence of water. Wetlands are often considered to be areas that facilitate the recharge and discharge of groundwater (Senanayake, *et. al.*, 2016). The exchange of this water is dependent on meteorological, fluvial, anthropogenic and geological processes (Winter *et al.*, 1998). An understanding of these components in the Wairarapa Valley is therefore required to assess functional relationships between surface water bodies and groundwater. Extensive geological and hydrological work has already been conducted in the Wairarapa Valley. These include historic reports commissioned to explore the potential of the groundwater resource in the region (Annear *et al.*, 1989, and Butcher, 1996). Begg & Johnston (2000) and Litchfield (2003) cover catchment geology and stratigraphy, and more recently Gyopari & McAlister, (2010a, b and c) have explored groundwater resource investigations and catchment hydrogeology and modelling. A thesis by Guggenmos (2010) further explores interactions between surface and groundwater in this region while GWRC and GNS have conducted studies on groundwater chemistry (Gyopari and McAlister, 2010c). This section summarises specific information relevant to the climate and hydrological operation of Lake Wairarapa and the lake's margin wetlands.

4.1 The Wairarapa Valley

The Wairarapa region is located on the south eastern end of the North Island of New Zealand. Covering a land area of 3,555km^2 (Gyopari & McAlister, (2010a), it spans approximately 100km from Pukaha Mount Bruce in the North to Kirikiri Bay at the southern tip of the North Island. The valley is bound by the Ruamahanga and Tararua Ranges in the West and the Waewaera and Pukatoi Ranges in the east. These ranges shelter the valley from the predominant westerly winds, and funnel southerly air flows up the valley. They are the primary influences on regional climate, creating a steep rainfall gradient from west to east across the valley (Figure 4.1) (6000mm in the ranges and 800-1000mm on the plains (GWRC, 2014). This subsequently leads to flashy river systems. Lake Wairarapa is the dominant surface water feature in this landscape covering an area of 78km[2] at the southern end of the valley. The region experiences a dry and warm climate (Figure 4.1) and is primarily used for agriculture, with plantation forestry, beef and cattle farming in the north and Eastern hill country, and dairy farming and vineyards in the central to southern end of the catchment.

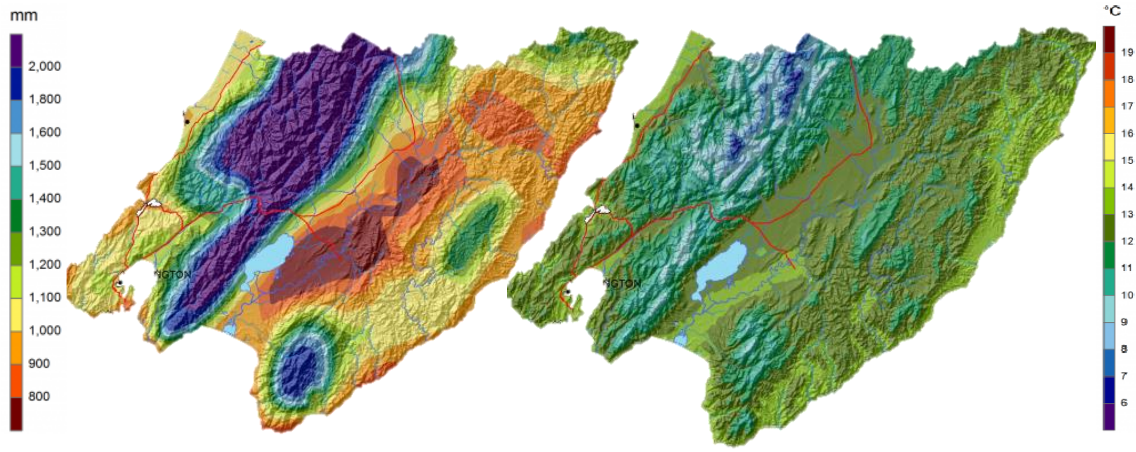


Figure 4.1: Mean annual rainfall (left) and temperature (right) over the Geater Wellington Region (NIWA, 2015)

4.2 Geology

The Wairarapa region is situated above the subduction interface of the Australian and Pacific plates, and is considered to be highly geologically active with "exceptionally high" rates of oblique convergence (42 mm/yr) (Beavan *et. al.*, 2002). Subsequent stresses from this tectonic activity (beginning in the Triassic-Jurassic era) has caused a series of lateral faults, the formation of the Rimutaka and Tararua Ranges (greywacke and argillite) in the west, and subsequent folding on the east by the Waewaera and Pukatoi Ranges (sandstone, mudstone, siltstone and limestone) (Figure 4.2).

The depression between these two features has undergone varying degrees of aggradation by cyclical erosion events, driven by climatic variability. Subsequently three distinct structural basins are present, the Puhitua Basin in the north, the Masterton Basin, and the Wairarapa Basin in the south. Lake Wairarapa and its associated wetlands are located in the Wairarapa Basin in the south. Focus will therefore be placed on the geological history, stratigraphy and hydrology and of this lower basin.

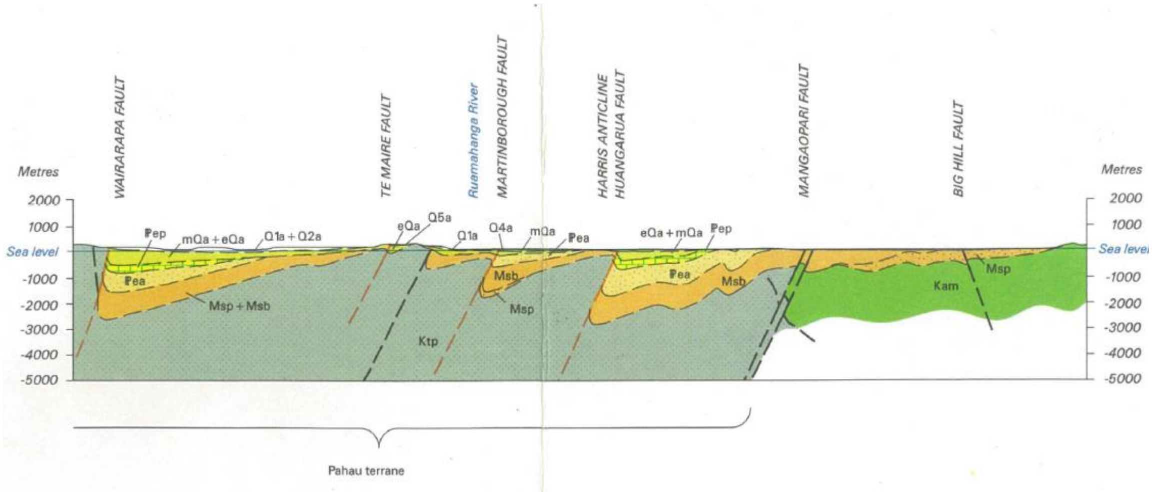


Figure 4.2: Geological cross section of the Wairarapa Valley, demonstrating the tectonic folding of the valley, soured from (Gyopari & McAlister, (2010a)

4.3 The Lower Valley

The lower valley (much like the Wairarapa Valley) has been influenced by faulting and folding from the Australian and Pacific Plates. Unlike the two northern basins this basin has been strongly influenced by successive changes in sea levels which have had significant effects on its structure. This has led to highly dynamic changes in processes related to drainage, erosion and deposition. The geology of the lower valley is presented in Figure 4.3 and in two cross section, one perpendicular (A-B) (Figure 4.4), and one parallel (C-D) (Figure 4.5), to the valley's structure.

4.3.1 Geological history

The lake's basin is an elongated depression created (and still subsiding) as a result of the folding of the Australian plate. Up-thrusting of impermeable greywacke ranges on the basins' lateral margins confine the system while up-thrusted blocks to the south isolate it from the sea (Figure 4.3). Successive glacial events have resulted in rapid erosion of the Tararua ranges and deposition of material into this depression. Intensified hydrological processes during interglacial periods increased the volume of material carried down the valley covering it with flood-driven sediments (Begg *et. al.,* 2000). As periodic warming continued, ocean levels rose which inundated the valley and deposited marine sediments. This process continued over glacial cycles while the valley subsided and ranges continued to be up-thrust, influenced the drainage and depositional process of alluvium sequences separating and confining deposits (Hicks and Shankar 2003; and Thompson, 2011).

The reworking of glacial deposits and subsequent overlaying of marine and flood driven sediments have developed a number of hydrostraphic units in this lower valley. Three laterally isolated, gravel-filled layers between 10-15m thick with medium-high hydraulic conductivity are found in the lower valley, (Q2, Q4, Q6) (Figure 4.5). These are confined by silt clay aquitards with very low hydraulic conductivity (Q1, Q3, Q5 and Q7). The Q2 layer (5-10m thick, 30-50m below the lake) is the widest spread of the aquifers and is a product of the outwash from the Ruamahanga and Tauherenikau rivers, and is confined by the Holocene aquitard. It is the most widely used for irrigation in the area and is recharged by the Ruamahanga River and groundwater seepage through the Tauherenikau fan (Guggenmos 2010).

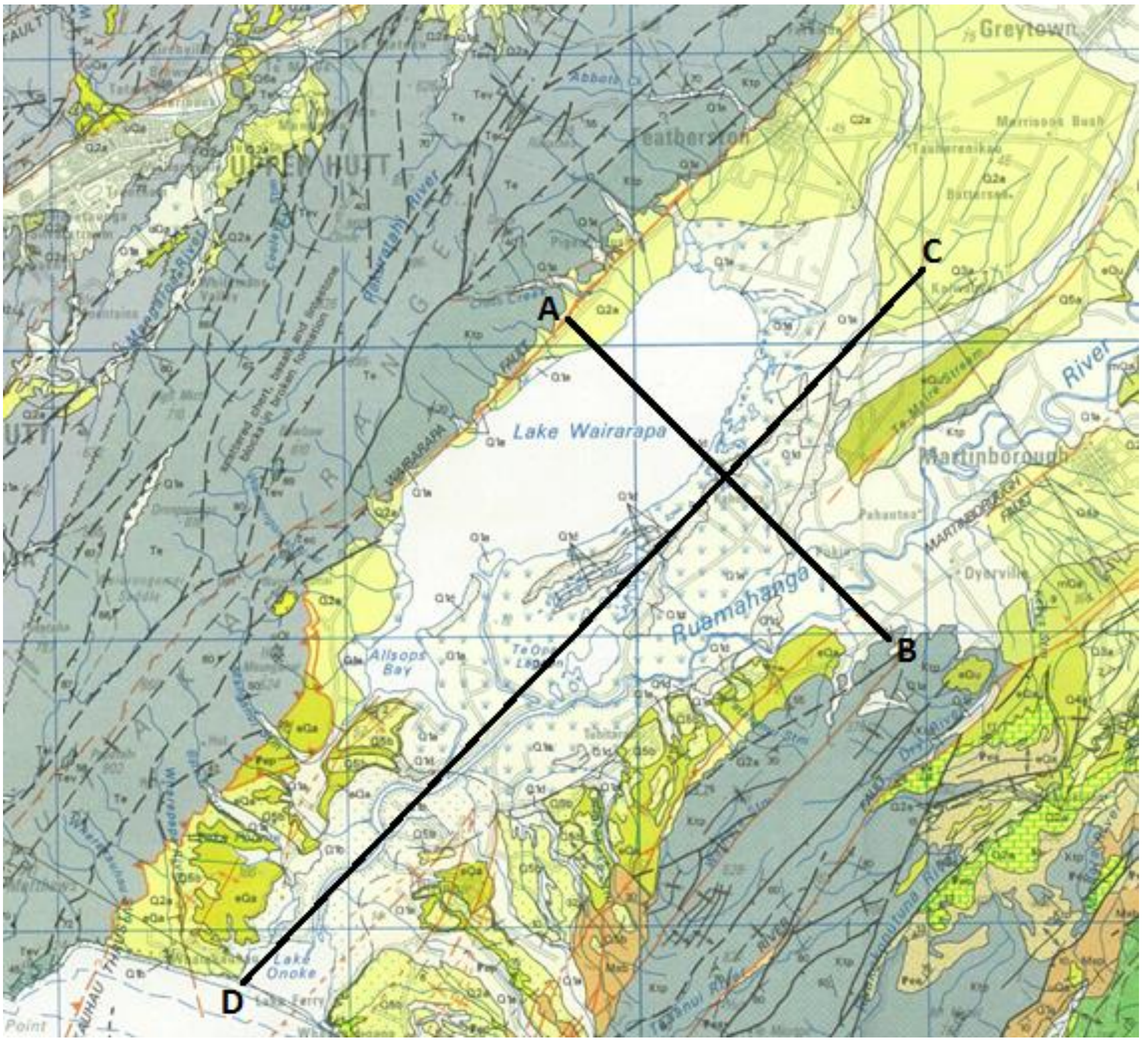


Figure 4.3: Geology of the Lower Wairarapa valley with cross sections through the valley identified (Gyopari & McAlister, (2010a)

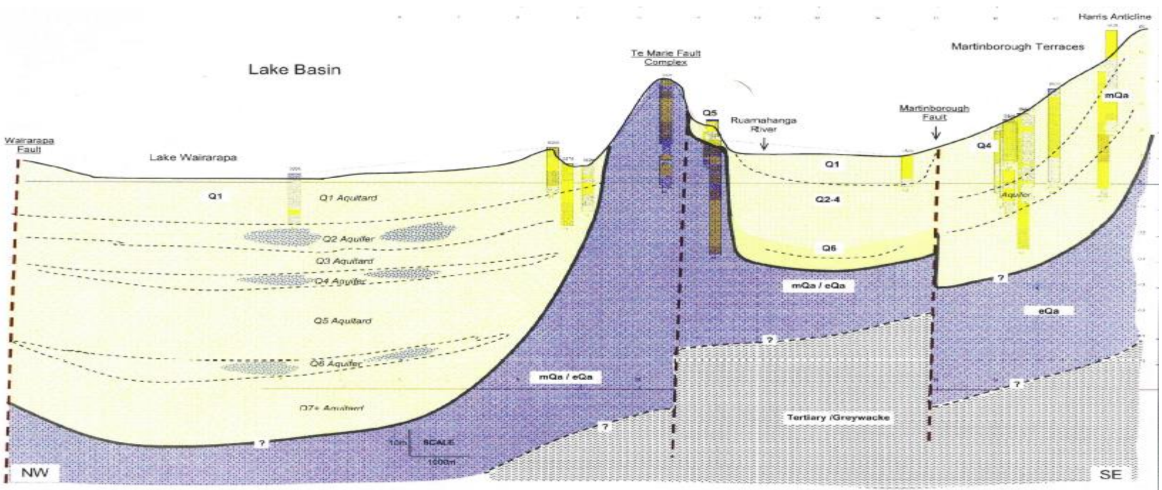


Figure 4.4: Cross Section A-B across the lower Wairarapa Valley showing aquifers and the aquitards beneath the lake (Gyopari & McAlister, (2010a)

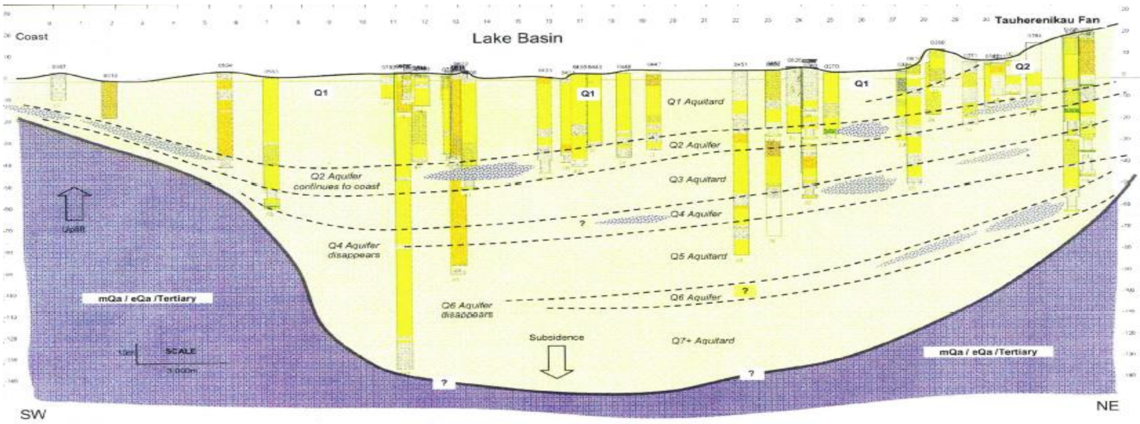


Figure 4.5: Cross Section C-D through the lake basin, showing bore logs and aquifers and aquitards (Gyopari & McAlister, (2010a)

As oceans stabilised to current levels ~7000 years ago, the sea extended up the lower valley. The uplifting of land around the lake forced the sea to retreat (as recently as 3,400 years ago) (Figure 4.6), slowly cutting off the inlets of Wairarapa and Onoke from the sea. With this retreat came the exposure of shorelines, and an increase in westerly winds which drove sand to form dune systems on eastern margins. These subsequently stabilised, trapping receding flood water and rainfall, forming wetland areas. The deposition of fluvial sediments would, under a natural regime, have continued, gradually filling in Lake Wairarapa (Trodahl, 2010).

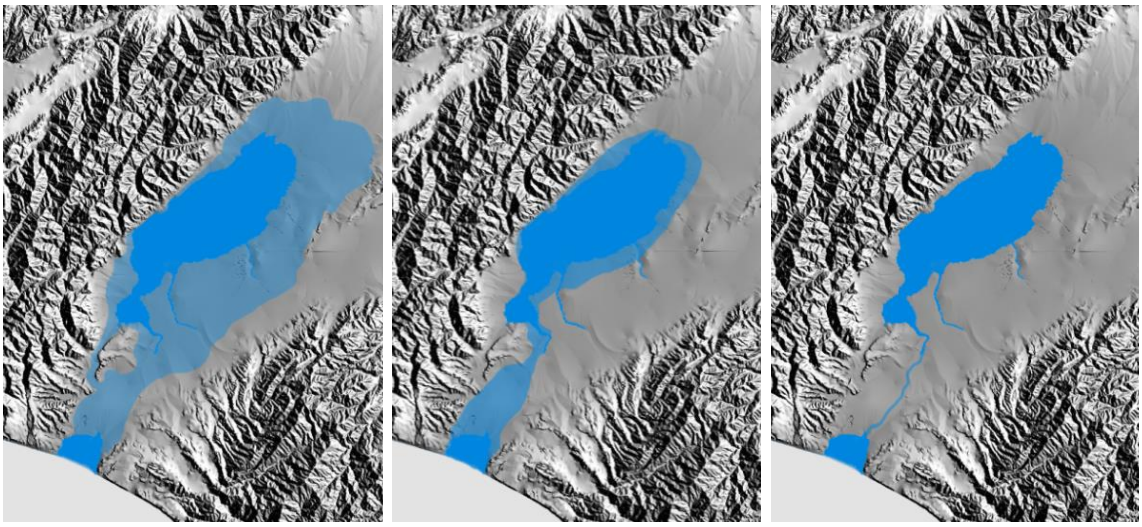


Figure 4.6: Successive changes in lake area as a result of tectonic uplift over the past 7000 years

4.3.2 Lake Wairarapa

Lake Wairarapa is the dominant surface water feature in the Wairarapa Valley. Located between the Aorangi and Rimutaka Ridges the lake sits on a structural depression, infilled with sands, silts and gravels eroded from the Rimutaka Ranges and upper valley geologies. The lake is the second largest in the North Island (78km^2), spanning 18km in length and 6km in width. It is a shallow (<2.5m) isothermal lake with a shallow bed gradient on its eastern margin (Trodahl, 2010). This gentle gradient provides a unique landscape for the development of many wetland types and features. In conjunction with fluctuating lake levels, lake beds along this margin are routinely exposed providing valuable feeding ground for many wading bird species. The low topographical relief beyond these lake margins creates ideal conditions for shrub-dominated wetlands and seasonal marshes GWRC, 2013).

Significant anthropogenic changes to regional hydrology as part of the Lower Wairarapa Development Scheme (LWVDS) have significantly altered this lake's hydrology (Figure 4.7). The lower Wairarapa Development Scheme (LWVDS) was one of the largest flood management projects to have been conducted in New Zealand. Beginning in 1963, the scheme sought to prevent flooding in the lower valley, and to convert more marginal land into productive farmland. Details of the scheme can be found in Table 4.1.

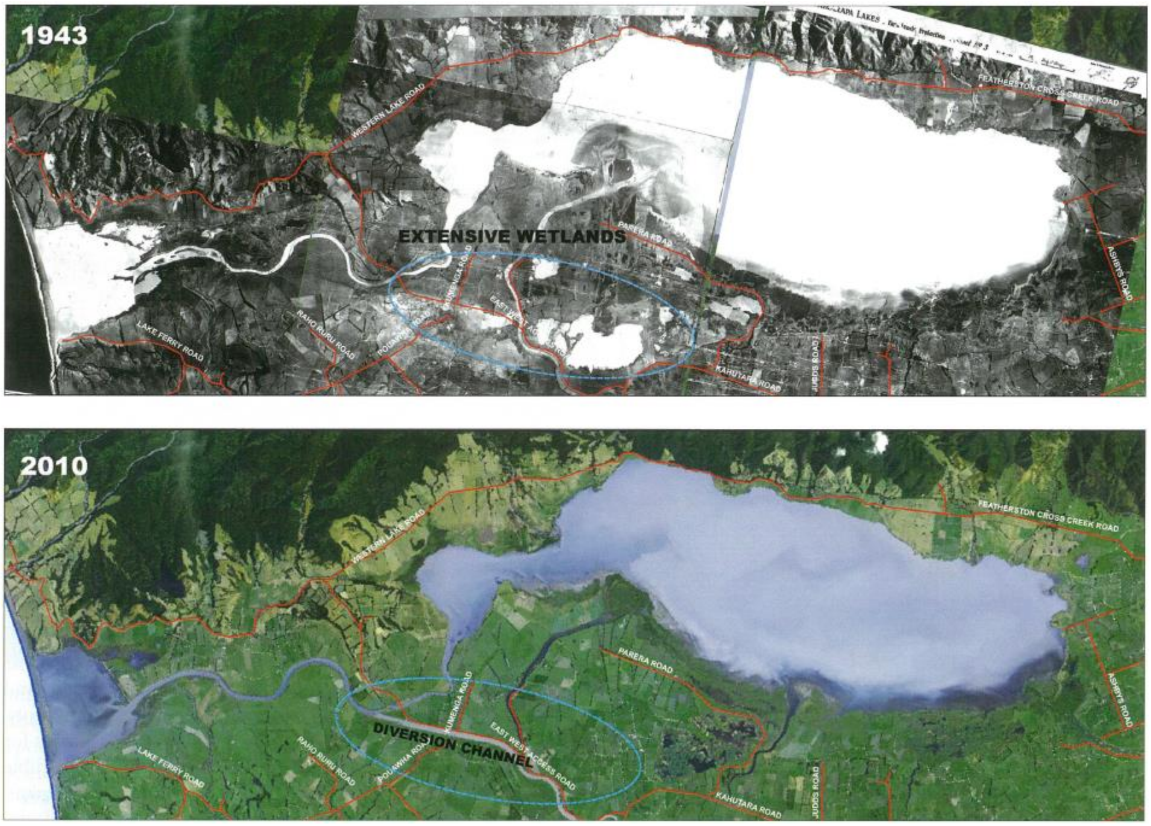


Figure 4.7 Effects on waterbodies and wetlands in the Lower Wairarapa Valley as a result of the Lower Wairarapa Valley Development Scheme (GWRC, 2013)

The primary change to the regions hydrology is a result of the 65km diversion of the Ruamahanga River from its natural course into Lake Wairarapa, across the Kumenga Peninsula and into the Lower Ruamahanga, south of the lake. This diversion has reduced the lakes catchment area from 3024km^2 to 572.5km^2 (Mahoney, 1960), reducing the annual volume of water entering the lake by 90% (GWRC, 2014) (Figure 4.8).

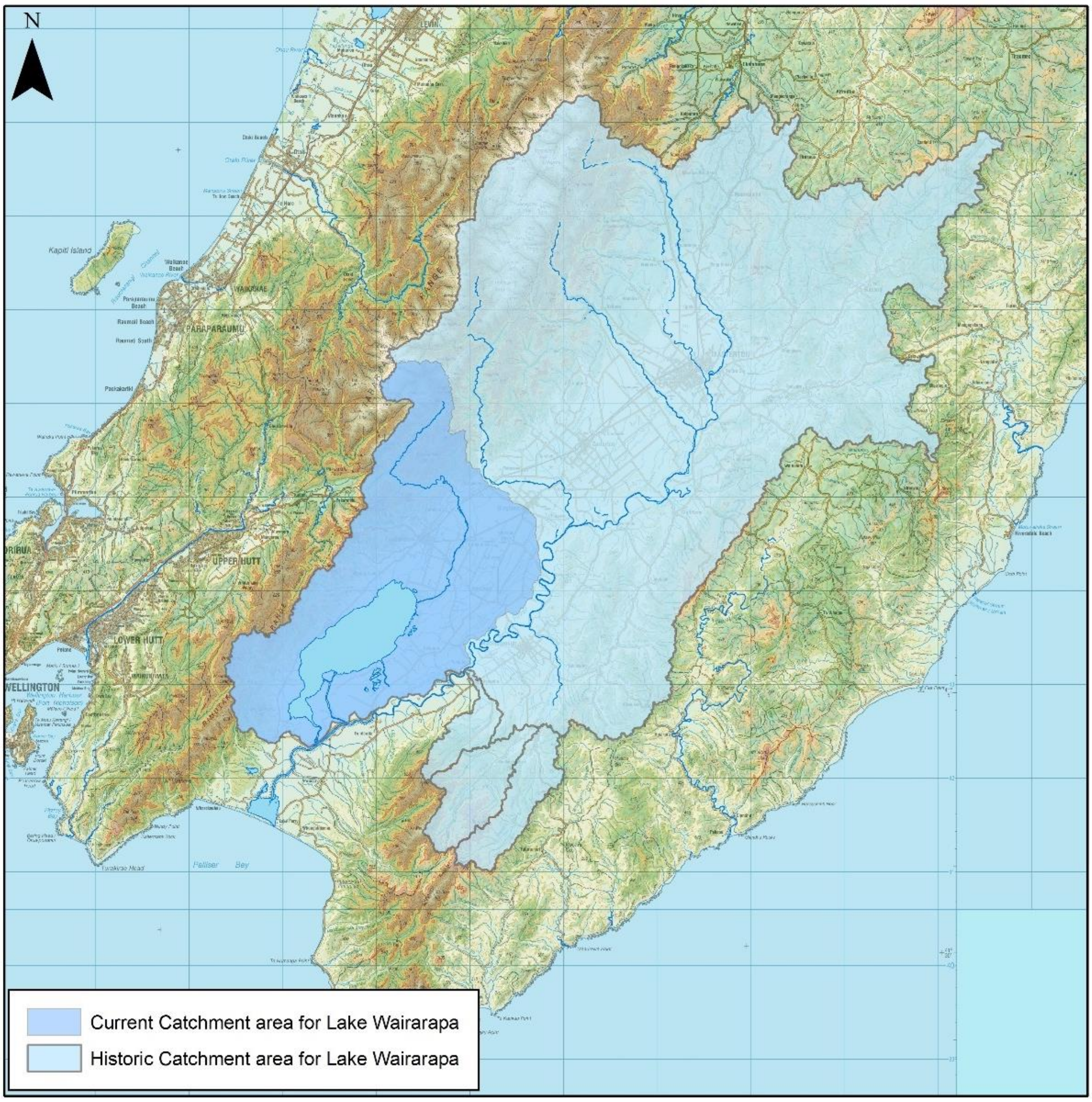


Figure 4.8 The n**atural** catchment **of Lake Wairarapa and the contemporary catchment areas following the Lower Wairarapa Valley Development Scheme**

Dominant surface water inflows are now the Tauherenikau River and Otukura Stream to the north and the Waiorongomai River at the south-western end of the lake. A number of small tributaries feed the lake from the western foothills of the Rimutaka Ranges. Discharges from the lower Wairarapa valley drainage scheme also occur along the lakes southern and eastern shores. Subsequently, the remainder of wetland habitats are void of any hydrological connection with the lake or any flooding seasonal flooding of the lake.

Shallow groundwater has been identified as a small component of the lakes water balance (estimated at 0.4 m^3/s) and hydro-chemical analysis of lake water has identified seepage from deeper confined aquifers (Nunny, *et. al.*, 2014). Outflows from the lake occur through six barrage gates at the southern end of the lake, evaporation, and a number of consented surface water takes for irrigation (Thompson 2011).

Lake levels are managed by GWRC under a consent (WAR 930149) to give effect to a Water Conservation Order placed on the lake in 1989. Lake levels are required to stay above certain thresholds at different times of the year to maximise flood storage in winter, maintain low lake levels for farming, and when possible fluctuate water levels to enhance ecological shoreline habitat. This is achieved through the use of six barrage gates located at the lakes' outflow. These gates are used to prevent backwater flows from the Ruamahanga River from entering the lake, and manage lake levels according to an agreed regime. Figures 4.9 and 4.10 and

Table 4.2 demonstrates the difficulty GWRC has had in achieving these seasonal levels throughout the year (

Table 4.2).

Table 4.1: Lower Wairarapa valley Development Scheme information (GWRC, 2014)

Scheme Information	Value
Present day value	NZ$ 86 million
Land protected`	31,500ha
Increase in productivity value	NZ$ 19.8m
Ruamahanga river diversion	65km
Total length of stop banks	190km
Drainage schemes	6
Culverts and floodgates	112

Table 4.2: Maximum seasonal water levels for Lake Wairarapa

Period	Maximum water level (m.a.m.s.l.)

01-Dec to 29-Feb	10.15
01-Mar to 31-May	10.0
01-Jun to 30-Sep	9.95
01-Oct to 30-Nov	10.0

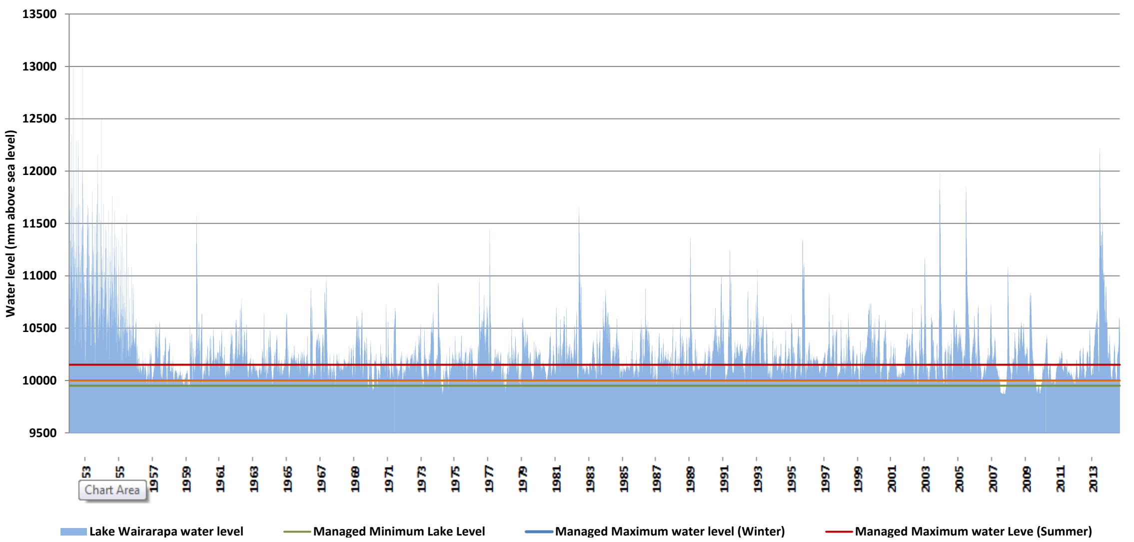


Figure 4.9: Lake Wairarapa water levels (mm above mean sea level) from Sep 1953 to May 2015 (Data sourced from GWRC)

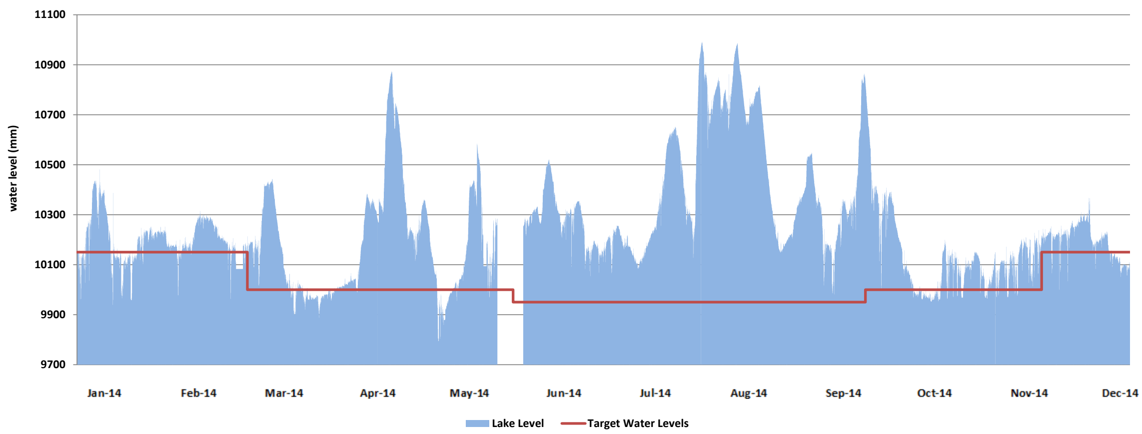


Figure 4.10: Lake Wairarapa Water Levels (2014) and target lake management levels. (Data sourced from GWRC)

4.4 Site locations

The gentle gradient of the eastern lake bed provides a unique landscape setting for the development of many wetland types and features. In conjunction with fluctuating lake levels, lake beds along this margin are routinely exposed providing valuable feeding ground for many wading bird species (Faulkner, 2016). The low topographical relief beyond these lake margins create ideal conditions for ephemeral shrub-dominated wetlands and seasonal marsh habitat.

Wetlands along the eastern margin were formed as receding flood waters, and rainfall was trapped or ponded behind low lying dune formations, created by wind driven (alluvial) sediments, from the exposed bed of Lake Wairarapa.

Despite the significant changes brought about by the LWVDS the gentle bathymetry of Lake Wairarapa coupled with remnant wetland systems provide nationally and internationally significant habitat for wader birds and migratory bird species, and is the largest wetlands complex in the lower North Island (10,448 ha) (Forsyth & Dixon 2004). Together with the beds of Lakes Wairarapa and Onoke, these wetlands are known as Wairarapa Moana and are regionally recognised as having a high degree of natural character and significant ecological, cultural/spiritual, and recreational value (WRC, 2014).

4.4.1 Wairarapa Moana wetland complex.

The Wairarapa Moana wetland complex comprises 33% of the swamp and 19% of the marsh wetlands that remain in the Freshwater Systems of New Zealand (FENZ) Manawatu-Wairarapa bioregion, and contains 2% of the national swamp wetlands (Cromarty and Scott; 1995). Six of the eight wetlands surrounding the lake are listed in the eleven highest-priority wetlands for protection in FENZ.

Within Wairarapa Moana, a cluster of wetlands located on the eastern shoreline have been selected for this study (Figure 4.11, Table 4.3). These wetlands have been selected for the following reasons:

- High ecological value
- The variation in their hydrology
- Spatial location (migratory pathways)
- Availability of climate data and previous studies.

Table 4.3: Area and dominant hydrological processes operating in each of the three wetlands studied

Wetland	Area (ha)	Dominant hydrology processes
Mathews Lagoon	270	Rainfall, inflow from Te Hopai Basin - evapotranspiration, outflow
Boggy Pond	159	Rainfall - Evapotranspiration
Wairio	134	Rainfall – Evapotranspiration – Lake Wairarapa
Total	*563*	
Te Hopai Basin area	1778	Rainfall – Evapotranspiration – Lake Wairarapa, Te Hopai Pump Drain

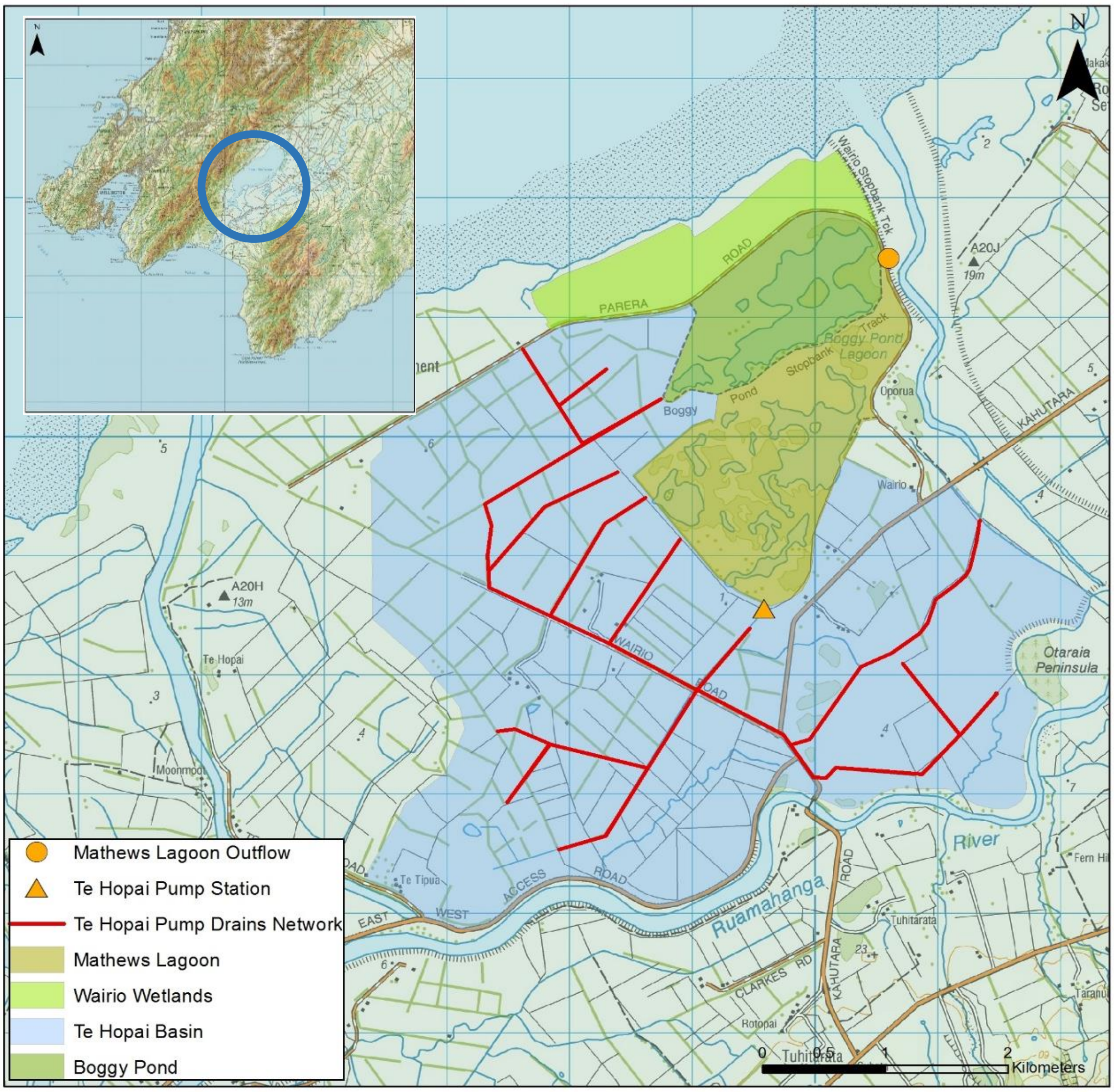


Figure 4.11 Wetlands of Wairarapa Moana selected for this study, Mathews Lagoon, Boggy Pond, and Wairio Wetlands, the Te Hopai basin, and its associated drainage scheme

4.4.2 Mathews Lagoon and Boggy Pond

Boggy Pond and Mathews Lagoon are remnant wetlands of what was once an expansive swamp marsh system on the lakes eastern shoreline. During the initial phases of the LWVDS, the construction of Perera Road separated these wetlands from any surface water interaction between with the lake and the Ruamahanga River. Historically, surface water flooding from Lake Wairarapa (through the blockage of Lake Onoke) and the Ruamahanga River would have seasonally flooded this low lying area.

These wetlands were protected in 1968 and managed by the Wellington Acclimatisation Society. In response to increased concerns about the loss of wetlands in the region, and the high level of biodiversity observed by the wildlife service, stop-banking work was conducted and completed in 1970 to prevent the system from drying out as a result of pumping of the Te Hopai depression. Part of the protection works involved the separation of the two wetlands by a common stop bank.

This separated these wetlands into two distinct hydrological units. Boggy Pond became almost completely isolated from any surface water interactions and thus reliant on precipitation and potentially shallow groundwater. Considerable drawdown occurred in this wetland through the 70s, and also during a particularly dry summer in 1982-83 (Ogle, 1987). While this fluctuation in level did create a myriad of habitats, used by a range of bird species not found in Mathews Lagoon, it was decided that a channel should be cut through the stop bank to allow water from Mathews Lagoon to flow into Boggy Pond.

Concerns over excessive ponding in Boggy Pond as a result of stop banking work led to an agreement between the Wildlife Service, the Wairarapa Catchment Board, and the Department of Lands and Survey in 1978 to manage water levels in the wetland to create a balance of dryland, shallow and deep water was to occur to "*maintain, and where possible improve, the general wildlife habitats* *provided"* (Buchanan, 1979) and address concerns about the flooding of nests in spring (Moore *et. al.,* 1984). This was to be achieved by allowing a drawdown of water level during summer months while inundating system in winter. A survey conducted in 1978 to identify a suitable operating range recommended the following operational water levels (Table 4.4).

Table 4.4: Operating levels favoured by the Wildlife Service and Wellington Acclimatisation Society for Mathews Lagoon and Boggy Pond (sourced from Ogle, 1989)

Parameter	Mathews Lagoon (m)	Boggy Pond (m)
Maximum controlled drawdown	103	103.5
Mean operating range	102-102.6	102-102.6
Minimum controlled drawdown	98.79	98.79

Drainage of the Te Hopai Basin in the early 1980's was seen as an opportunity to provide a source of water to these wetlands via a pump station and channel into Mathews Lagoon. This however presented new challenges, as the nutrient-rich runoff from these farms, caught in the drainage channels and pumped into Mathews Lagoon, became a concern. The proposed solution was to open a channel in the stop bank separating the wetlands, allowing the waters of Boggy Pond to dilute the concentration of nutrients (Ogle, 1987).

This cut in the stopbank altered the unique water regime at Boggy Pond, undermining the overall biodiversity of these wetlands. This became immediately apparent to the Acclimatisation Society in 1984 who agreed to repair the stop bank and install an adjustable control gate - this work however never occurred (Ogle, 1987).

Concerns mounted in 1989 over the absence of water fowl and losses in nationally threatened plant species observed in these wetlands. A drier than average summer and further drainage of land to the south of the wetlands and reduced water levels throughout both wetlands and alternative sources of water were looked in to. It was again decided that by repairing the hole in the stopbank, sufficient water would be present to keep Mathews Lagoon full while allowing seasonal fluctuations in water level in Boggy Pond (Ogle, 1989). Since this work, no further changes to the hydrology of these wetlands has occurred.

4.4.3 Wairio Block

The Wairio Block refers to a network of man-made wetlands, on 132ha of land located between Boggy Pond and Lake Wairarapa. Historically this area was part of an extensive Kahikatea swamp forest, which was burnt and cleared by pre-European Maori to provide access to the lake. Later farming and flood protection work by European settlers further altered this area of land into marginal land for beef farming. In 1987 DOC took over the land with the objective of restoring it for conservation. In 2005 DOC signed a management agreement with Ducks Unlimited (DU) to commence restoration work back to a pre-development state. A staged approach to restoration was adopted where different sections would be developed over time. Two low earth dams were constructed in the northern sections followed by excavation to lower the area. Further earthworks have occurred over the course of this study, considerably limiting the validity of some of the results.

The hydrology of this area has been heavily altered by the LWVDS, specifically drainage (Airey *et. al*., 2000; and Armstrong 2004). Due to its proximity to the lake it is likely that these wetlands may share a relationship with Lake Wairarapa. Management notes by DU have highlighted that water supply will come from the lake in times of flooding, rainfall and associated overland flow. Currently work is being conducted by GWRC to identify if the possibility exists to divert water from Mathews Lagoon into this complex. To achieve this it has been calculated that a head will need to be generated of between 0.3 to 0.5m at the current outflow point of Mathews Lagoon. This would require the damming of the outflow culvert. A trial was conducted 29 July 2014 and found this feasible, however the trial dam broke, restricting outflow through the culverts (Ogle, 1987).

4.4.4 Current Management

Boggy Pond and Mathews Lagoon are now classified as Government-purpose reserves under section 22 of the Reserves Act and are now managed by DOC with the Fish and Game Council regulating waterfowl hunting and the operation of the water level regime.

Wairio Block wetlands are currently co-managed by DOC and DU. Together with the local community, the Wairio Wetland restoration committee comprises of representation from DOC, DU. GWRC, Forest & Bird, Fish & Game, local Iwi (Ngāti Kahungunu) and neighbouring farmers, the Taratahi Agricultural Training Centre, Rotary, and Pirinoa, Kahutara and Martinborough Primary Schools (Johnson, 2012).

5 Methodology

5.1 Surface water interactions

5.1.1 Wetland water levels

Surface water levels for Boggy Pond and Mathews Lagoon were collected by Shi (2014), but not in Wairio Stage 1. A water level recorder was therefore installed in the south eastern corner of this wetland, and water level monitoring in Mathews Lagoon and Boggy Pond continued using equipment and locations set up by Shi (2014). The periods of data collected can be found in Table 5.1. Upon retrieval of data, the unvented pressure sensors were corrected for atmospheric pressure and adjusted to the GWRC datum. Atmospheric pressure collected at GWRC meteorological site on the eastern lakeshore was used since data collected from the barometric pressure were found to be erroneous. All data were converted to a common pressure unit (mmH_2O) (Table 5.2) before being compensated for barometric pressure (also adjusted to mmH_2O) and adjusted to the GWRC datum. Water level data can be found in Appendix A.

Table 5.1: Periods of record for surface water levels

Sensor	Start	Finish
Boggy Pond	3/07/2013	25/06/2014
Mathews Lagoon	24/06/2013	22/04/2014
Wairio Wetlands	6/12/2013	4/09/2014*

Table 5.2: Conversion factors used for each sensor

Sensor	Recording units	Conversion used (to mmh^20)	Stage adjustments (mm)
GWRC Barometric Pressure	hPa	10.19716	N/A
Boggy Pond	kPA	101.9716	10023
Mathews Lagoon	kPa	101.9716	10275
Wairio Wetlands	psi	703.0696	10102

5.1.2 Lake Wairarapa

Lake level data were obtained from Burlings, a lake level monitoring site, operated by GWRC on the western shoreline of Lake Wairarapa. Lake levels have been collected at this site since December 1974. Historically a lake level monitoring station existed on the eastern shoreline, 250m south of the Oporua Spillway, between February 1988 and November 1994. Inspection of this data suggested that significant 'set up' of lake level was experienced on the eastern shoreline during periods of high wind speed (Figure 5.2). No formal study has been conducted to quantify this set up, or any baroclinic seiche effects, caused as a result of shear stresses from wind on the lake's surface.

Due to the shallow nature of the lakes eastern shoreline, and the periodic flooding of shoreline marshes and potentially the Wairio wetlands as a result of wind set up, an assessment of the eastern shore's lake level was required. A barometric pressure transducer was installed at the outflow of the Oporua spillway in December 2013.

Data collected (5min) demonstrated high frequency oscillations caused by small waves on the lake surface (Figure 5.3). These oscillations were not present in either the lake record at Burlings or the historic eastern shoreline record (water level equipment was housed in a stilling well, effectively smoothing the 'noise' in the water level record). A moving average was therefore applied to the data at varying frequencies (10, 20, 30, and 60min) to remove some of these oscillations, (Figure 5.1). A 30 min moving average was deemed best suited at removing this noise, while retaining the natural fluctuations in lake level.

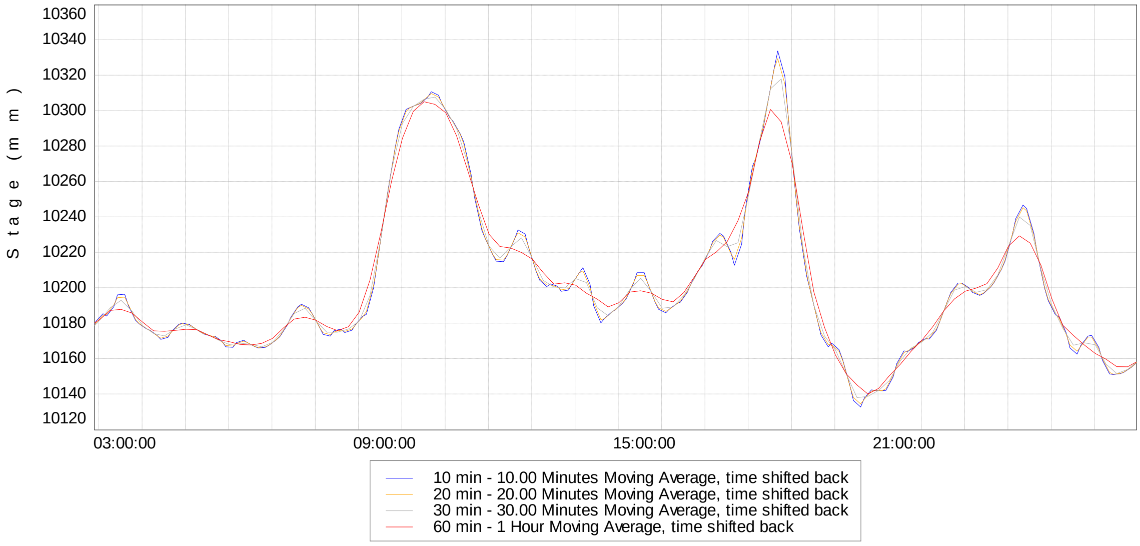


Figure 5.1: Smoothing effect of the moving averages applied to the water level recorded on the eastern shoreline

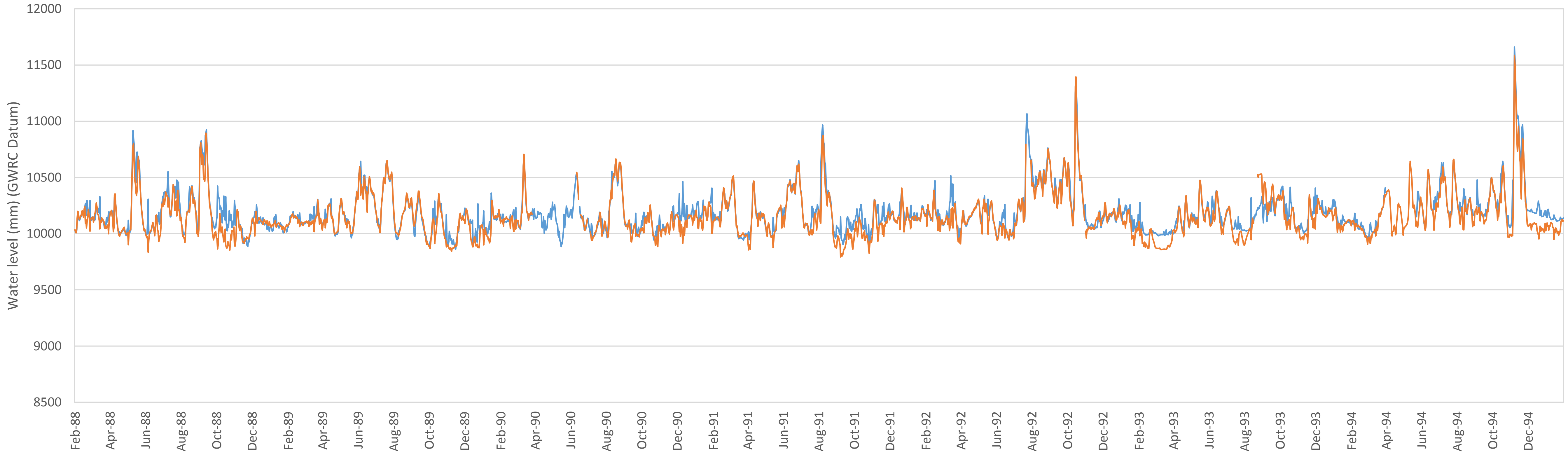


Figure 5.2: Historic lake level at eastern lakeshore and Burlings (shown in Fig. 5.13)

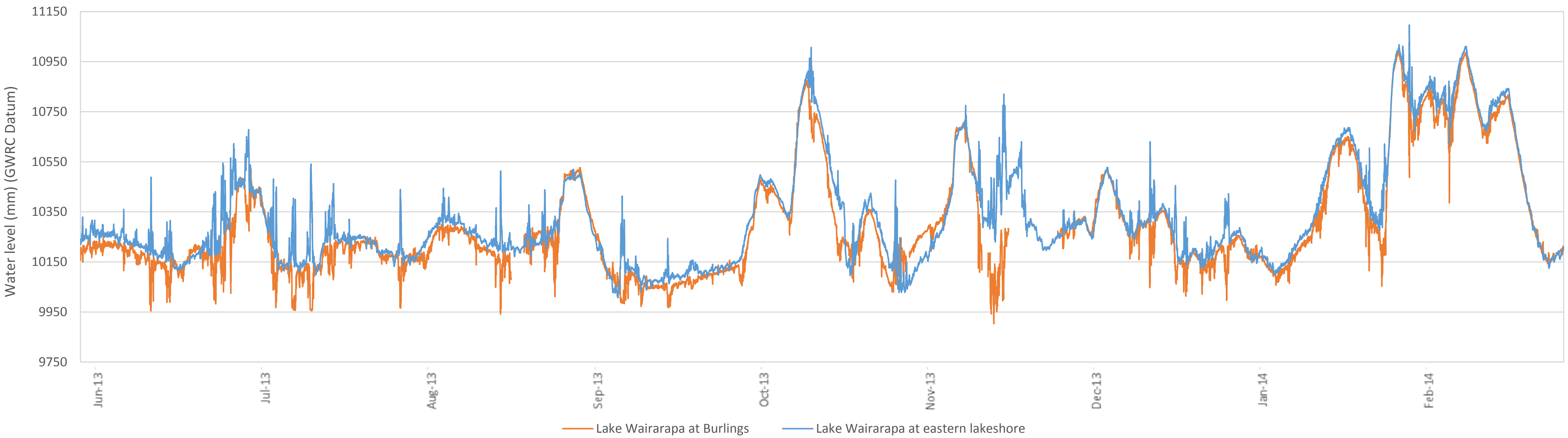


Figure 5.3: Lake level data collected during the study period from both lake shores

5.2 Rainfall distributions over the wetland system

Rainfall does not fall uniformly over a land surface, but demonstrates extreme spatial and temporal variability making it one of the more challenging components of meteorology to study and quantify (Millan *et. al.,* 2005). During an initial site visit, high wind speeds were creating shear stress on the surface of Lake Wairarapa which created a wind induced "spray". While this was not rainfall, the volume of water being deposited over the eastern lake margin was significant. This may lead to substantial differences in the volume of rainfall falling on each wetland during high wind speed periods. Since westerly winds are predicted to increase with climate change, this may exacerbate this distribution.

While GWRC operate a rainfall site on the eastern shore of Lake Wairarapa its design is not conducive to capturing wind driven rain, nor does it catch rainfall over each wetland. A network of specifically designed rain gauges was installed throughout the wetland system, to quantify the spatial distribution of rainfall.

5.2.1 Rain gauge design

Rain gauges are the primary instrument used to collect point estimates of precipitation. These comprise of a circular opening situated level that catches rainfall and either stores it to be measured manually (storage gauge) or records its volume or weight. The most common type of rain gauge used for remote sensing is the tipping bucket rain gauge (TBR). Unlike a storage gauge, a TBR provides high resolution data over an event or period as opposed to the total volume over the rainfall period. This is achieved through the use of a tipping bucket where a collection funnel tips from side to side as it fills with a pre-determined volume of water (e.g. 0.2mm). As the bucket tips a magnet is passed over a plate creating a pulse that is recorded and logged.

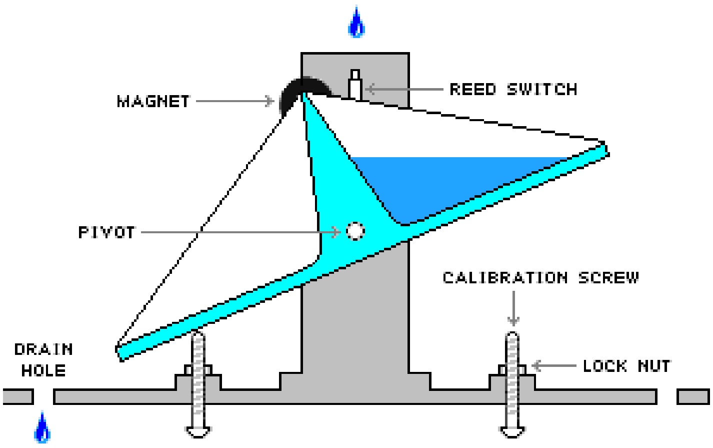


Figure 5.4: An example of the operation of a tipping bucket rain gauge

However, as with all remote sensing equipment there can be issues associated with the use of TBR's. TBR's are known to under record rainfall during high intensity rainfall events (Linsley, 1973 and Folland, 1988). This can be a result of rainfall losses in the time it takes the bucket to tip, 'bouncing' of the bucket itself, and in some cases static charging of the gauge during storm events. A study by (Villarini *et. al.,* 2008) demonstrated rainfall rate-error with the use of TBR's could be as large as 35% under high intensity rainfall events and 8% for less extreme events. While credited as being accurate over low-mid intensity events, losses are also observed when a partially filled bucket may not hold enough rainfall to tip, leaving it to either evaporate or count towards the next rainfall event. Tipping bucket rain gauges are therefore often accompanied by a catch gauge to act as a check on the total volume caught over the periods between site inspections and recent design developments have seen the addition of a weighing pan under the gauge to gain a more accurate total of rainfall volume (Hewston and Sweet 1989 and Rodda & Dixon, 2012).

The design of the enclosure of a rain gauge can to some degree mitigate some of the issues associated with TBR's, but variations in design can alter sources of under catch (Table 5.3). The greatest causes of inaccurate rainfall collection are associated with the rain gauge location, aspect and exposure to the wind (Smoot 1971; Bruce & Clark 1966; and Rodda & Dixon, 2012).

Table 5.3: Sources of errors recorded in tipping bucket rain gauges (Rodda & Dixon, 2012)

Source	Error (%)
Evaporation	-1.0
Adhesion	-0.5
Colour	-0.5
Inclination	-0.5
Splash	1.0

Often rain gauges are installed above the ground surface to lower maintenance costs and prevent unwanted objects or surface water from entering the gauge itself. Unfortunately this leaves the gauge exposed to wind, and susceptible to errors in rainfall catch during high wind conditions. Work by Duchon and Biddle (2010) on the effect of wind speed on under catch found that significant variation occurs when wind speeds exceed 5–6 m/s (at a height of 2 m). Wind speeds greater than 5-6m/s occurred 41.9% of the time over the study period and 58% of the time while rainfall was observed.

The effect of wind on collected rainfall increases with the height the gauge sits above the ground. NEMS standards designate heights for different gauge types - the one used at the GWRC meteorological site is an OTA tipping bucket gauge which is to be installed at 473 mm. There are three main methods used to minimise errors associated with wind: the design on the gauge itself, constructing a wind shield around the gauge (Figure 5.5), or burying the gauge in the ground. Of the three methods, design increments have some measurable effects on wind catch (Hughes *et. al.*, 1993), while properly shielded gauges can demonstrate considerable improvement in catch volumes (Figure 5.5).

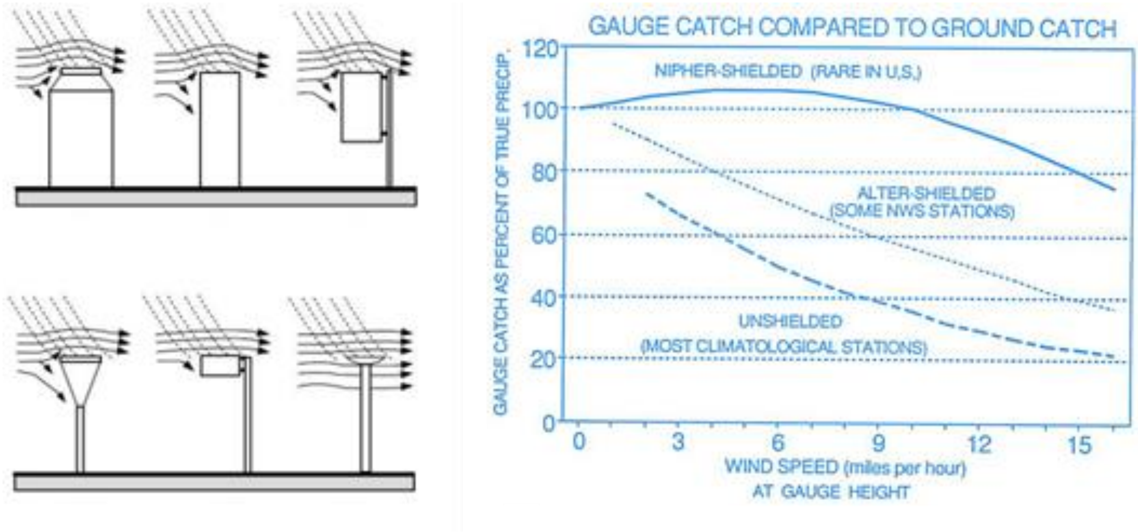


Figure 5.5: Left, Shapes of precipitation gauge body. Top left, indicates the shape having the worst aerodynamic properties with the bottom right having the best. Arrows show the streamlines and the dashed lines the trajectories of precipitation particles. Right: differences in gauge catches compared to ground catch for different wind speeds (Goodison *et. al.,* 1998)

The most widely recommended method of collecting rainfall in windy areas is to either mount the rain gauge in a pit or construct an earth (turf) bank to smooth wind flow (NEMS, 2013). Studies comparing pit gauges to counterpart 'on-ground' rain gauges have demonstrated that during calm events pit gauges catch between 3% to 6% more rainfall (Rodda & Dixon, 2012), and over windy periods pit gauges suffer very low to negligible wind-induced errors (WMO, 2008).

Placing a rain gauge in a pit is often cost-prohibitive as pits either need to be pumped out to prevent flooding, designed to drain water, or designed so that instrumentation is water tight. Pit gauges are often used in experiments to derive relationships between rainfall and wind speeds and provide correction coefficients that can later be applied to rainfall totals. Since this study was particularly interested in the distribution of wind-driven rainfall, as well as its spatial distribution pit gauges were selected as the desired rain gauge type. A comparison in catch would be conducted with GWRC OTA tipping bucket gauge for calibration.

5.2.2 Design

The design of the pit gauges took into account the issues discussed in the previous section. Each gauge was designed with the same diameter opening as the GWRC OTA tipping bucket gauge (200mm) and consisted of a funnel sealed to a garden waste bin. The rim of the lid was lined with a rubber seal that would allow the lid to be sealed shut. High groundwater levels were an issue during wetter periods therefore bricks were placed in the base of the bins to prevent displacement from water. A collection bottle was then used to store rainfall. Mesh screens were inserted in the opening of the containers to prevent clogging of the nozzles by debris. Lids were painted white to minimise thermal radiation on the chamber.

In accordance with NEMS (2013, p13) the shape of the gauge's orifice was sharply inclined, had vertical sides, and accommodated a funnel which sloped steeply down into the receptor (angles are specified in WMO, 2008).

Figure 5.6: Constructed pit gauges for use in the measurement of wind driven rain on the eastern shore of Lake Wairarapa

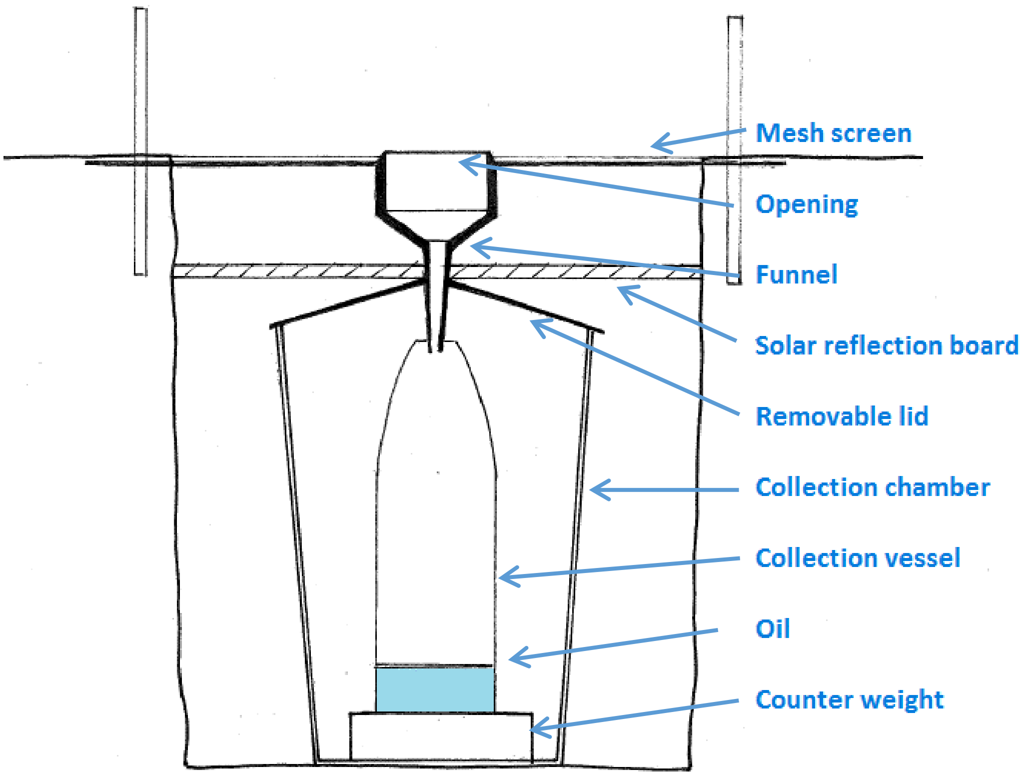


Figure 5.7: Cross sectional design of pit rain gauges used in this study

5.2.3 Testing

Rain gauges were tested before the initiation of field experiments to identify whether the design of the gauge would misrepresent rainfall either through the evaporation of captured rainfall or the addition to totals through the accumulation of condensation. Two gauges were filled with 50mm of water, placed in the collection chamber and positioned in the ground, and two gauges were left empty. All gauges were left in the sun for three days and volumes recorded (Table 5.4). Results indicated that refinement of the collection vessel would be needed. A board was placed over the top of the lids to reflect solar radiation, with a ventilation hole in the lid itself. A few mm of oil was then added to the water in the containers to prevent evaporation. A further test was conducted which identified that over the course of another four days issues had been mitigated (

Table 5.5).

Table 5.4: Gauge testing results following the initial trial

	Gauge 1	Gauge2	Gauge 3	Gauge 4	Observations
Initial	50mm	50mm	0	0	Visible condensation
7 hours	46mm	57mm	2mm	1mm	Visible condensation

Table 5.5: Gauge testing results following gauge refinement

	Gauge 1	Gauge2	Gauge 3	Gauge 4	Observations
Initial	50mm	50mm	0	0	No visible condensation
7 hours	50mm	50mm	0	0	No visible condensation
Overnight	50mm	50mm	0	0	No visible condensation

As a sensitivity test, after the study period ended, the rain gauges were returned to Wellington and randomly positioned within a 5m by 10m area in Karori. Over 4 rainfall events, totals were collected to see if variation between the gauges occurred. After each event gauges were randomly repositioned. Results, detailed in Table 5.6, identify a total 1.5mm difference between gauges over all four events. These differences were not associated with a specific gauge. This is within a ±10% margin of error used to determine if gauge construction was responsible for different catch volumes.

Table 5.6: Rainfall test results

Event	Rainfall (mm)					
	Lake	Control	Wairio	Boggy	Mathews	Variation
06/03/2015	15.0	15.0	14.5	15.5	15.0	1mm
07/03/2015	16.5	16.0	17.5	16.0	15.5	2mm
17/03/2015	12.0	12.5	13.5	12.0	13.0	1.5mm
22/03/2015	5.00	4.50	4.00	4.50	4.50	1mm
Sum	**48.5**	**48.0**	**49.5**	**48.0**	**48.0**	**1.5mm**

5.2.4 Site location

Pit gauges were deployed in in a spatially representative area to reflect each wetland being studied (Wairio Wetlands, Boggy Pond and Mathews Lagoon) and prominent wind direction (determined by a wind plot of wind direction and speed

(Figure 5.8)). Site selection within each representative area, and installation were conducted in accordance with NEMS (2013) guidelines and British Standard (BS EN 13798) specifications for reference rain gauge pits, specifically:

- Objects or shelter within 50m that may cause underexposure were avoided
- Grass was trimmed back to ground level in a $9m^2$ area around the gauge
- Distance between the nearest trees and the gauge pit were greater than twice the height of the tree (This was impractical at the lake site due to the die-off of trees, therefore the site selected was set on the windward side of potential obstructions)
- The ground surface surrounding the rain gauge was maintained as short grass
- A few mm of oil were added to prevent evaporation.

Primary consideration was also given to the exposure of the rain gauge to strong winds, effort was taken to maximise the exposure of the rain gauge to unimpeded wind flows by finding locations where there was a long line of sight in the direction of prevailing wind and the lake. A wire mesh was then placed over the hole to minimise over-catch caused by raindrops hitting near the orifice and to help break up wind turbulence (Vuerich *et. al.,* 2009). A photo with a Sontech Suneye was taken from the orifice of each gauge to identify any significant obstructions (Figure 5.13).

One pit gauge was installed as close to the GWRC eastern shore meteorological site as possible to provide comparison of rainfall rates between the pit gauge and the GWRC OTA tipping bucket gauge.

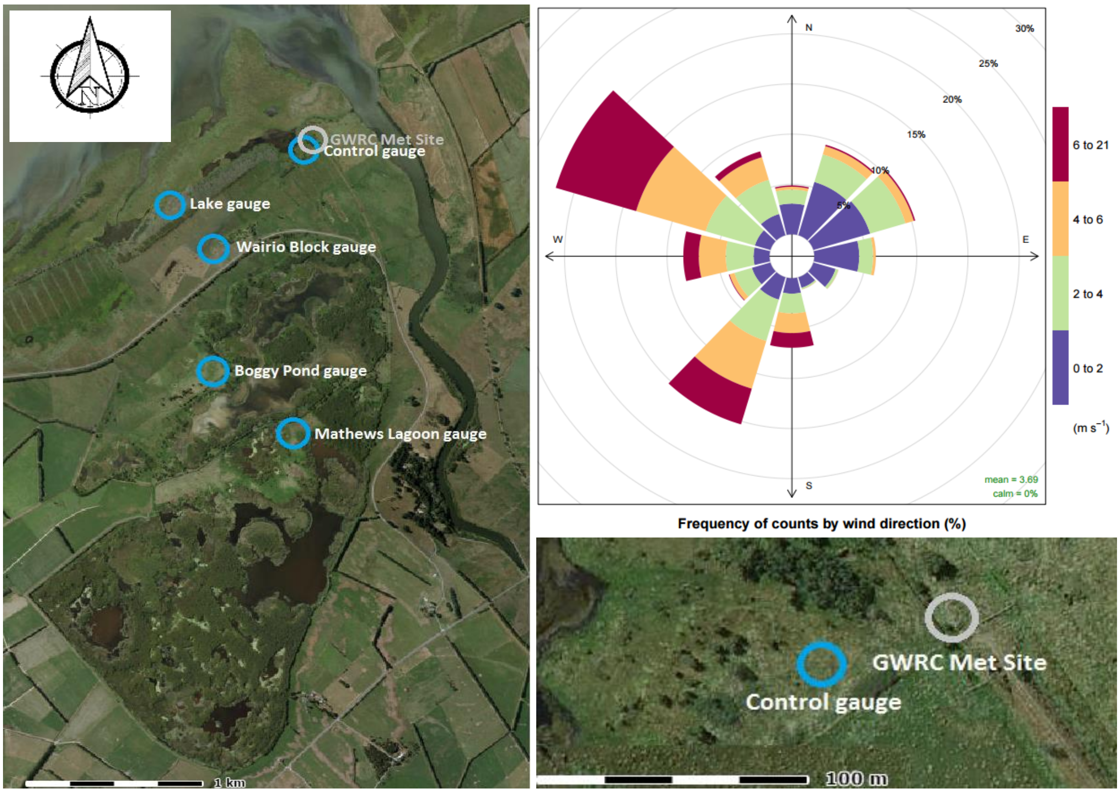


Figure 5.8: Wind plot showing the dominant prevailing wind direction recorded at the GWRC Met Site on the eastern shore of Lake Wairarapa, and the distribution of the pit gauges through the wetland system, oriented as best as possible to align with the dominant wind direction

Figure 5.9: Installation of two pit gauges, the control gauge and the Lake Wairarapa gauge (prior to the inclusion of the solar reflection boards)

5.10: Exposure surrounding Wairio Block pit gauge

5.11: Exposure surrounding Lake Wairarapa pit gauge

5.12: Exposure surrounding Mathews Lagoon pit gauge

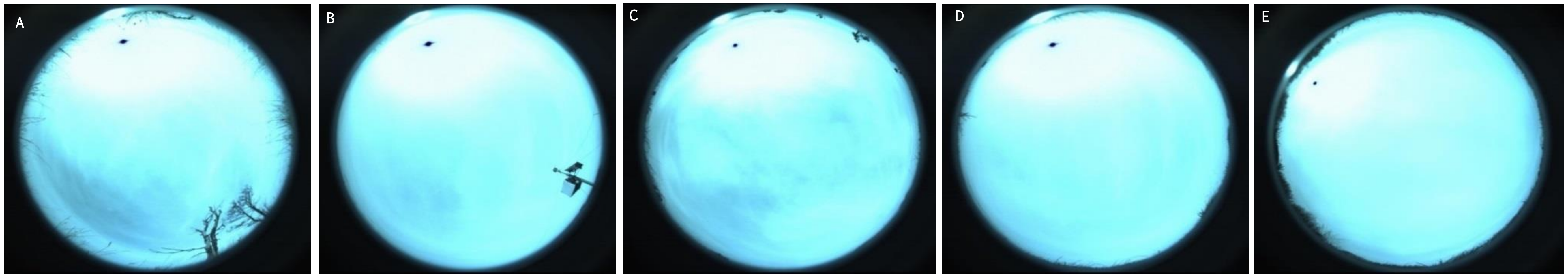


Figure 5.13: A - Lake Wairarapa gauge; B – GWRC eastern shore met site; C – Control gauge; D – Boggy Pond; and E – Matthews Lagoon.

5.3 Wetland surface water inflows

Surface water inflows into Mathews Lagoon have been measured at the Te Hopai Pump drain since 20 March 2013 (Figure 5.14). Measurements have been conducted by inferring flow rates within the upper drainage channel from the running times of the two Archimedes screws used to pump water from the Te Hopai Drain into Mathews Lagoon. While it has been identified that the condition of the screws is not known (over time their rating changes), the calibration of flow rate to running times has occurred recently, and therefore flows are deemed suitably accurate. The key variable in this study will not be the volume, but the seasonal timing and duration of pumping, this can be suitably inferred from this data set.

No surface water inflows exist for Boggy Pond, other than potential seepage through the common stop bank. Wairio Block Stage 1 receives overland from the surrounding watershed. This inflow will have changed significantly in its nature over the course of this study as progressive stages of development within the watershed have isolated new ponds, restricting some inflows into this lower wetland.

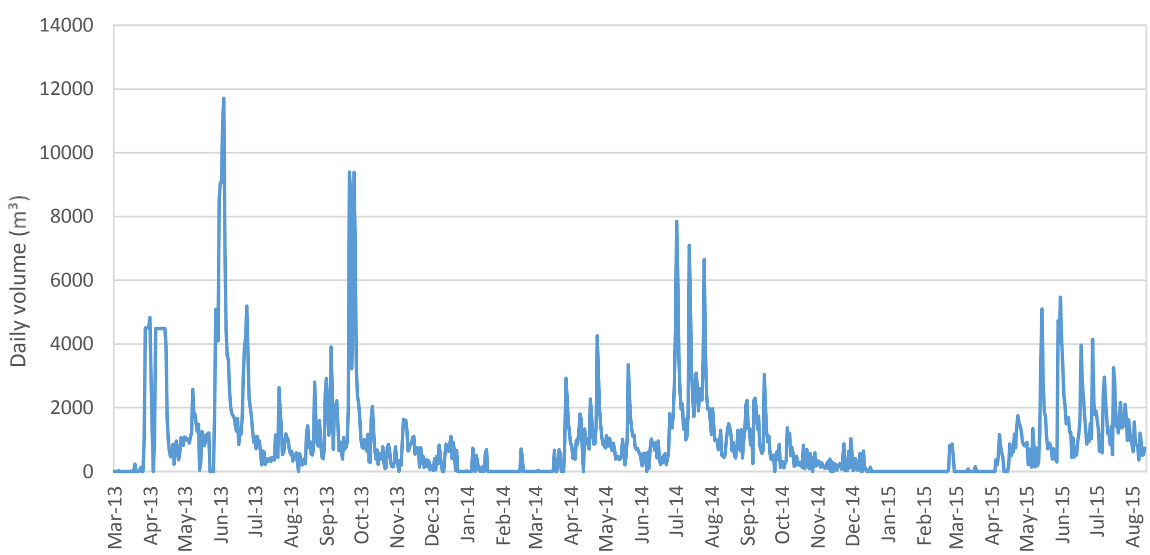


Figure 5.14: Daily total volume, pumped into Mathews Lagoon from the Te Hopai drainage network

5.4 Wetlands surface water outflows

Outflows from Mathews Lagoon are controlled through an outlet culvert under Parera Road. This culvert is controlled by flood gates, which in turn respond to the changes in pressure between the water level in the wetlands, and the water level at Lake Wairarapa. As part of study on the nutrient regimes of Boggy Pond and Mathews Lagoon, Shi (2014) derived a rating curve to generate an outflow series from Mathews Lagoon (Figure 5.15).

Flows through the section selected to gauge (3-5m upstream of the culvert) are slow, and therefore no change in section area is expected to have occurred over the gauging period. This should result in a relatively stable rating curve. However, due the nature of the outflow being controlled by relative changes in pressure, the rating curve derived from these gaugings is considered not suitable for the derivation of a reliable outflow series. However, gaugings do indicate that flows are not likely to exceed 1.6 m^3/s.

This assessment has been based off the following points.

- A limited number of gauging's (nine)
- Limited constraining points at the lower end
- Narrow stage range and discharge range
- A very weak stage discharge relationship

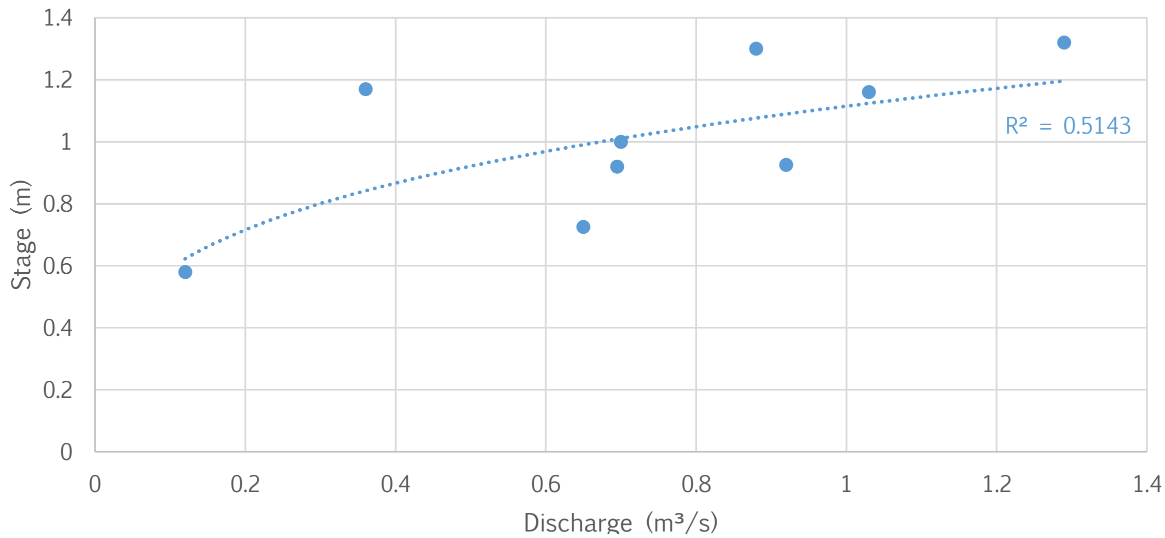


Figure 5.15: Rating curve derived by Shi (2014) for outflow from Mathews Lagoon (2014)

5.5 Groundwater

A lack of understanding about shallow groundwater exists around this study area, however local piezo metric contours indicate that the local groundwater system converges on Lake Wairarapa (Gyopari & McAlister, 2010a). Bore logs for 30 bores surrounding these wetlands were collected from the GWRC. These logs indicate a shallow clay pan is present between 0-17m (Figure 5.16 and Table 5.7). Bore logs can be found in Appendix B.

Groundwater from deeper aquifers is likely to be confined from these wetlands, due to the aquitards discussed in 4.3.1. Furthermore the presence of the shallow clay pan identified from the bore logs indicates any groundwater that does enter or leave each wetland is likely associated with shallow groundwater systems (less than 20m). Since November 2011 GWRC has been collecting shallow groundwater levels at 14 locations around Lake Wairarapa as part of the Lake Wairarapa water balance study (Figure 5.17). Of these, six sites are located within close proximity of the wetlands in this study. Data from these bores will be used to assess any relationship between groundwater, and each wetland.

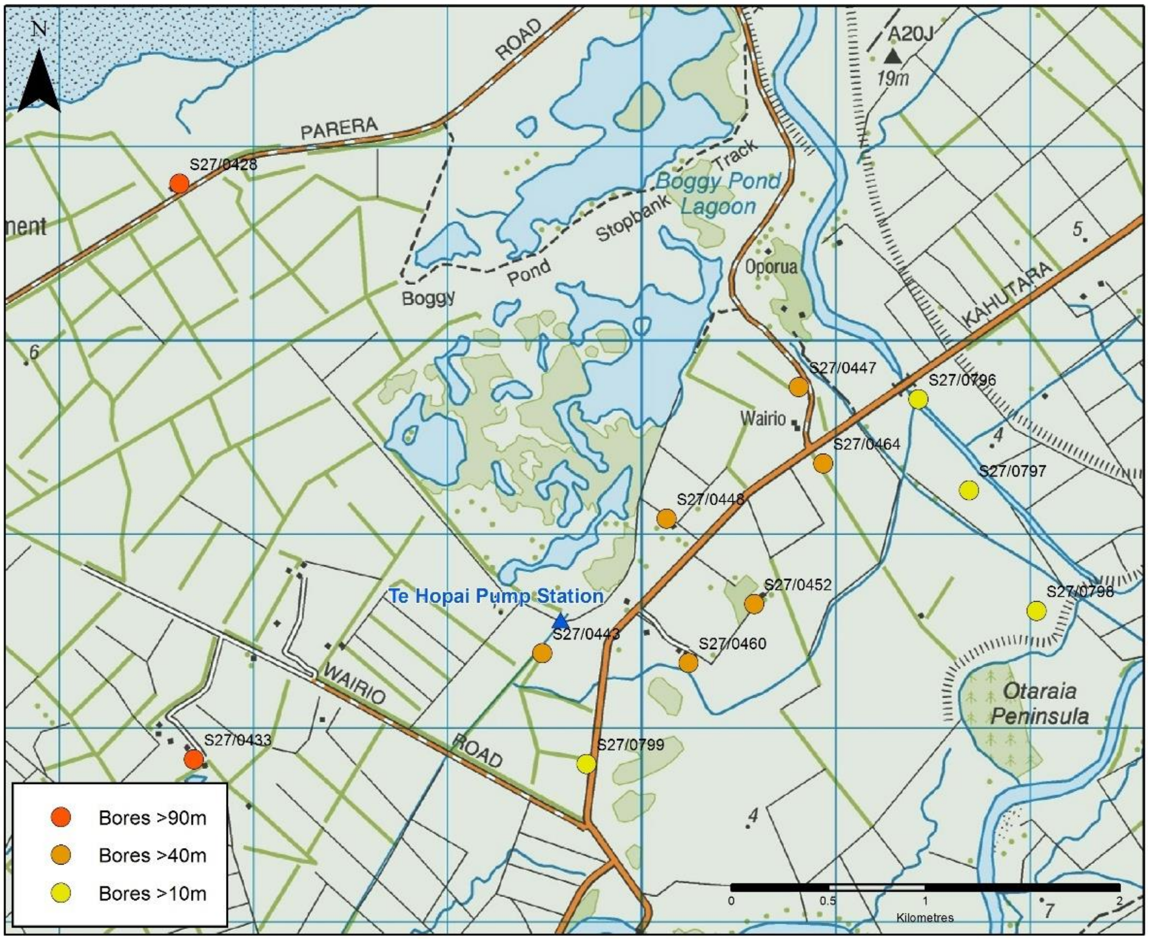


Figure 5.16 Groundwater bores and associated depths with data held by GWRC around the Te Hopai basin and study wetlands

Table 5.7: Depth to clay in selection of bores close to study wetlands

Bore	Depth to clay (m)	Depth of clay pan (m)	Description
S27/0447	7	13	Clay/Silty Clay
S27/0425	5	14m	Clay
S27/0443	0	32m	Soft blue clay with sand layers/light medium to hard clay
S27/0448	0	26.5	Soft papa clay/ hard white clay
S27/0427	16.9m	5	Clay/silty clay
S27/0428	7	20	Grey stiff clayey silt with with some broken shells
S27/0796	0	0.6	Surface clay
S27/0460	3	25	Soft grey clay

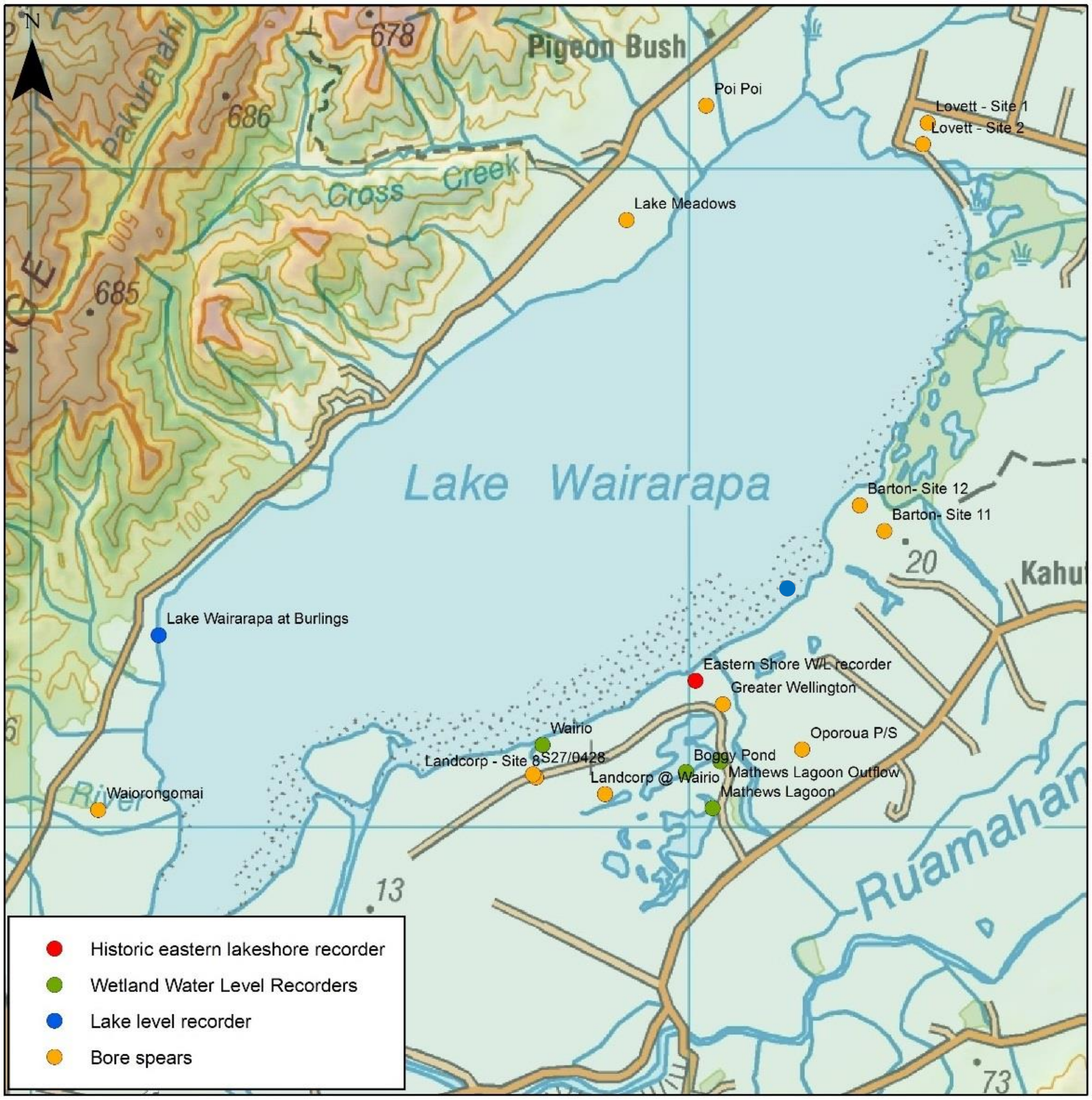
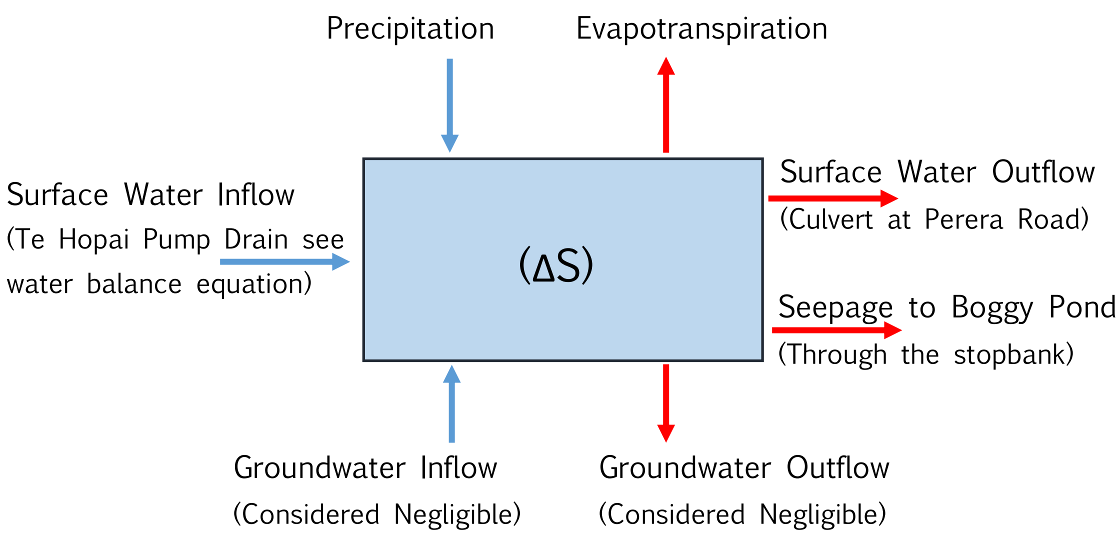


Figure 5.17: GWRC groundwater sensors around Lake Wairarapa used in this study

5.6 Water Balance

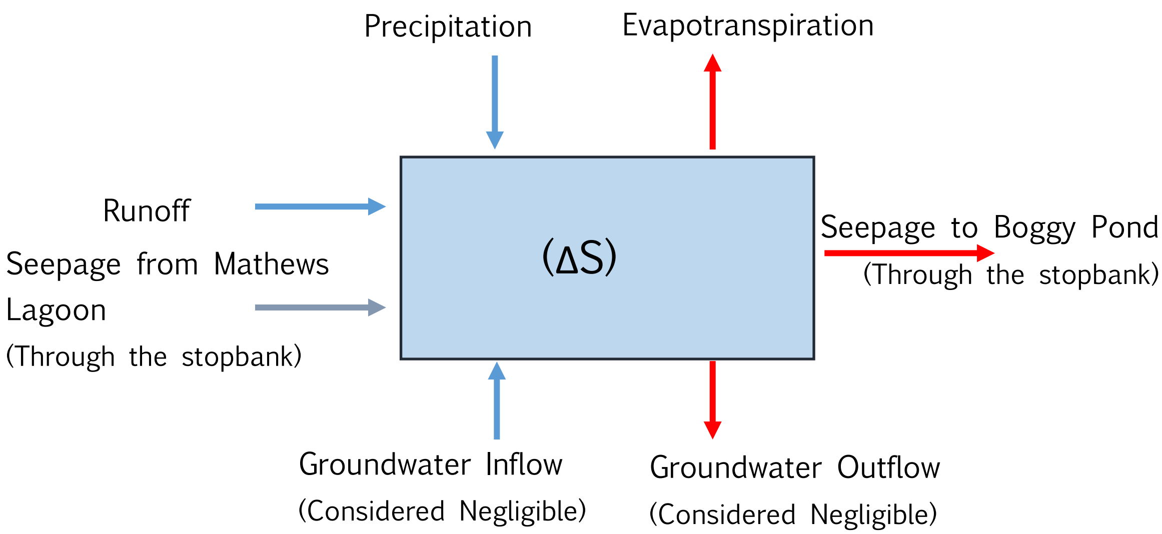
As discussed in Chapter 3, the sources and losses of water from a wetland can be accounted for in a mass balance equation. This equation quantifies the relative importance of inputs and outflows of water in a wetland.

The significance of components in the water balance equations for the three wetlands being studied vary. Theoretical schematics, and the subsequent equation which will be used for each to quantify the potential effects of climate change on each wetland are presented in Figure 5.18 to Figure 5.20. Each component of the mass balance equations, including source, derivation and adjustments for climate change are detailed in the following sections.



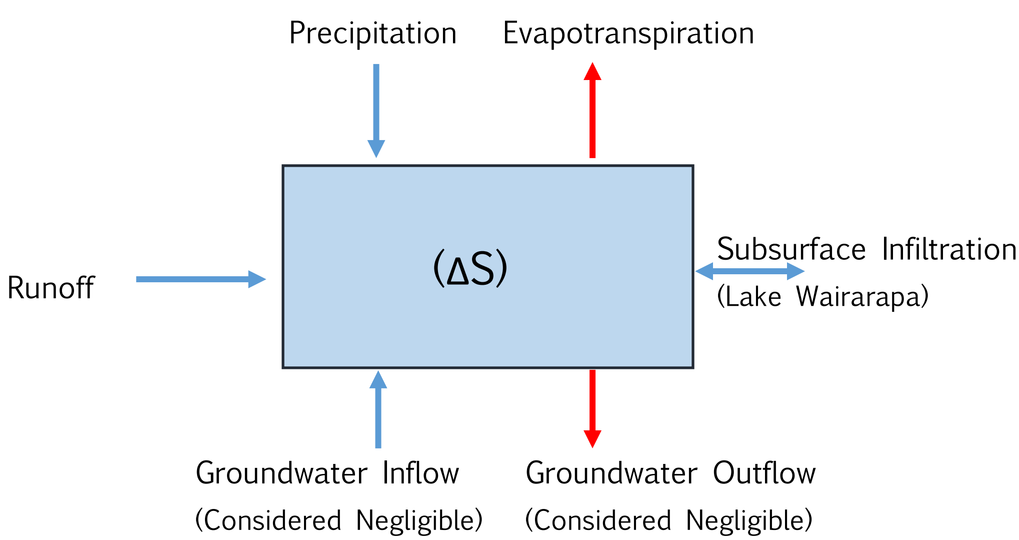
$$\Delta S = P + Si + Gi - Eo - (So + S) - Go$$

Figure 5.18: Theoretical water balance schematic and equation for Mathews Lagoon



$$\Delta S = P + R + Si + Gi - Eo - Go - So$$

Figure 5.19: Theoretical water balance schematic and equation for Boggy Pond



$$\Delta S = P + R + I + Gi - Eo - Go - I$$

Figure 5.20: Theoretical water balance schematic for Wairio Stage 1 wetlands

Where:

- ΔS = change in storage volume
- P = net precipitation
- S_i = surface water inflow
- S = Seepage
- G_i = ground water inflow
- Eo = evapotranspiration
- I = infiltration
- S_o = surface water outflow
- G_o = ground water outflow

5.6.1 Evapotranspiration

Evapotranspiration refers to the combined transfer of liquid water to water vapour through the process of vaporisation from both evaporation and transpiration, each of which are processes that occur simultaneously in a wetland environment (Lott & Hunt, 2001). In warm climates (like the Lower Wairarapa valley), evapotranspiration can be a dominant component in a wetlands water balance, accounting for between 20-70% of wetlands water loss (Arnold *et al.*, 2001; Bradley, 2002; Sanderson *et al.*, 2008; Sun *et. al.*, 2011). Determining accurate rates of evapotranspiration is difficult, as its components occur both directly from the water surface, and indirectly through exposed soils or vascular plants (transpiration). Furthermore the proportion to which each of these processes operate change throughout the year, with major disturbances, and as wetlands naturally develop.

Potential transpiration (PE) is the theoretical maximum amount of water lost from a system, (assuming an unlimited water supply) (McConchie, 2000). However, because of limitations to water availability, this maximum is often not achieved.

The actual evaporation (AE) is a function of both the PE and the water available, and therefore is more characteristic of the actual amount of water lost.

Evapotranspiration is driven by energy. This comes from direct solar radiation, turbulence and vapour pressure gradients (McConchie, 2000). Transpiration, the conversion of water to water vapour occurs inside the plant, and its release (controlled by the stomata), is also a result of the fore-mentioned climate variables, but also the availability of water to the plant.

Soil moisture availability and meteorological conditions are therefore critical components required to calculate evapotranspiration rates. These include levels of solar radiation, temperature, humidity, and wind speed, while accurate measurements of net radiation (R_n) and soil heat flux (G) are critical to improving accuracy (Mitsch and Gosselink, 2000, Arnold *et al.*, 2001).

Field measurements of evapotranspiration are possible with lysimeters, however, these are costly, and require trained field technicians to operate properly (UNFAO, 2015), therefore, evapotranspiration is commonly calculated. Development in techniques associated with estimating evapotranspiration have provided a plethora of options over recent years. Different methods have been used by wetland scientist to determine the best performing equation. Wossenu (2007) found that the Penman-Monteith equation best estimated ET of cattail and mixed marsh vegetation, while the Penman-combination equation was most suitable for the open water/algae system (Wossenu, 2007).

A comprehensive review by Drexler *et al.,* (2004) found that, due to the variability in wetland type, of the more advanced methods to estimate PE, no single method stood out for wetland environments.

Providing that sufficiently accurate climate data is available it is widely considered the FAO Penman-Monteith method is the standard method for the computation of

Evapotranspiration (ET_o) (FAO UN, 2015). This equation is built on the Penman Original equation, developed in 1963, and was the first to consider both the energy and aerodynamic aspects of crop evapotranspiration. This was later modified in 1977 by the UN Food and Agricultural Organisation (FAO), where adjustments for day and night time weather conditions were introduced. FAO Penman-Monteith method is now considered to be one of the most accurate methods of evapotranspiration when all the available meteorological and climate variable data are available (McMahon *et. al.,* 2013). Due to the availability of regionally-specific climate data in close proximity to the wetlands being studied, this method is considered most appropriate

The FAO Penman-Monteith method to estimate ET_o is as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2(e_s - e_a)}{(\Delta + \gamma)(1 + 0.34u_2)}$$

Where:

- ET_o is reference evapotranspiration (mm day^{-1})
- R_n is net radiation at the crop surface (MJ m^{-2} day^{-1})
- G is soil heat flux density (MJ m^{-2} day^{-1})
- T is mean daily air temperature at 2m height (°C)
- U_2 is wind speed at 2m height (m s^{-1})
- e_s is saturation vapour pressure (kPa)
- e_a is actual vapour pressure (kPa)
- e_s-e_a is saturation vapour pressure deficit (kPa)
- Δ is slope vapour pressure curve (kPa °C^{-1})
- γ is psychrometric constant (kPa °C^{-1})
- 900 is the coefficient of reference crop in kJ^{-1} kg °C day^{-1}

Estimates of evapotranspiration were calculated manually using the above equation for the 2013 daily data collected from GWRC meteorological site on the eastern shoreline of Lake Wairarapa. This site was installed in 2012 specifically for the calculation of evapotranspiration, and therefore provides daily values for temperature, atmospheric pressure, relative humidity and wind speed.

5.6.2 ET_0 performance

Results from the 2013 ET_0 equation were compared with automatically calculated evaporation from NIWA's climate site at Martinborough EWS to assess appropriateness prior to its use modelling future climate scenarios (Figure 5.21). This climate site provides ET_0 from three methods, 1963 Penman Original, Penman open water, and Preistley-Taylor PET. Detailed descriptions of each method can be found in McMahon *et. al.,* (2013). ET_0 has been shown to be relatively uniform across large areas, particularly areas of little topographic or aspect variability (McConchie, 2000), the use of ET_0 from this site as a "check" is therefore considered suitable. Monthly totals of ET_0 from these climate sites for 2013 are present in Table 5.8 and Figure 5.21.

All methods show a similar trend in evaporation rates, however, the Penman Open Water method estimates high rates of ET_0 over the winter period. The FAO Penman-Montieth equation calculates a higher rate of ET_0 for most of the year, aside from November through February where Penman Potential method calculates a greater ET_0. This is not considered to be unusual. The FAO Penman-Montieth-equation is regarded as being a more accurate method, and relative differences in climatic parameters between sites is expected to create some difference (i.e Martinborough experiences lower temperatures over the winter period than at the eastern lakeshore).

Table 5.8: NIWA pre calculated methods of evaporation vs 2013 monthly totals

Method	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Penman Open Water	159	122	105	57	42	35	35	40	66	88	117	137
(Penman Potential ET_0)	140	105	78	35	12	0	3	21	47	81	115	133
Priestley-Taylor	162	122	98	50	29	19	21	35	64	96	131	149
FAO Penman-Monteith	159	122	105	57	42	35	35	40	66	88	117	137

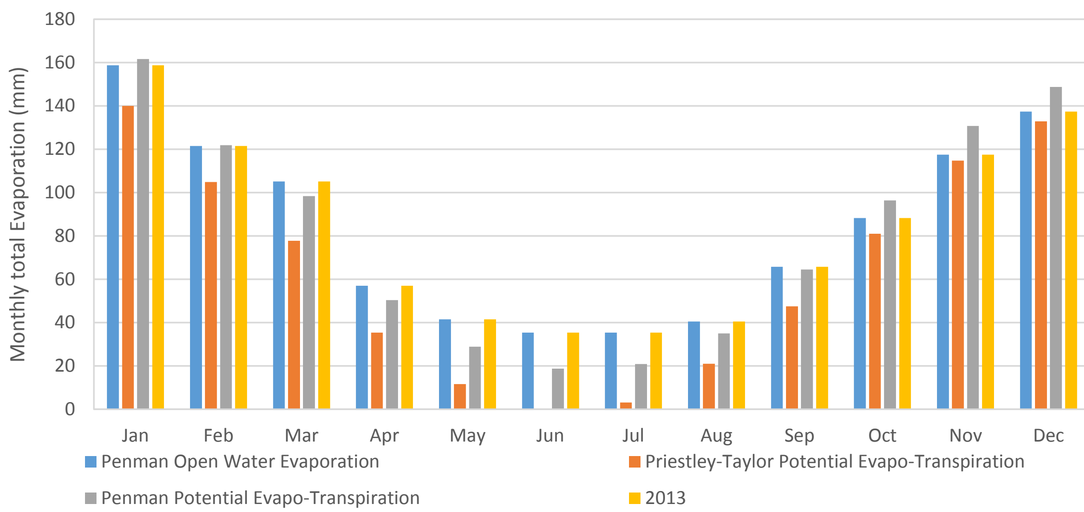


Figure 5.21: Comparison of NIWA-derived methods of evapotranspiration and FAO Penman-Monteith method for 2013

A further check on the suitability of the model for the lower valley was conducted by comparing ET_0 performance to rainfall. For the 2013-2014 year, ET_0 accounted for 1063.5mm of the 1080.5mm rainfall (98%) recorded at the eastern lakeshore (Figure 5.22.) This is appropriate when considering the dry nature of the catchment and that the PE will not always necessarily achieved throughout the whole year (i.e. surplus water in winter will runoff).

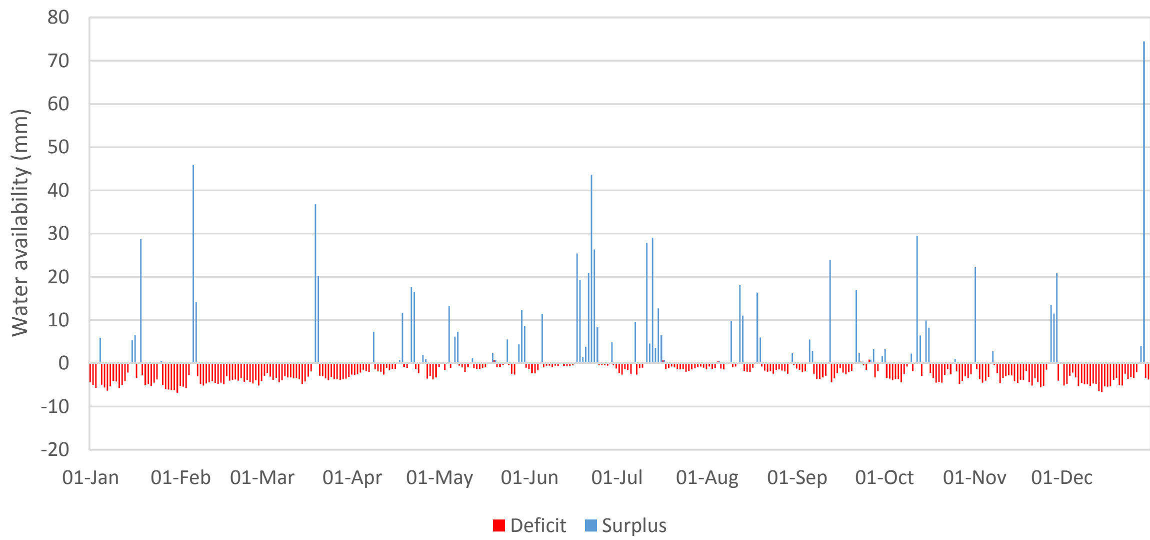


Figure 5.22: Rainfall / evaporation deficit and surplus for 2013 calculated using FAO Penman-Montieth equation for ET_o

5.6.3 Calculation sensitivity

Sensitivity analysis was conducted on the equation to determine its responsiveness to three forcing scenarios. Increases of 2%, 5% and 10% were applied independently to the current temperature (^{0}C), wind speed and radiation intensity (Ra) (Table 5.9). No forcing of relative humidity was made as adjustments were made automatically in the equation as a function of temperature.

Changes in Ra were the most influential on increasing ET_0, while changes to wind speed were the least significant. Changes to radiation intensity are difficult to project due to future cloud cover, atmosphere composition, GHG concentration etc. and are therefore only generalised as seasonal changes in MfE's 2016 climate downscaling manual. Care will therefore be taken in the derivation of radiative adjustments to prevent erroneous overestimation of ET_0.

Table 5.9: Results of the sensitivity analysis conducted on various components of the Penman Montieth equation

Parameter	Sensitivity Forcing (%)		
	2	5	10
Temp	101%	103%	107%
Mean Wind speed	100%	101%	102%
Radiation Intensity	102%	104%	109%

5.6.4 Climate scenarios

The 2013 evapotranspiration equation will be used to identify patterns in the water levels in each of the wetlands being studied. This equation will also be adapted to determine the responsiveness of ET_0 to projected future changes in climate.

The 2013 equation will be used as a base model, representative of seasonal fluctuations in evapotranspiration. Components of the equation will be adjusted to reflect the climate in the lower valley over historical reference period future climate projections are based (1986-2005). Projected changes in climate will then be run off this ET_0 model for the seasonal minimum, maximum and mean predictions of temperature, wind speed, solar radiation, and relative humidity, over each RCP, to determine the sensitivity of ET_0 to climate change.

5.7 Regional data

Data required for the calculation of ET_0, for climate analysis, and the wetland water budgets, has been obtained from a selection of spatially and temporally appropriate climate stations across the lower Wairarapa valley (Figure 5.23 and Table 5.10).

Three climate stations are present, one on either shore of Lake Wairarapa (operated by GWRC) and one at Martinborough (operated by NIWA). Details and measurement from each site can be found in Table 5.10.

Table 5.10: Climate stations in the lower Wairarapa valley.

Site ID	Parameter	Period of operation
Wairarapa Eastern and Western Lake Shores	Temperature	06 Dec 2013 -present
	Wind speed	
	Wind Direction	
	Barometric pressure	
	Relative Humidity	
Martinborough EWS	Temperature	01-Apr-2001- present
	Wind speed	
	Wind Direction	
	Solar radiation	
	Sunshine hours	
	Evaporation	
	Dew point temperature	
	Soil moisture (%) and SMD	

Figure 5.23: GWRC meteorological stations in the vicinity of the study site

5.8 Temperature

5.8.1 Data acquisition

The principal driver of predicted changes in rainfall and ET_0 is temperature. Temperature data for regional climate analysis has been collected from Martinborough EWS, while temperature used in the FAO Penman-Monteith equation has been sourced from the meteorological station on the eastern lakeshore.

5.8.2 Grounding

Temperature projections by NIWA for the Wairarapa use the 1986-2005 climate as a reference period. Subsequently, evapotranspiration calculation that will be adjusted for climate change will need to be 'grounded' in the temperature record for that period. Monthly temperatures for 2013 were, over the year, roughly 10% higher than the mean monthly temperatures over the reference period (Figure 5.24). Monthly adjustments were therefore made to the 2013 ET_0 model based of the results in Table 5.11.

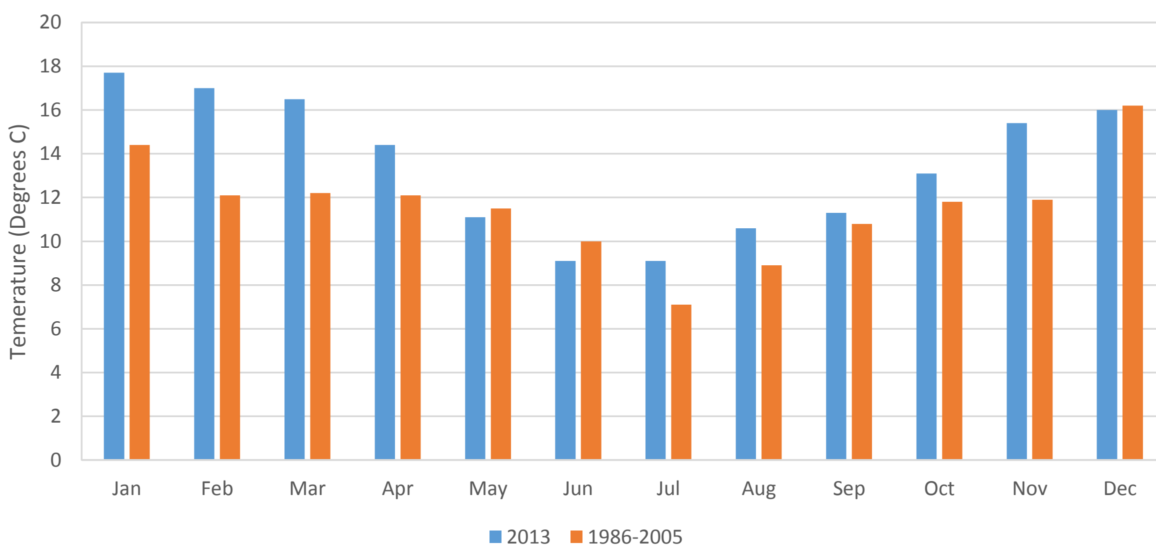


Figure 5.24: Monthly temperature for 2013 and 1986-2005 reference period

Table 5.11: Mean monthly temperatures for 2013 and 1986-2005

Month	2013 mean monthly temperature (°C)	1986-2005 (°C)	Difference (°C)
Jan	17.7	14.4	3.3
Feb	17	12.1	4.9
Mar	16.5	12.2	4.3
Apr	14.4	12.1	2.3
May	11.1	11.5	-0.4
Jun	9.1	10	-0.9
Jul	9.1	7.1	2
Aug	10.6	8.9	1.7
Sep	11.3	10.8	0.5
Oct	13.1	11.8	1.3
Nov	15.4	11.9	3.5
Dec	16	16.2	-0.2

5.8.3 Adjustment for climate change

Projected temperature increases for the Wellington region over all four RCP's out to 2040 and 2090 are presented in Table 5.12 and Table 5.13. The initial value represents the projected average temperature increase over all models nested within each RCP. The values in the brackets represent the 5th and 95th percentile over all models within each RCP.

These temperature increases are used to adjust seasonal rates of evaporation and adjust rainfall intensities for each climate scenario run for each wetland (based of the methodology described in Section 5.12.5).

Table 5.12: Predicted seasonal changes in temperature for the Lower Wairarapa valley (2031-2050 average, compared to 1986-2005)

Season	Mean temp increase (°C)			
	RCP 8.5	RCP 6.0	RCP 4.5	RCP 2.6
Spring	0.9 (0.4, 1.3)	0.7 (0.2, 1.1)	0.8 (0.4, 1.1)	0.7 (0.3, 1.0)
Summer	1.1 (0.5, 1.7)	0.8 (0.3, 1.4)	0.9 (0.4, 1.4)	0.7 (0.2, 1.2
Autumn	1.1 (0.7, 1.5)	0.9 (0.2, 1.2)	0.9 (0.4, 1.4)	0.8 (0.3, 1.2)
Winter	1.2 (0.7, 1.6)	0.8 (0.3, 1.3)	1.0 (0.6, 1.3)	0.7 (0.3, 1.1)
Annual	1.1 (0.6, 1.6)	0.8 (0.3, 1.2)	0.9 (0.5, 1.2)	0.7 (0.3, 1.1)

Note: these data are from Table 5 in Ministry for the Environment (2016)

Table 5.13: Predicted seasonal changes in temperature for the Lower Wairarapa valley (2081-2100 average compared to 1986-2005)

Season	Mean temp increase (°C)			
	RCP 8.5	RCP 6.0	RCP 4.5	RCP 2.6
Spring	2.7 (1.9, 3.6)	1.6 (1.0, 2.4)	1.3 (0.7, 1.9)	0.6 (0.2, 1.2)
Summer	3.1 (2.2, 4.7)	1.9 (1.0, 3.6)	1.4 (0.7, 2.6)	0.7 (0.2, 1.4)
Autumn	3.1 (2.2, 4.4)	1.9 (1.0, 3.1)	1.5 (0.8, 2.2)	0.7 (0.1, 1.5)
Winter	3.2 (2.4, 4.2)	1.9 (1.2, 2.9)	1.5 (0.9, 2.1)	0.7 (0.3, 1.3)
Annual	3.0 (2.2, 4.3)	1.8 (1.1, 2.8)	1.4 (0.9, 2.1)	0.7 (0.3, 1.3)

Note: these data are from Table 6 in Ministry for the Environment (2016)

It is important to note that MfEa (2016) has identified that the daily minimum (Tmin) and maximum temperature (Tmax) will not increase in unison, but will evolve differently from the temperature mean, creating a greater range in temperature over time. This has been identified in a number of climatic studies, i.e. (Ghasemi, 2016) analysis of seasonal temperature variations in central England (over the past 220 years).

Analysis of the temperature record at Martinborough EWS from 2001 (Figure 5.25) indicates that Tmax is increasing 2.8 time faster than Tmin (Figure 5.26). Since components of evapotranspiration are calculated using both Tmin and Tmax, adjustments relative to each should be made. This was considered, however suitable adjustments could not be determined. Subsequent adjustments to mean temperatures, (detailed in Table 5.12 and Table 5.13) were therefore applied to both Tmin and Tmax.

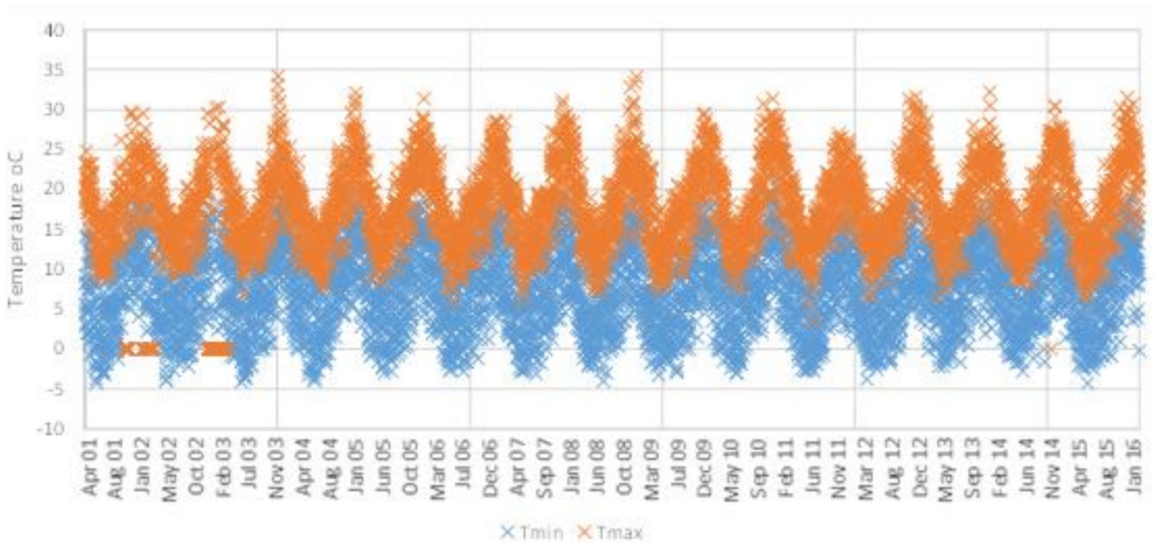


Figure 5.25: Daily Tmin and Tmax temperatures recorded at Martinborough EWS (2001-2016)

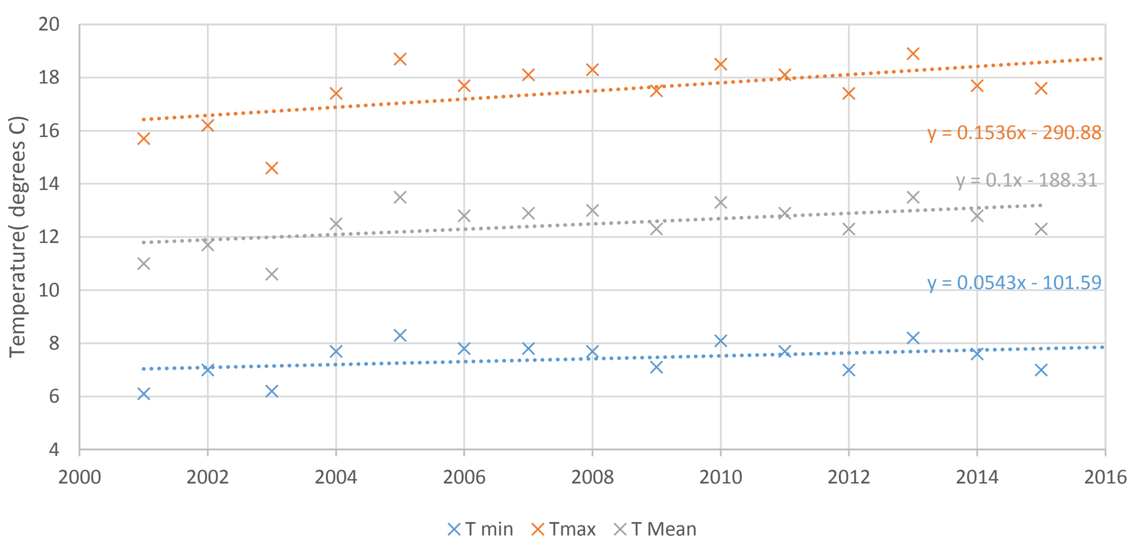


Figure 5.26: Increase in annual TMean (grey), TMin, (blue), and Tmax (red) temperature recorded at Martinborough EWS

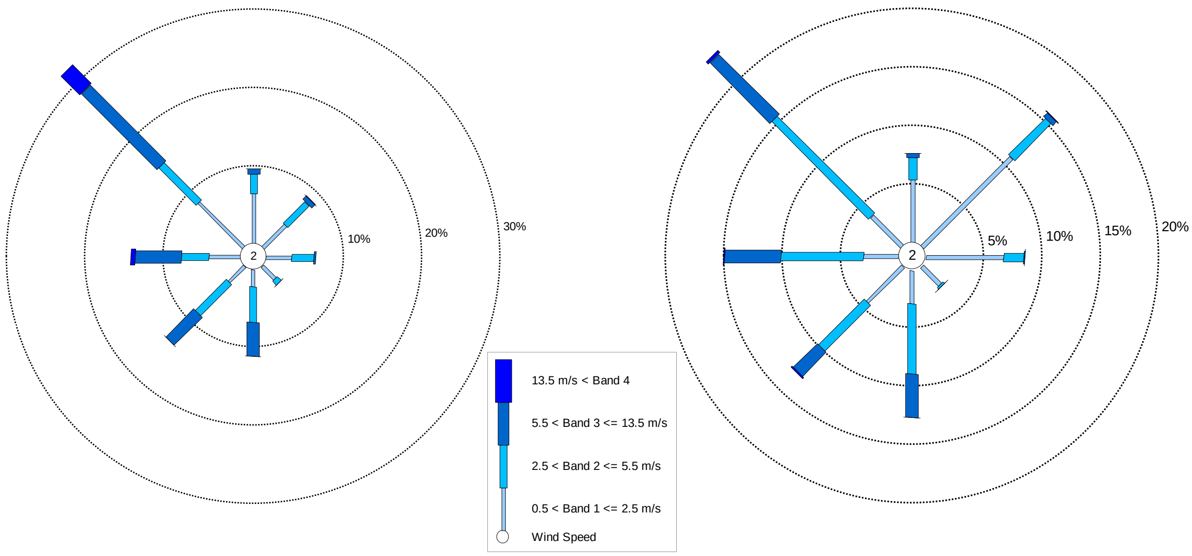
5.9 Wind Speeds

Wind speed and its direction is an important meteorological component for two aspects of this study.

- Wind speeds are an important component in the derivation of evapotranspiration
- High wind speeds have the potential to tear water off the surface of Lake Wairarapa and deposit it on the eastern shoreline, over the wetlands being studied

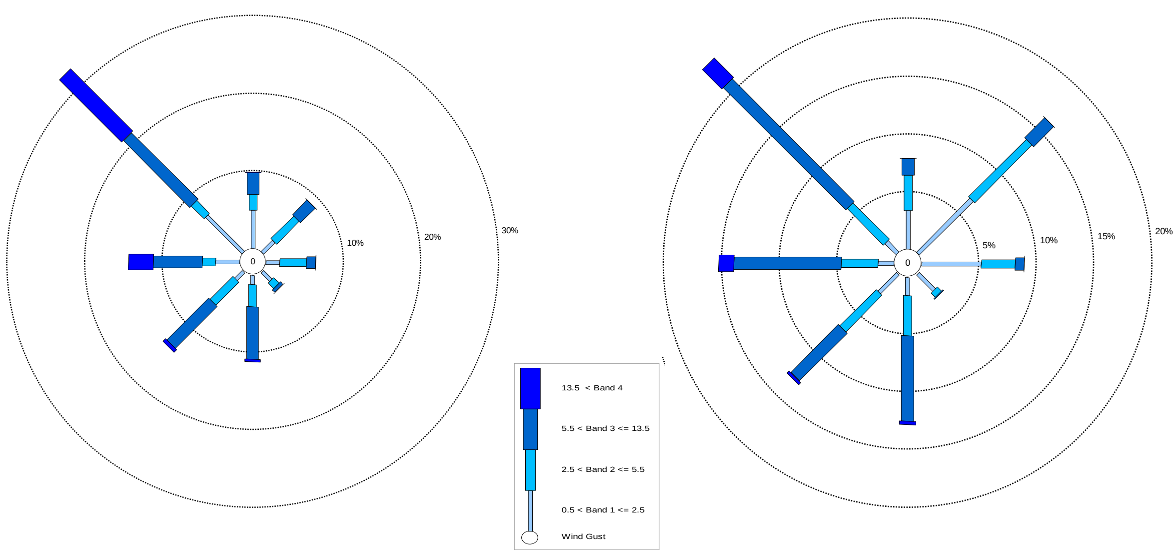
5.9.1 Data acquisition

Wind speed, and wind direction data were obtained from Lake Wairarapa meteorological sites on the eastern and western shoreline of Lake Wairarapa (Table 5.14). Wind rose plots for both mean wind speeds (5min) and maximum wind gusts are presented in Figure 5.27 and Figure 5.28, and summary statistics can be found in Table 5.14. The dominant wind direction is from the north-west, both in frequency and intensity. Wind speeds are both consistently stronger and less variable on the western lake shore. For the purpose of determining wind speed stresses on Lake Wairarapa, the average wind speed between each site will be used.



Met Station Western Lakeshore   Met Station Eastern Lakeshore

Figure 5.27: Wind rose plots for the west and east shorelines of Lake Wairarapa (mean wind speed at 2.5m) (ms^{-1})



Met Station Western Lakeshore   Met Station Eastern Lakeshore

Figure 5.28: Wind rose plots for the west and east shorelines of Lake Wairarapa (max wind gusts at 2.5m) (ms^{-1})

Table 5.14: Eastern and Western lake shoreline wind speeds for 2013

Location	Max	Mean	Std Dev	Lower quartile.	Median	Upper quartile.
Met Site West 2013	45.6	4.57	4.03	1.60	3.40	6.20
Met Site West	45.6	4.63	3.94	1.60	3.59	6.40
Met Site East 2013	19.8	3.20	2.37	1.5	2.60	4.30
Entire record	45.6	3.33	2.45	1.50	2.80	4.60

5.9.2 Grounding

Insufficient data exists from the GWRC meteorological site to determine a suitable adjustment of wind speeds observed in 2013 to the baseline period of 1986-2005. While wind speed records at Martinborough EWS extend back to 2001, the highly dynamic nature of wind prevents correlation between sites. Wind speeds at Martinborough are far less gusty (expressed as the standard deviation) than those at the eastern lakeshore and are typically slower. No grounding of wind speed will be conducted. This is not considered to affect results as the sensitivity analysis conducted on the ET_0 model found wind speeds to have a negligible (2%) effect on the overall rate of evapotranspiration.

5.9.3 Adjustment for climate change

Considerable uncertainty over how wind speed may change as a result of climate change exists (NIWA(a), 2016). Changes in wind speed are driven by changes in mean sea level pressure gradients (MSLP). MSLP is expected to increase over the summer and decrease over the winter, driving more north easterly airflows over summer and stronger westerlies over winter (MfE(b), 2016).

Past estimates had led MfE and NIWA to predict an increase in wind speed across the Wellington Region of between 2% and 5% in winter and spring and decrees by the same margin in summer and autumn. (Begg & Johnston, Geology of the Wellington area. Institute of Geological and Nuclear Sciences 1:250 000 geological map 10, 2000) estimates a 10% increase in westerly winds over the next 30 years and 20% increase by the end of the century. Wratt *et. al.,* (2003) predict the frequency of wind speeds over 30m/s may double by 2080. The most recent predictions by MfEd (2016) identify an increase in the mean wind speed of up to 10% by the end of the century in Marlborough and Canterbury, but provide no further predictions.

Based off rough estimates detailed above, and a brief analysis of the seasonality of the 30 strongest 24hr average wind speeds observed on the eastern shoreline (Figure 5.29), the following adjustments (as a % of the daily mean wind speeds recorded over the 2013-2014 period) to the wind speeds are deemed suitable[2] (Table 5.15).

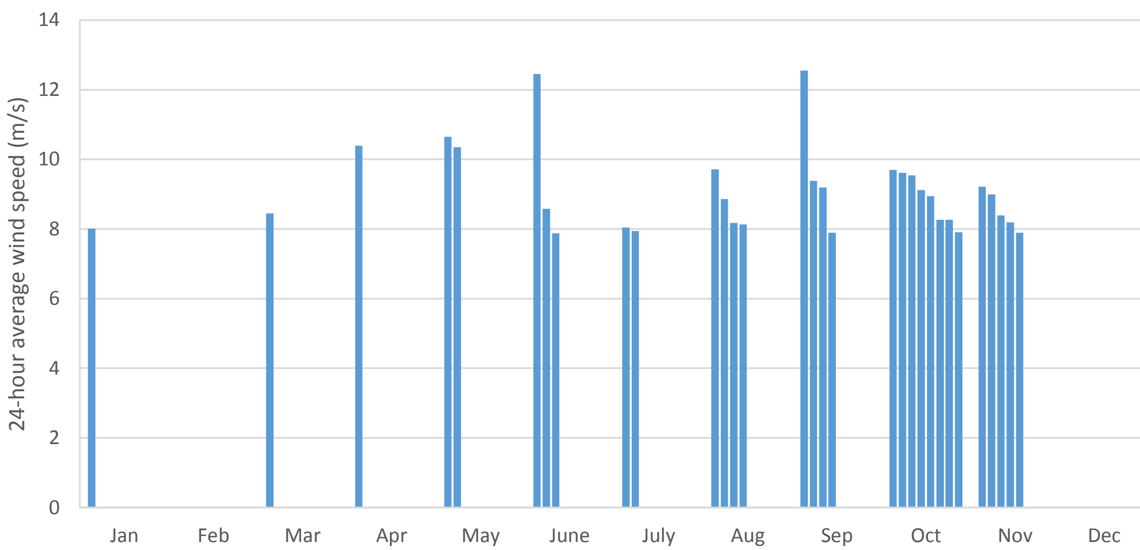


Figure 5.29: Seasonality of strongest winds (24 hour average) recorded at Lake Wairarapa at the eastern lakeshore in 2013

[2] Sensitivity analysis conducted on the equation found that increases in wind speed (of 10%) had a marginal (<2%) effect on the total ET_0.

Table 5.15: Seasonal adjustments to be made to the ET_0 equation for wind speed out to 2040 and 2090

Season	Adjustment to seasonal mean wind speed (%)			
	Spring	Summer	Autumn	Winter
2040				
RCP 8.5	1.0	1.5	4.0	5.0
RCP 6.0	0.9	1.2	3.0	4.0
RCP 4.5	0.7	1.0	2.0	3.0
RCP 2.6	0.5	0.8	1.0	2.0
2090				
RCP 8.5	2.0	3.0	8.0	10.0
RCP 6.0	1.6	1.5	6.0	9.0
RCP 4.5	1.4	1.3	5.0	8.0
RCP 2.6	1.0	1.1	3.0	6.0

5.10 Relative humidity

Relative humidity is important in the regulation of transpiration (Gaffen and Ross, 1999). Relative humidity is the ratio of actual vapour pressure to saturation vapour pressure (the saturation vapour pressure being the amount of water vapour the air can hold at a given temperature before it condenses). Relative humidity data was collected from the GWRC meteorological on the eastern lakeshore Figure 5.30.

MfEc, (2016) have predicted a reduction in relative humidity across the Wairarapa region, over all seasons, driven by temperature. Predictions of a 1-2% decrease in relative humidity per degree increase in mean temperature. Relative humidity will therefore be reduced for each climate scenario run as a function of mean temperature applied.

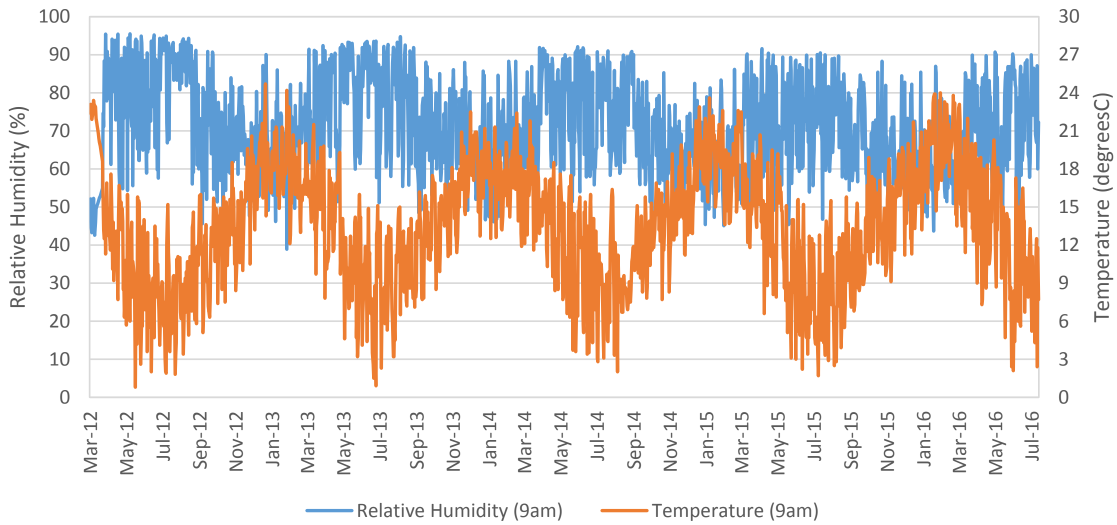


Figure 5.30: Relationship between relative humidity and temperature at GWRC Eastern Lake Shore (2013)

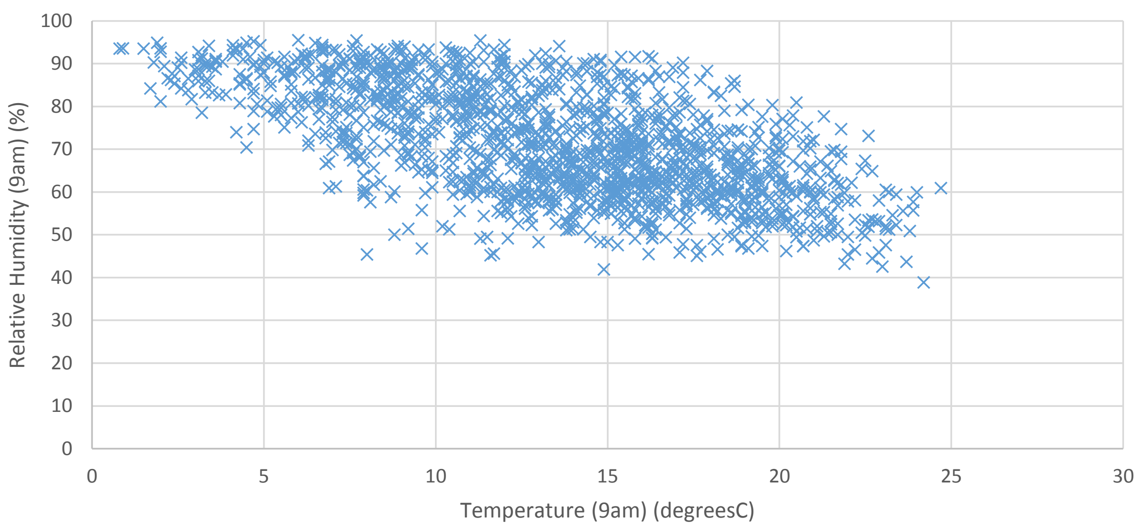


Figure 5.31: Correlation between temperature and relative humidity at eastern lakeshore

Dew-point temperature, (the temperature at which the air cannot hold all the water vapour which is mixed with it), can be a more accurate parameter for measuring humidity and has been used more often in studies of climate (Robinson, 1998).

An increase in mean atmospheric water vapour content is expected with climate change. It is not documented how dew point temperatures may change i.e. whether it will be proportional to changes in mean temperature, or changes in variability.

However, potential increases in rainfall may occur, as the maximum persisting precipitable water will increase with temperature, as a function of the Clausius-Clapeyron relationship (Figure 5.32) (Milks 2013).

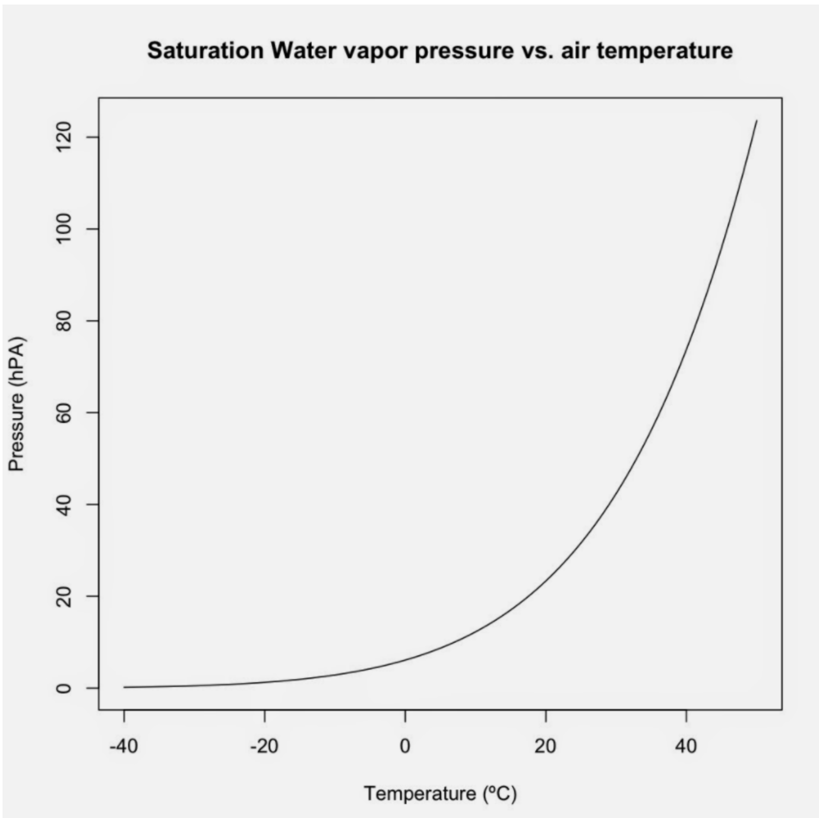


Figure 5.32: A typical phase diagram depicting the Clausius-Clapeyron relationship (Milks, 2013)

It is possible therefore that a temperature increase of, say, 2˚C could result in an increase in high intensity rainfalls by up to 10%; this is likely to be well within the uncertainty already inherent in the derivation of rainfall estimates provided by NIWA (discussed in Section 5.12.5). Dew point temperature has been collected from NIWA through its online database (Cliflo) for both Wellington and Masterton. Only month totals were available (Figure 5.33), and demonstrate a differing pattern. Dew point temperature in Masterton is far more varied than wellington, indicating a greater variability in climate. Unfortunately, insufficient data was available for a comprehensive study of dew point temperature over time in the Wairarapa region.

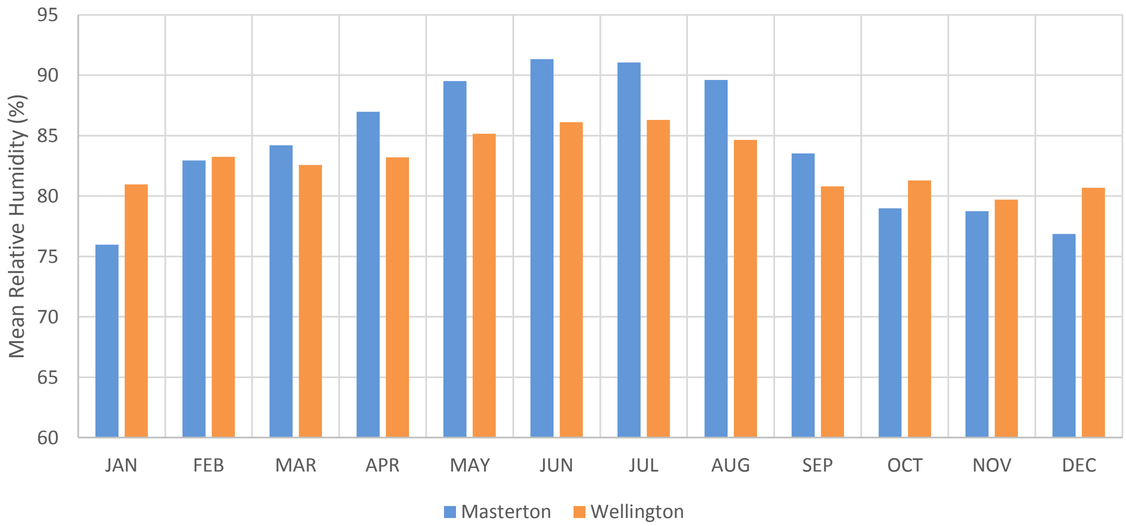


Figure 5.33: 2016 mean 9am relative humidity for Wellington and Masterton (Cliflo, 2016)

5.11 Solar radiation

Daily net radiation (MJ m^{-2} day^{-1}) is required as a key component in the calculation of ET. Unfortunately, these data are not always commonly available. A method to calculate this from two variables, (daily extra-terrestrial radiation (Ra) and mean daylight hours) has been developed and built into the FAO Penman-Monteith equation. These data were taken from FAO irrigation and drainage paper 56 (Allen, *et. al.,* 1998) and are presented in Table 5.16 and Table 5.17.

Values for Ra are presented as the Ra on the 15th day of each month, as opposed to a mean over the month. The Ra on the 15^{th} day of each month are considered to be suitably representative (error $< 1\%$) of Ra averaged over all days within a month (Allen, *et. al.,* 1998).

Tabulated data collected from Allen *et. al.,* (1998) only provide data for latitudes 40 and 42 degrees south. The study site is located at approximately 41 degrees south. Taking the mean of each monthly value was considered appropriate and was therefore used.

Table 5.16: Daily extra-terrestrial radiation (MJm^{-2}) for different latitudes for the 15th day of the month

Latitude (deg)	Jan	Feb	Ma	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
42 deg	43.3	37.7	30.1	21.2	14.6	11.6	12.8	18	26.2	34.7	41.6	44.6
40 deg	43.4	38.1	30.9	22.3	15.8	12.8	13.9	19.1	27.1	35.3	41.8	44.6
Average (41 deg)	43.4	37.9	30.5	21.8	15.2	12.2	13.4	18.6	26.7	35.0	41.7	44.6

Table 5.17: Mean daylight hours (N) for different latitudes for the 15th of the month

Latitude (deg)	Jan	Feb	Ma	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
42 deg	14.6	13.6	12.3	10.9	9.7	9.1	9.3	10.4	11.8	13.2	14.4	14.4
40 deg	14.6	13.6	12.3	10.9	9.7	9.1	9.3	10.4	11.8	13.2	14.4	14.4
Average (41 deg)	14.6	13.6	12.3	10.9	9.7	9.1	9.3	10.4	11.8	13.2	14.4	14.4

5.12 Rainfall

Increases in temperature are accompanied (where water is available) by increases in water vapour entering the atmosphere and increases in air's ability to hold moisture. The spatial and temporal distribution of rainfall is therefore expected to deviate significantly from historic norms. Assessment of changes in rainfall is therefore critical for these wetlands.

Thirty one automatic rainfall stations, operated by NIWA and GWRC are present in the lower Wairarapa valley, providing a significant spatially distributed dataset for the area (Figure 5.34, Figure 5.35 and Table 5.18).

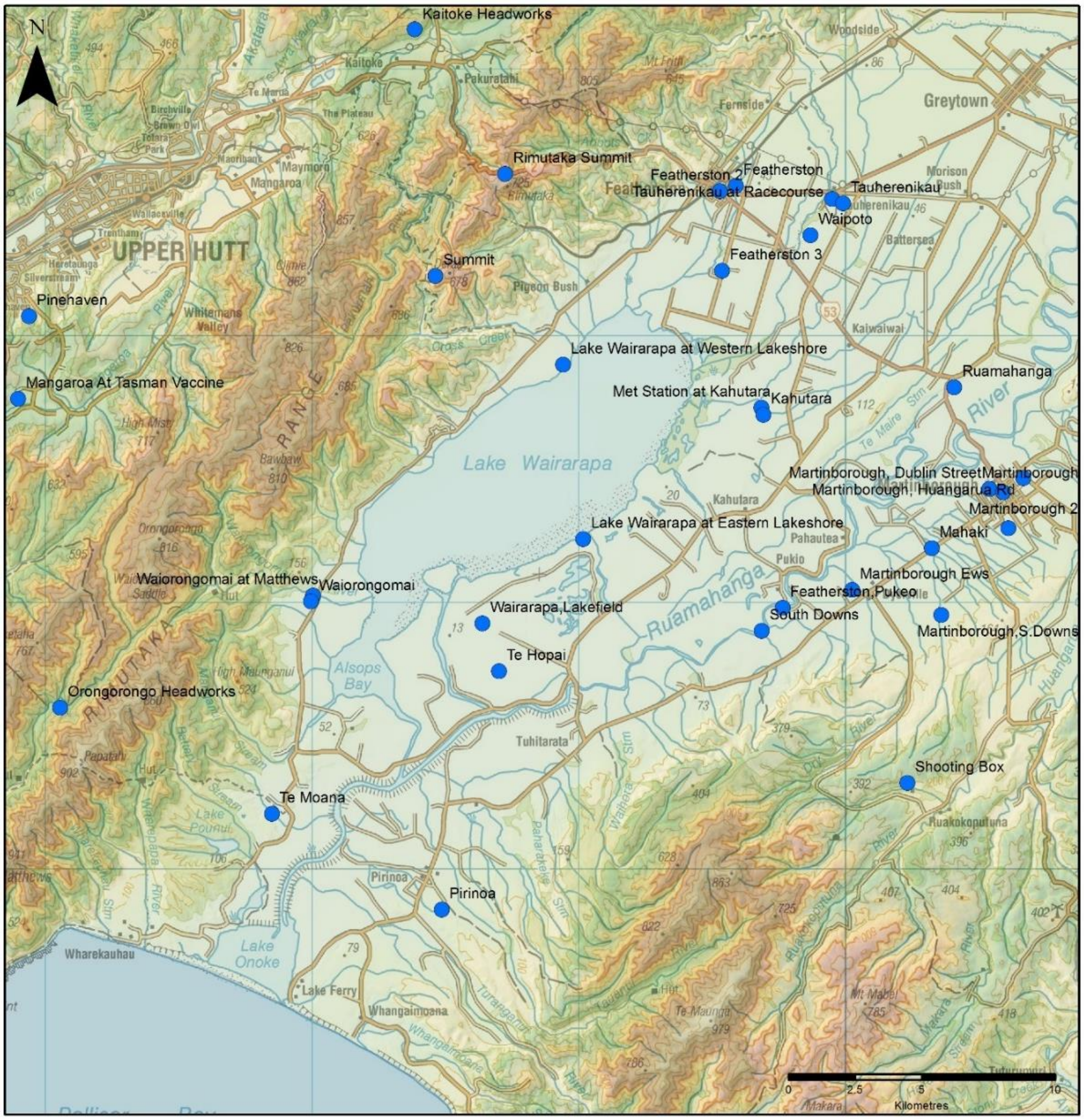


Figure 5.34: GWRC and NIWA operated rainfall sites in the Lower Wairarapa valley

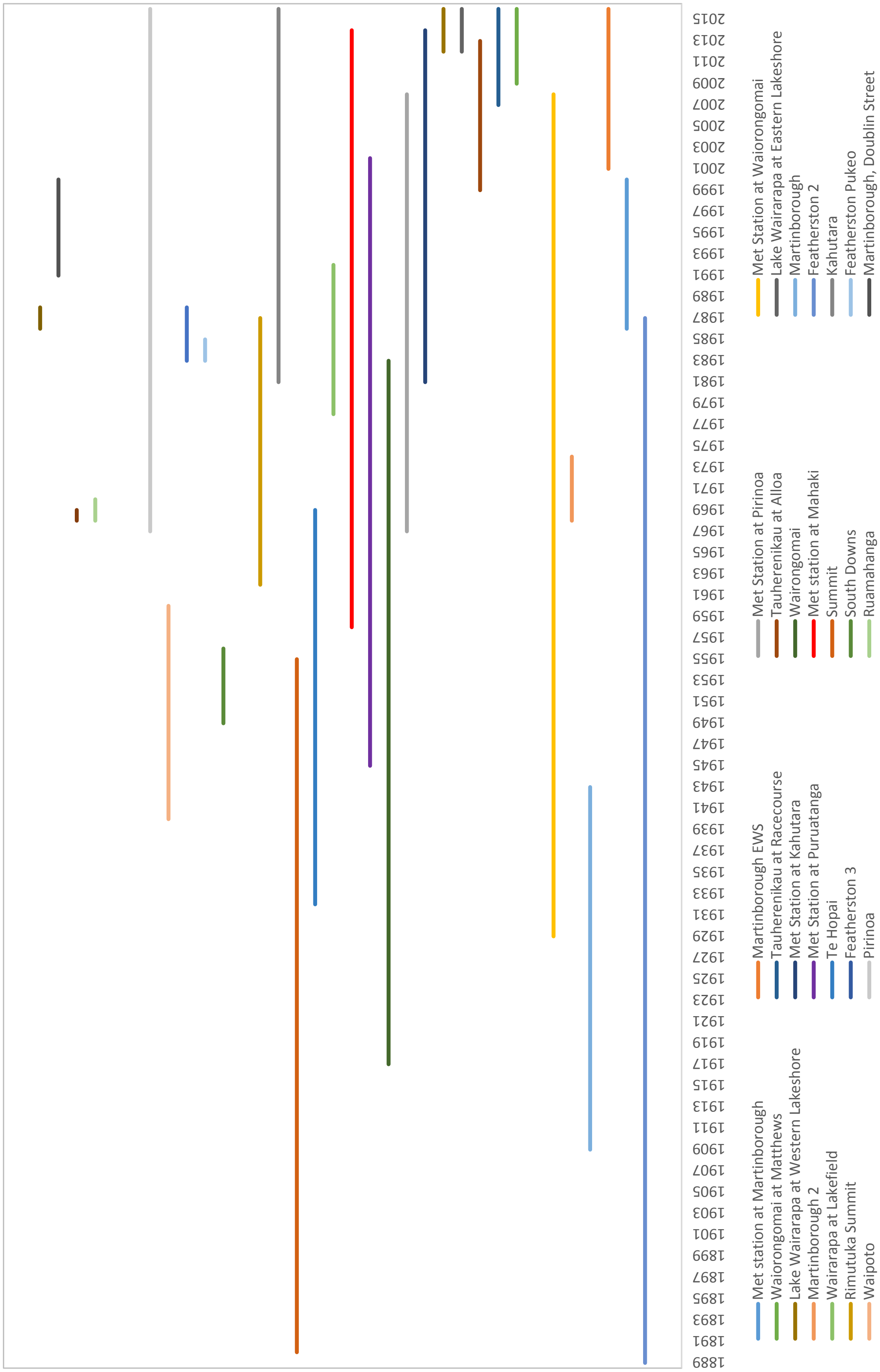


Figure 5.35: Rainfall records in the Lower Wairarapa valley

Table 5.18: Rainfall sites and period of operation in the Lower Wairarapa valley

Site ID	Agency	Opened	Closed	Period of Record (years)
Gauges still operating				
Kahutara	NIWA	01-Oct-81	present	34
Pirinoa	NIWA	01-Jan-67	present	48
Waiorongomai at Matthews	GWRC	18-May-09	present	7
Tauherenikau at Racecourse	GWRC	04-Jul-07	present	9
L Wairarapa at Eastern Lakeshore	GWRC	27-Mar-12	present	4
L Wairarapa at Western Lakeshore	GWRC	27-Mar-12	present	4
Martinborough Ews	NIWA	03-Apr-01	present	14
Records longer than 30 years				
Te Hopai	NIWA	01-Jan-32	31-Mar-69	37
Summit	NIWA	01-Jan-1890	31-Oct-55	65
Waiorongomai	NIWA	01-Nov-28	31-Dec-93	62
Featherston 2	NIWA	31-May-1889	30-Nov-87	98
Tauherenikau	NIWA	01-Mar-63	31-Mar-94	31
Martinborough	NIWA	01-Jan-09	30-Jun-43	34
Met Station at Pirinoa	GWRC	01-Jan-67	01-Jul-08	41
Met Station at Mahaki	GWRC	02-Jan-58	01-May-14	56
Met Station at Puruatanga	GWRC	01-Jan-45	01-Oct-02	57
Met Station at Kahutara	GWRC	01-Oct-81	01-Jul-15	34
Records less than 30 years and no longer current				
Wairarapa,Lakefield	NIWA	01-Jun-78	31-May-92	14
Rimutaka Summit	NIWA	01-May-62	31-Jul-87	25
Featherston 3	NIWA	01-Apr-06	31-Aug-07	1
South Downs	NIWA	01-Oct-49	31-May-56	7
Featherston,Pukeo	NIWA	01-Aug-83	30-Apr-85	2
Featherston	NIWA	01-Nov-1883	31-Oct-1888	5
Waipoto	NIWA	01-Mar-40	30-Sep-60	20
Ruamahanga	NIWA	01-Jan-67	31-Dec-70	3
Martinborough,S.Downs	NIWA	01-Jan-67	31-Dec-69	2
Martinborough, Dublin Street	NIWA	01-Oct-91	30-Apr-00	9
Martinborough 2	NIWA	01-Feb-68	31-Aug-74	6
Martinborough, Venice St	NIWA	01-Jan-86	31-May-89	3
Martinborough, Huangarua Rd	NIWA	01-Oct-86	31-Jan-00	14
Tauherenikau at Alloa	GWRC	18-Aug-1999	05-Mar-13	14

5.12.1 Rainfall event duration

To determine a suitable duration to run event analysis over, and to identify the type of rainfall events experienced over the study site, the duration of the largest seven rainfall events recorded at the eastern shore met site were examined (Figure 5.36). The critical event duration for these larger rainfall events range from 10 hours (May 2013) to 28 hours (March 2013). It is therefore considered that the use of daily totals for rainfall analysis is appropriate.

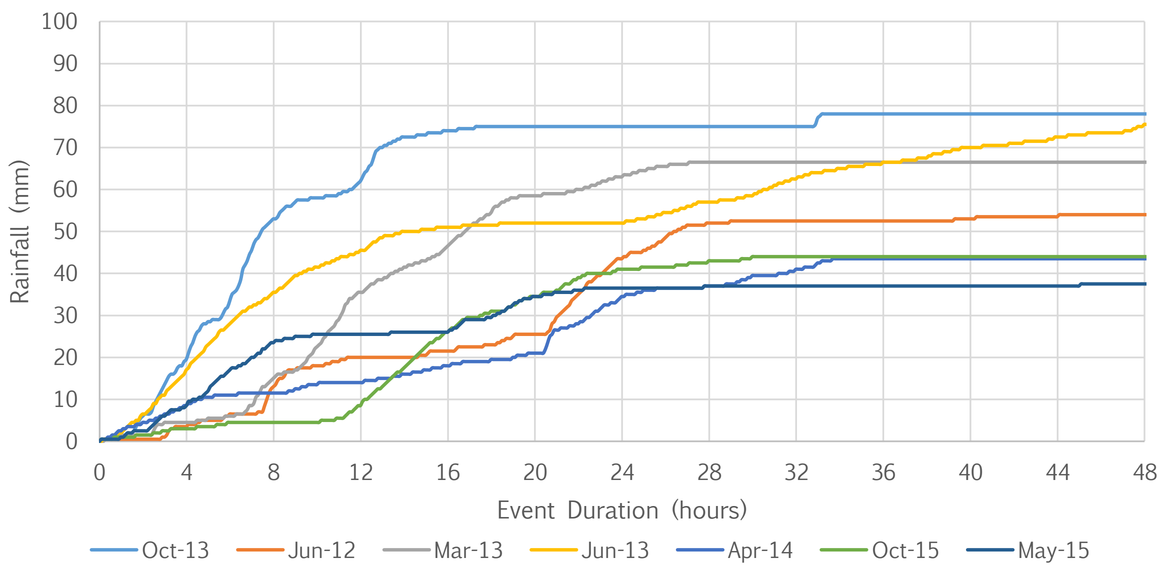


Figure 5.36: High resolution (5-min totals) cumulative rainfall plots for the seven largest rainfall events recorded at Lake Wairarapa at the eastern shoreline

5.12.2 Regional climate

Large scale climate signals have been proven to modulate New Zealand's rainfall and surface (Mullan *et. al.,* 2001). This is not an issue when analysing long-term records that include a number of oscillations e.g. positive and negative phases of the IPO, or El Niño and La Niña phases of ENSO The effects of both phases of the oscillation will be inherent in the record, and their effects will therefore be identifiable in the results of any rainfall analysis. Since the climate data collected and analysed deals with long term trends, any signal needs to be identified. When assessing trends in climate variables a 30-year period is generally recommended.

The use of shorter periods of record can result in added uncertainty that is greater than the actual observed climate trends (Thevenard, 2010).

To identify whether these oscillations are reflected in the rainfall records of the lower valley, rainfall records over 30 years in length in the lower valley were collected and analysed (Figure 5.37 and Figure 5.38).

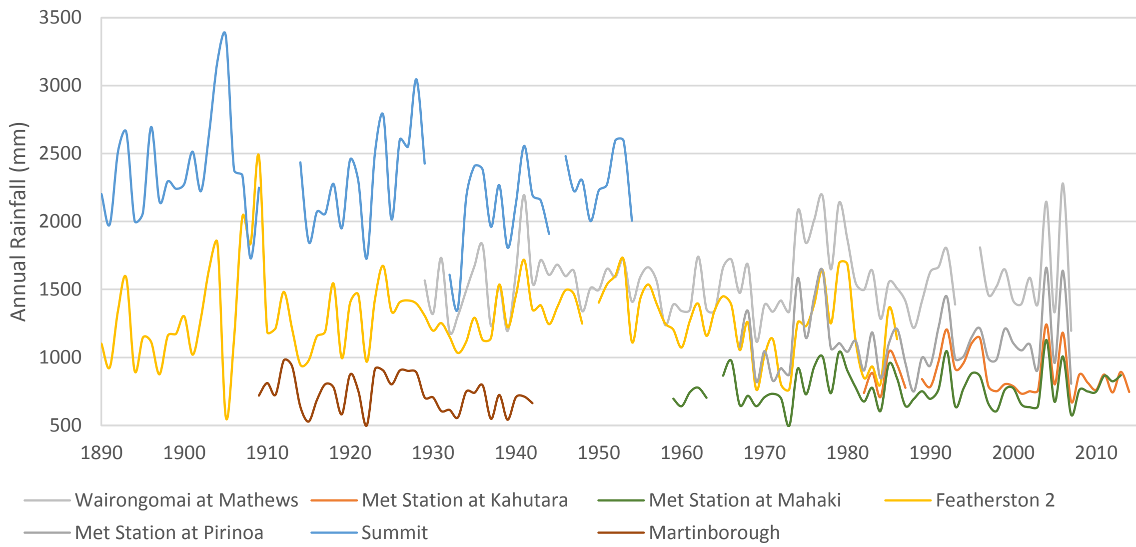


Figure 5.37: Annual rainfall totals for selected long term rain gauges in the lower Wairarapa valley

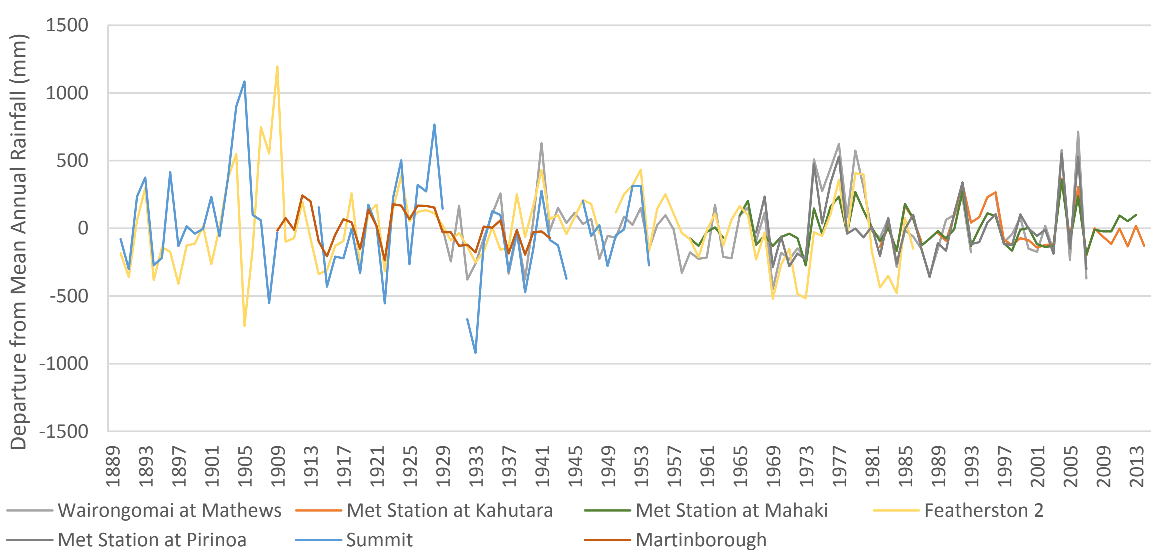


Figure 5.38: Departure from long term annual means for lower Wairarapa valley

5.12.3 Localised rainfall

The most spatially suitable rainfall gauge for rainfall over the study site is a GWRC operated OTA tipping bucket gauge on the eastern shoreline of Lake Wairarapa. Records began only in 2014, consequently this has been nested within another record to determine how it sat within the climate of the Wairarapa.

Rainfall data was therefore obtained from the meteorological station at the eastern shoreline and a rainfall station at Kahutara, operated by NIWA, and located only 6km from the eastern shore gauge. While this station is no longer operating, its relatively long record (34 years) should allow for robust estimates of the likely variability in rainfall both seasonally and annually on the lakes eastern shoreline.

24-hour rainfall totals over a concurrent period of record were correlated (30 March 2012 to 01 July 2015). A strong correlation (r^2 0.75) exists between the two records (some variation can be attributed to the timing) (Figure 5.39). The rainfall record at Katutura was therefore scaled to create a synthetic record for the meteorological station at eastern lake shore over a 34 year period (Figure 5.40).

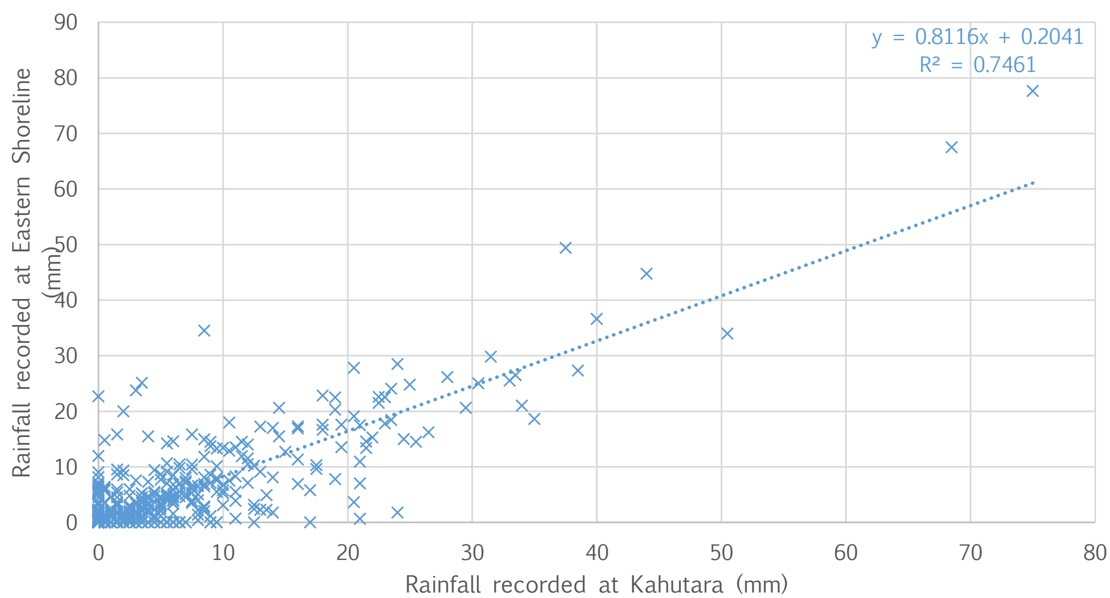


Figure 5.39: Correlation over concurrent period of record, Kahutara and eastern lakeshore 1 Oct 1981-1 July 2015

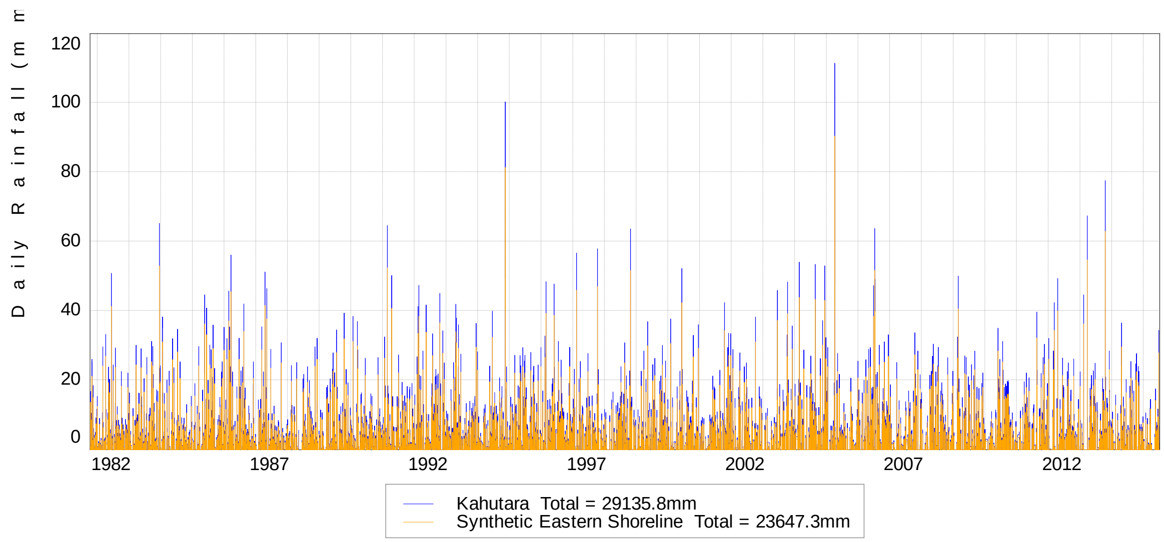


Figure 5.40: Synthetic rainfall record derived for Met Site at eastern shoreline from Kahutara rainfall record 1 Oct 1981-1 July 2015

5.12.4 Grounding

The synthetic dataset for Kahutara was used to assess annual and seasonal variations in rainfall over its period of record. Mean annual rainfall for the 2013 year was 791mm, 16% less than the mean rainfall over the 1986-2005 climate period. This however was not seasonally consistent (Figure 5.42). Annual mean rainfall over these periods are presented in

Table 5.19. Therefore, adjustment of the rainfall for the 2013 year will need to be considered when grounding the wetland response to climate, monthly adjustments are presented in Table 5.20:

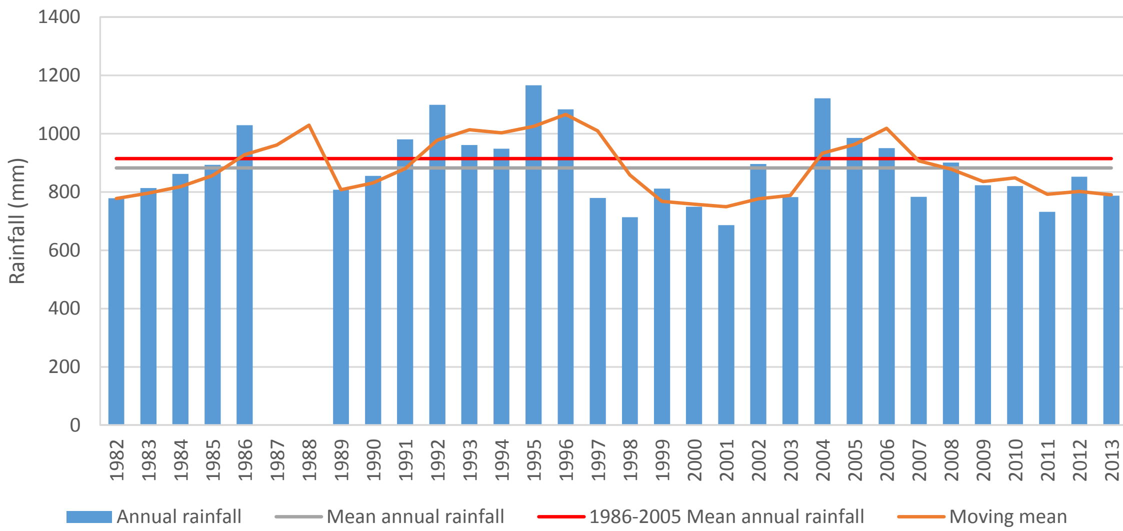


Figure 5.41: Annual rainfall, and mean annual rainfall at Kahutara

Table 5.19 Annual rainfalls over the 32 year rainfall record at Kahutara

	2013 annual rainfall (mm)	Annual mean rainfall (mm)	1986-2005 annual mean rainfall (mm)	Adjustment (%)
Kathutara synthetic record	791	882	915	16

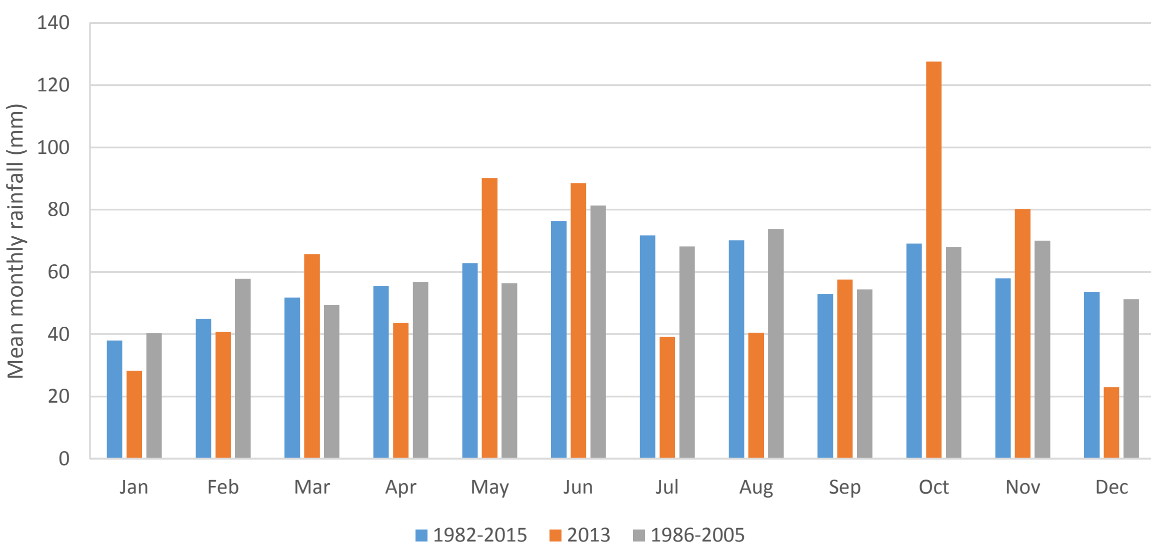


Figure 5.42: Mean monthly rainfalls at Kahutara - Note: The lower than average rainfalls in January and February attributed to the 2012-2013 drought

Table 5.20: Seasonal adjustment table for rainfall record at Kahutara

Month	Monthly mean rainfall (mm)			
	1982-2015	2013	1986-2005	Adjustment
Jan	38	28.25	40.3	1.43
Feb	44.96	40.82	57.85	1.42
Mar	51.83	65.66	49.36	0.75
Apr	55.56	43.66	56.73	1.30
May	62.79	90.18	56.39	0.63
Jun	76.36	88.55	81.38	0.92
Jul	71.73	39.2	68.24	1.74
Aug	70.16	40.5	73.78	1.82
Sep	52.92	57.55	54.41	0.95
Oct	69.1	127.58	67.97	0.53
Nov	57.95	80.19	70.05	0.87
Dec	53.57	22.97	51.21	2.23

5.12.5 Rainfall adjustment for climate change

A methodology had been developed for determining the projected increase in rainfall as a result of climate change in New Zealand (MfEa, 2016). This method recommends a geographically orientated seasonal adjustment (%) to rainfalls for both 2031-2050 and 2081-2100. MfEc (2016) have provided seasonal adjustments for two locations in the Wellington Region, Masterton and Paraparaumu. Adjustments for Masterton are the closest available for the lower Wairarapa Valley.

Mean, minimum and maximum seasonal adjustments to rainfall, proposed by MfEa (2016) can be found in Table 5.21. The initial value represents the predicted average increase in rainfall (as a %) over all models nested within each RCP. The values in the brackets represent the 5th and 95th percentile over all models within each RCP. The inherent error associated with these percentage adjustments is significant, (i.e. 55% for RCP 6.0, out to 2090).

Table 5.21: Seasonal adjustments made to the rainfall in Masterton

Season	Rainfall adjustment % (Masterton)			
	Spring	Summer	Autumn	Winter
2040				
RCP 8.5	-1 (-8,8)	0 (-12,7)	-1 (-8, 8)	-2 (-11,6)
RCP 6.0	0 (-7,10)	3 (-8,18)	2 (-12,10)	0 (-5, 8)
RCP 4.5	1 (-6,10)	1 (-8,13)	-1 (-8, 9)	-1 (-10,10)
RCP 2.6	0 (-7,9)	2 (-6,10)	0 (-6, 9)	0 (-8, 6)
2090				
RCP 8.5	-3 (-18,10)	8 (-4,28)	3 (-10, 12)	-7 (-24,5)
RCP 6.0	-1 (-23,11)	2 (-39,16)	0 (-30,8)	-4 (-31,12)
RCP 4.5	0 (-7,7)	3 (-8,13)	1 (-9, 10)	-2 (-14,8)
RCP 2.6	2 (-5,9)	-1 (-11,8)	1 (-6, 11)	1 (-5, 8)

Note these data have been taken from Table 10 and table 11 in MfE, 2016.

The closest regional setting to the lower valley are adjustments based at Masterton. A brief comparison of rainfall from both locations identify that while Masterton often receives more rainfall than Lake Wairarapa (a Mean Annual Rainfall (MAR) of 979mm and 875mm, respectively (Figure 5.43)), since 2012, rainfall has been fairly similar, both in depth and its temporal distribution (Figure 5.44). However, rainfall adjustments based at this location are grounded in the 1986-2005 period where a greater variation in annual rainfall is observed (Figure 5.43).

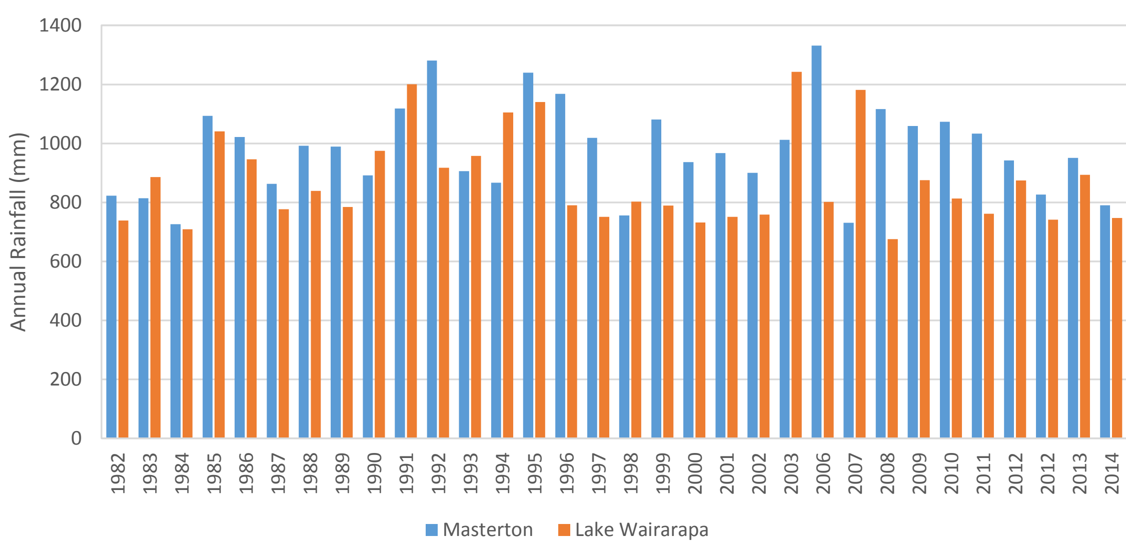


Figure 5.43: Annual mean rainfall at Masterton and Lake Wairarapa

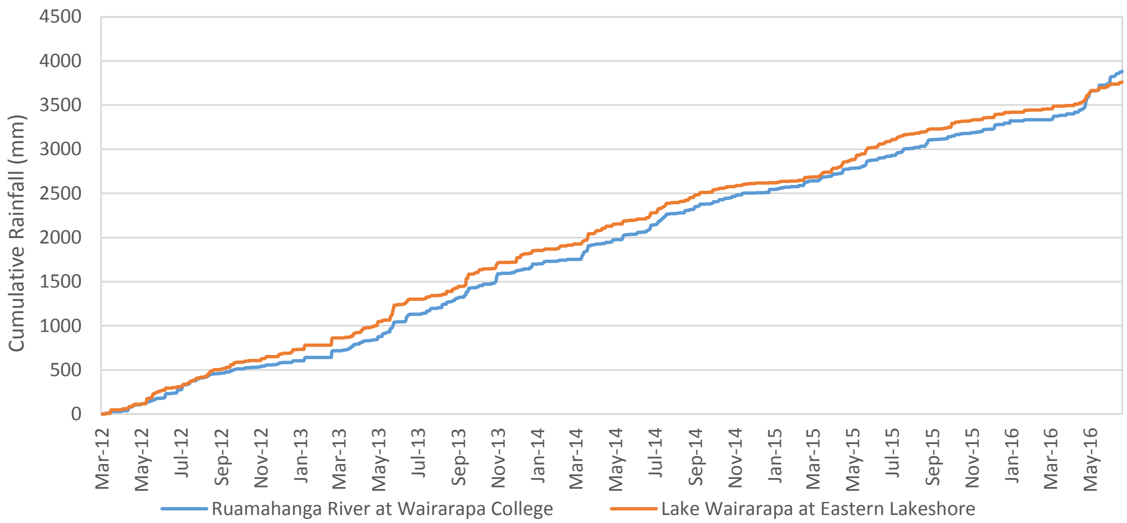


Figure 5.44: Cumulative rainfall recorded at Lake Wairarapa and Masterton 2012-2016

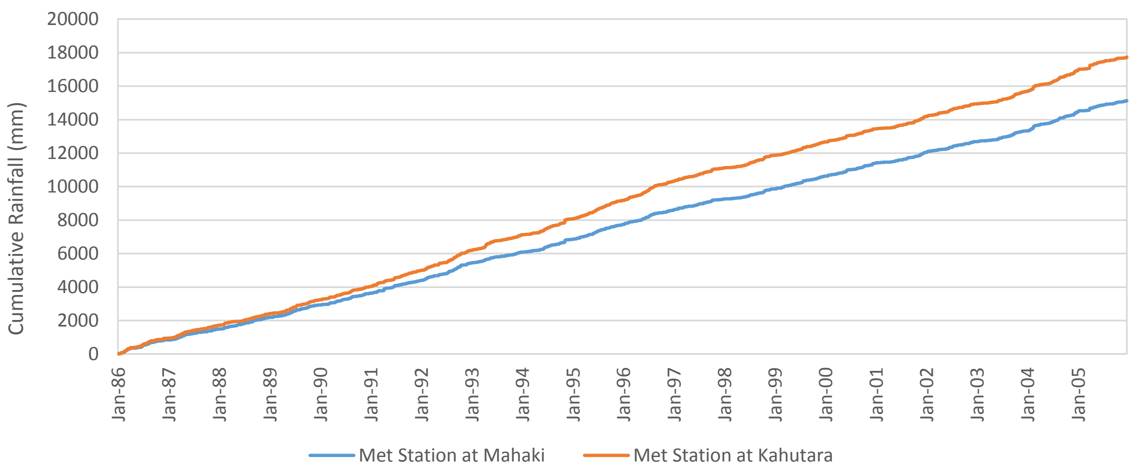


Figure 5.45: Rainfall at Masterton (Mahaki) and Lake Wairarapa 1986-2005 period

5.12.6 High intensity rainfall events

Low frequency, high intensity rainfall events are predicted to increase with climate change (as a function of the Clausius-Clapeyron equation (Figure 5.36). This increase in precipitation is going to come at the expense of more frequent, shorter duration events (Trenberth, 2011).

A methodology was developed in 2010 by MfE to account for the increases in intensity of rainfall events of different frequencies, intensities and durations. This methodology recommended a percentage adjustment per degree of warming that should be applied to the rainfall totals of varying return periods (Table 5.22). While this methodology was based off downscaled climate models from the IPCC 4th assessment report, adjustments are based off predicted temperature increases, and therefore can be applied to the more recent temperature predictions released by MfEa (2016).

Table 5.22: Factor of percentage adjustment per 1ºC to apply to extreme rainfall (from MfE, 2010 Table 1)

Duration	2	5	10	20	50	100
24 hours	4.3	5.4	6.3	7.2	8.0	8.0

Note: these data are from Tables 1 in Ministry for the Environment (2010).

This method does not help to identify how the frequency of large or small rainfall events may change, but does allow for the adjustment of volumes based off existing records.

Design rainfall events are derived from a frequency analysis of rainfall data at Kahutara. This record allows for reasonably robust estimates of rainfall intensities out to 70 years (twice the length of record). While it is not the longest record in the lower valley, (a record exists at Wairongomai spanning 1929-2008) it is the most spatially representative (Figure 5.35).

Frequency analyses were undertaken on the annual rainfall maxima of 24 hour duration events (Section 5.12.1) derived from the entire length of rainfall record. Three types of statistical distributions were assessed to determine how well they model the actual annual rainfall maxima and flow series (i.e. Gumbel, Pearson 3 (PE3) and Generalised Extreme Value distribution GEV). The distribution which provided the best fit to the annual maxima series (in this case PE3) was be used to estimate the annual exceedance probabilities (i.e. AEPs) or average recurrence intervals (i.e. ARIs) of each design rainfall.

In accordance with standard practice, the frequency analyses was performed on a 12-month partition. That is, only the largest rainfall event of each duration in each year was plotted, and the most appropriate statistical distribution fitted to those annual values. It is sometimes difficult to find a single statistical distribution that provides a 'perfect' model of the annual maxima series. In these situations some subjectivity is required in selecting the more appropriate model. The criteria adopted in this study involved the balancing of:

- The distribution that provided the best-fit through all the data points;
- The distribution with the most realistic shape; and
- The distribution that provided the closest approximation to the extreme values.

While this process may appear subjective, in most cases the choice of a specific statistical distribution for the annual maxima series results in only relatively minor differences in the estimated frequencies. Results of this frequency analysis were adjusted for climate change based off the annual mean temperature increase projected for Masterton presented in Table 5.12 and Table 5.13, and the percentage adjustments detailed in Table 5.22.

5.13 Drought

A critical aspect of this study is the likely increase in drought. Since the dominant source of water into Mathews Lagoon is pumped water from the Te Hopai drainage network, present and future irrigation practises within this basin need to be considered. The duration of time spent in drought, and the relationship between this and the occurrence of pumping of the drainage network will be highly relevant to this study.

Government agencies identify drought as a significant problem for New Zealand's economy (MfEb, 2016). Increases in drought are a function of increases in evapotranspiration, driven by temperature, and a decrease in rainfall, which affects soil moisture and groundwater recharge. Predictions for the Wairarapa range from an increase of time spent in drought of 5-10% by 2050 (NIWA, 2015) to a doubling of time spent in drought by 2100 (NIWA, 2011).

Currently soil moisture data is collected at a number of stations around the lower Wairarapa valley, the most suitable are operated by NIWA at Kahutara and Martinborough EWS. Martinborough EWS climate station has a record of 16 years and measures soil moisture (%), while also calculating the soil moisture deficit from rainfall and Penman Potential Evapotranspiration (PET), Figure 5.46. The Kahutara record only provides the SMD, but has a record spanning 33 years Figure 5.47.

Two levels of drought classification are used by NIWA for soils, “severely dry” when the SMD is between -110 and -130mm, and “extremely dry” when the SMD drops below -130mm. The method used to assess when the critical drought period will finish in this study (discussed below) varies from the method employed by NIWA, however, the drought classification method provided by NIWA will be used to identify historic trends in drought, both annual and monthly.

While evapotranspiration and rainfall is not expected to vary considerably between these two sites, each are in markedly different soil classification areas, with different hydraulic properties (Table 5.23). Martinborough EWS is located on the Martinborough terrace (elevation 25m asl), while the Te Hopai basin is located in close proximity to Lake Wairarapa (elevation 6m asl). Soils at NIWA climate site are well drained with low available water and a high drought vulnerability, while soils at Te Hopai are poorly drained, with high levels of available water and low drought vulnerability. Furthermore the Te Hopai basin is extensively irrigated.

While this generates some constraints on the appropriateness of data collected, it does allow for some general interpretation of the drought period in the lower valley. Analysis of this data will therefore focus on data collected at Kahutara, as it most appropriately represents the soil type found around the wetlands being studied.

Table 5.23: Soil properties for Martinborough EWS and Te Hopai Basin

Parameter		Martinborough EWS	Kahutara	Te Hopai Basin
Elevation		25	12	6
Soil Classification		Fluvial Recent Soils	Recent Gley Soil	Recent Gley Soils
Parent Material		Alluvium	Alluvium	Alluvium
Texture profile		Sandy	Silty Loam	Loam Over Clay
Drainage Class		Well drained	Poorly drained	Poorly drained
Drought Vulnerability		High	Low	Low
Relative Runoff Potential		Very Low	Medium	Medium
Profile Available Water				
	0 - 100cm	Low (40 mm)	High (185 mm)	High (243 mm)
	0 - 60cm	Low (40 mm)	Very high (163 mm)	Very high (152 mm)
	0 - 30cm	Low (23 mm)	Very high (92 mm)	Very high (81 mm)

Data collected from S-map Soil Reports conducted by Landcare research – Appendix C.

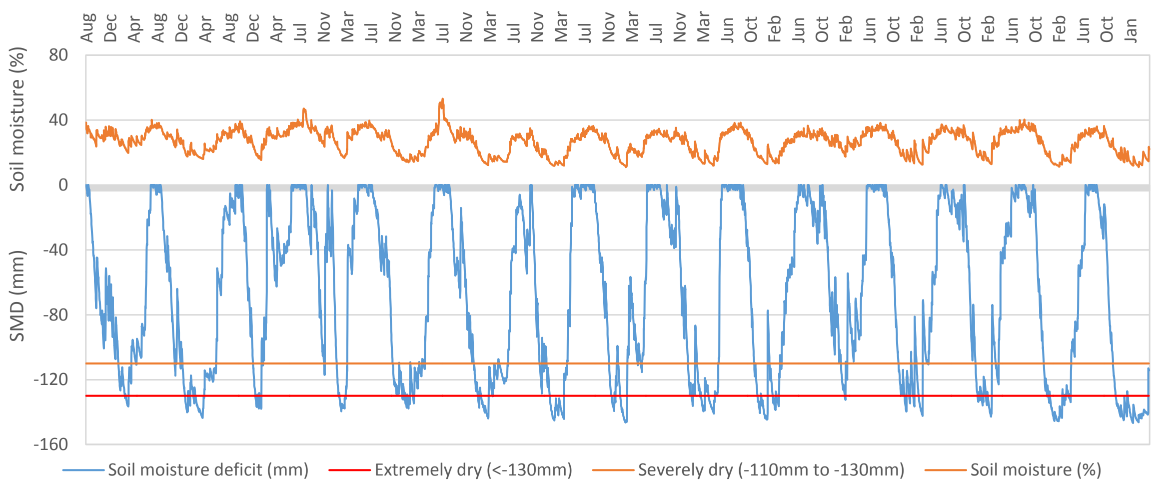


Figure 5.46: Soil moisture deficit and soil moisture % at Martinborough (2001-2016) (Cliflo 2016)

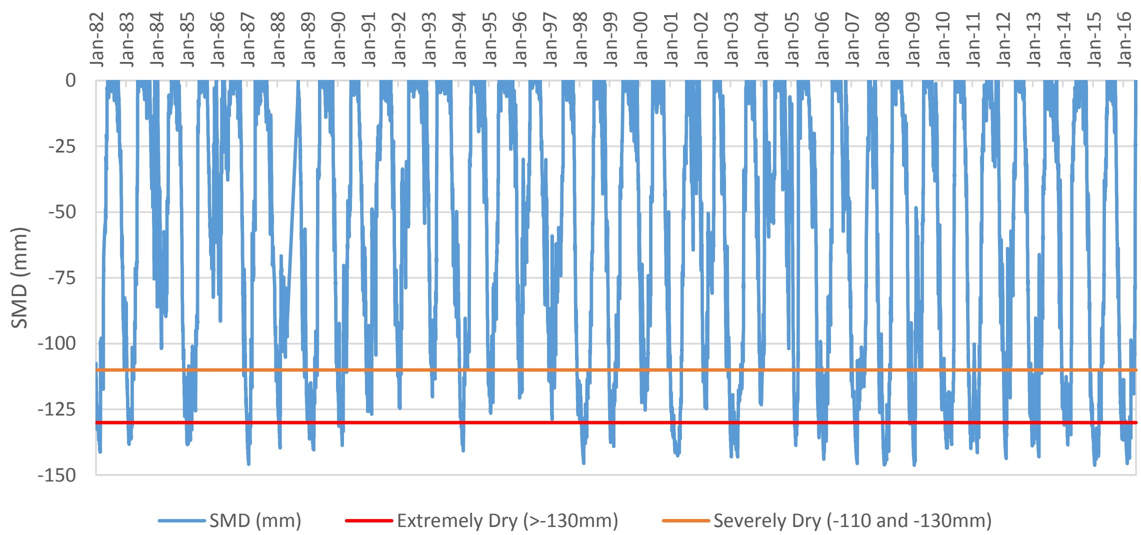


Figure 5.47: Soil Moisture Deficit recorded at Kahutara (1981-2014)

5.13.1 Drought sensitivity to climate change

To identify any potential changes in the drought period, brought about by MFE's projected changes in meteorological conditions, SMD simulations will be run for each evapotranspiration scenario run, relative to potential changes in rainfall.

Because we are dealing with a wet environment, and subsequently a shallow rooting depth, the 0-30cm PAW value of 81mm (identified in Table 5.23) will be used. for the simulation. However, each simulation will need to be "warmed up" to account for the likely deficit in soil moisture at the start of the year. The simulation will therefore be run over 365 days, with the initial SMD set at 0mm. The SMD at the end of the simulation (December 31st) will then be used as the starting SMD value for the actual simulation.

Because the simulations will be run with potential evaporation, it will be assumed that when the SMD reaches 50% of the soil's PAW (i.e. 40mm) actual evaporation will occur at 10% of PE to account for the stress placed on plants. Under this scenario, SMD peaks at 72% of PAW. This is considered suitable, as permanent wilting point will not likely be reached.

5.13.2 2012-2013 drought

It is important to note that the start of this study occurred on the back end of the 2012-2013 drought. This drought affected many regions throughout New Zealand, including the Wairarapa. The economic effect of the drought for New Zealand has been estimated at $1.3 billion (MPI, 2013). The drought was caused by a stationary high pressure system over the Tasman sea and was not attributed to climate change (Porteous & Mullan, 2013). Subsiquently, lower than average rainfall occurred from September to February. The effects were most pronounced in the Eastern hill country and Northern Wairarapa, however the soil moisture deficit in the lower Valley extended out longer than usual, peaking in mid March (Figure 5.48).

The implications for this, and potential relevance to the conclusions drawn from evapotranspiration, and pumping rates from the Te Hopai Basin will be discussed in the following section

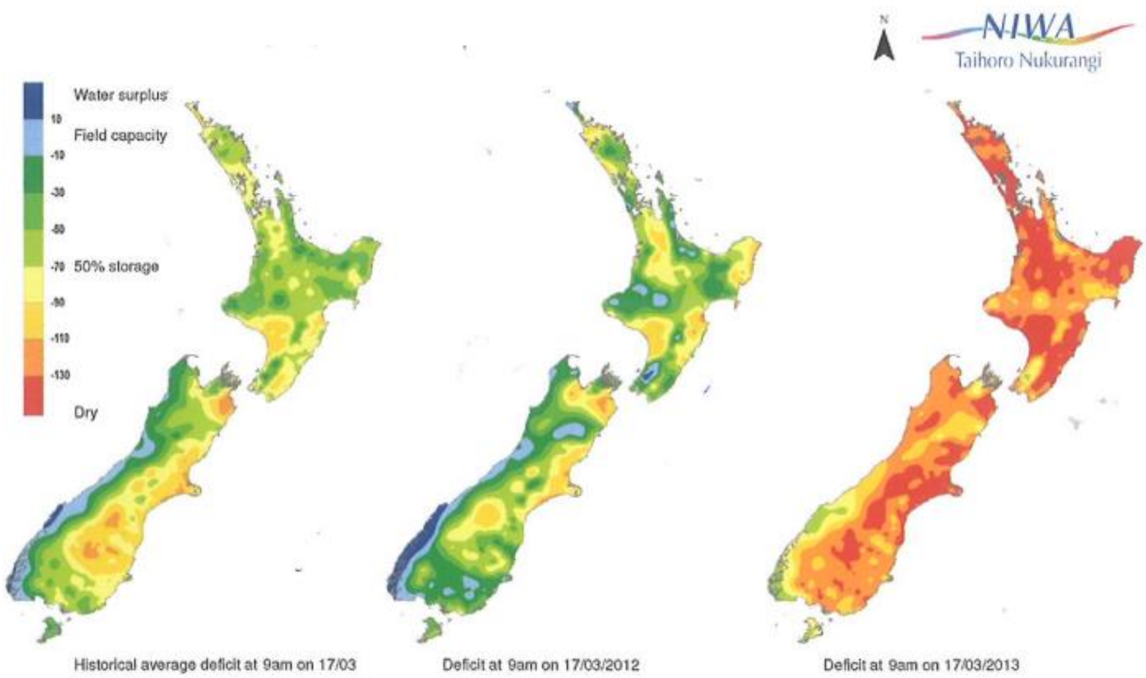


Figure 5.48: Soil moisture deficit (mm) at 9am on 17 March 2013 (NIWA, 2015b)

5.14 Flooding

While drought is identified as a significant issue for the lower valley, changes in the spatial and temporal distribution of rainfall are likely to disproportionately amplify rainfall in the Tararua and Rimutaka Ranges. This will have pronounced effects on flooding of the Tauherenikau and Ruamahanga Rivers, and, depending on the management of the lake, lead to more intensive inflows, and subsequently higher lake levels.

Currently, quantification of how changes in precipitation events will affect stream runoff, particularly flooding events, has not been conducted (MfE, 2010). In the absence of any detailed study, it is currently accepted that increases in rainfall will produce similar increases in runoff. While this is outside the scope of this study, a preliminary investigation, using the methodology used to adjust design rainfalls (detailed above in section 5.12.6) was applied directly to the flow series on the Taherinkau River at Gorge, which feeds the Lake Wairarapa directly (and has a flow series from 1977 to 2016), and the Ruamahanga River, at Waihenga Bridge (flow series from 1957-2016) (Figure 5.49 and Figure 5.50, respectively). This site is the furthest down river prior to the commencement of flood protection works and is therefore expected to have a natural record of peak flood events.

These records are also useful in determining how the climate of the Wairarapa region sits within a historical context. Flow records of long duration are useful in identifying climatic oscillations as larger rivers act to aggregate, what can often be highly variable rainfalls, over a larger area. This acts as a better proxy of climate than point rainfall.

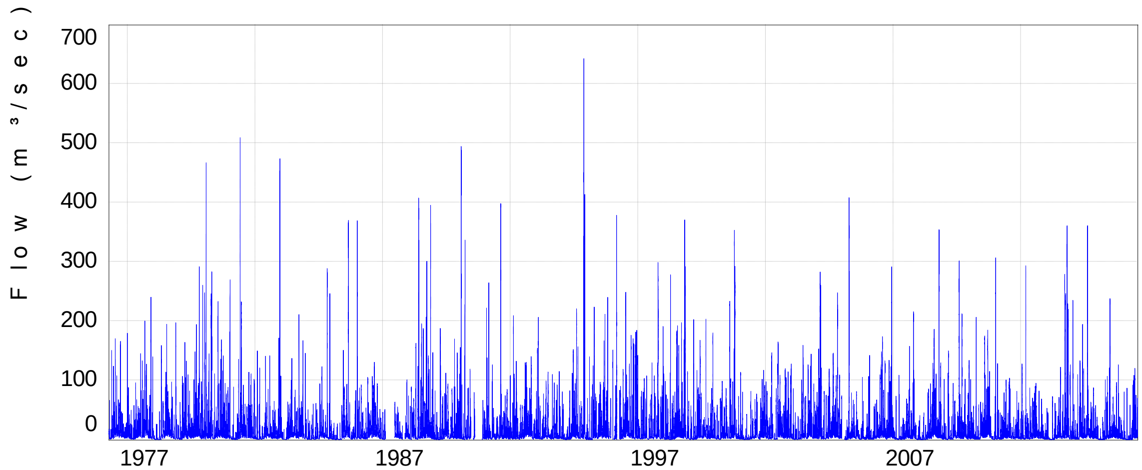


Figure 5.49: Instantaneous flow record at Tauherenikau at Gorge

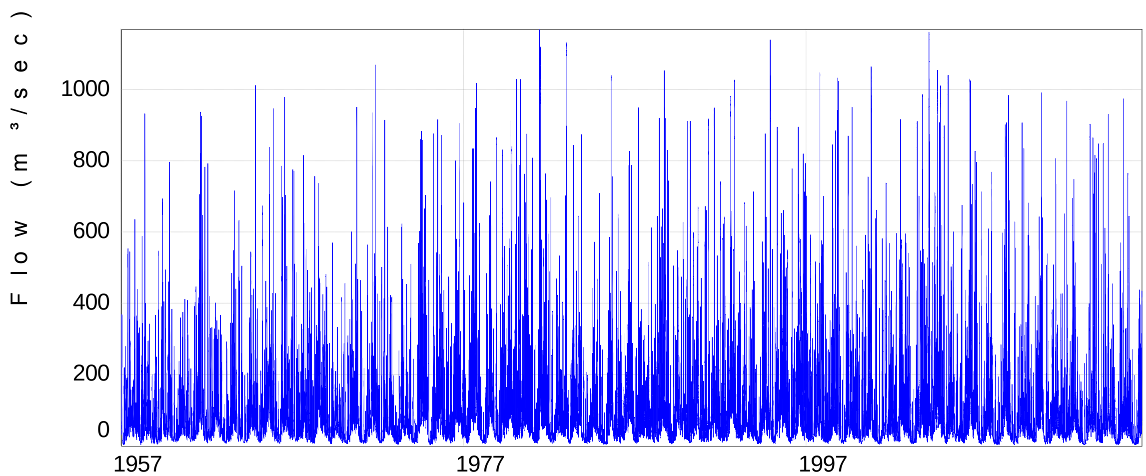


Figure 5.50: Instantaneous flow record at Ruamahanga at Waihenga Bridge

A frequency analysis was conducted on the Ruamahanga River. This river has an average flow 10 times that of the Tauherenikau River, and therefore considered more influential. Using the methodology described above, results indicate that MfE's 2016 regional temperature projections out to 2030-2050, would increase the 100-year ARI event from 1121m^3/s to between 1184m^3/s (RCP 2.6) and 1210m^3/s (RCP 8.5). Under the 2090 scenario the 100-year ARI peak flow would likely increase between 1184m^3/s (RCP 2.6) and 1390m^3/s (RCP 8.5). The largest event on record was 1172 m^3/s during May 1981. This caused significant flooding down the Ruamahanga River (Figure 5.52). The predicted increases in flow, under the worst case scenario are therefore 5% and 19% larger than current climate (2040, and 2090 respectively).

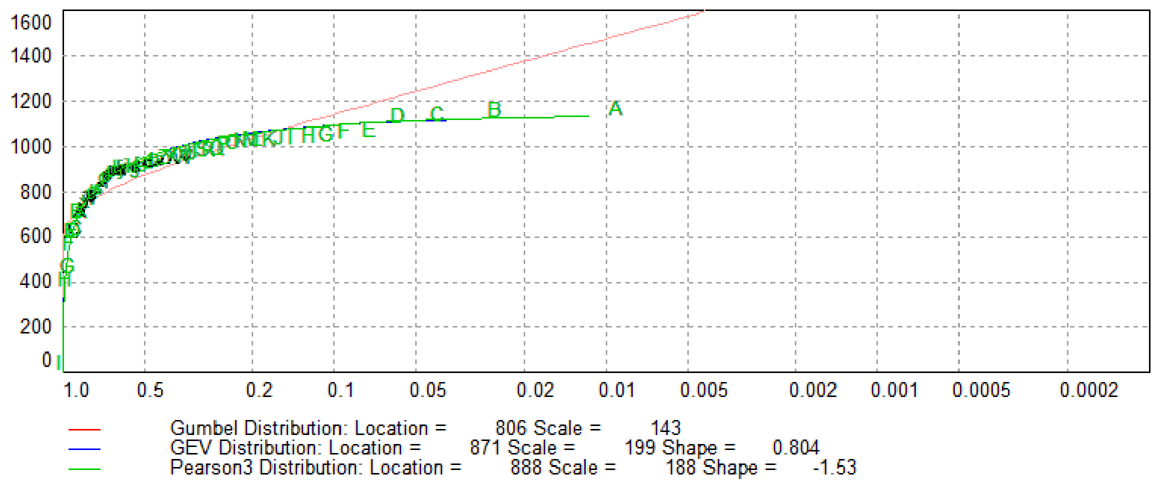


Figure 5.51: Frequency analysis on the Ruamahanga River instantaneous flow series

Figure 5.52: Flooding in the Ruamahanga River, May 1978, Sourced from Schrader, (2016)

Plots of the mean annual flow recorded in the Ruamahanga and Tauherenikau Rivers are presented in Figure 5.53. These identify that likely climate of the Ruamahanga Valley during the study period was similar to that of the climate used by MfEc (2016) to base its climate predictions off.

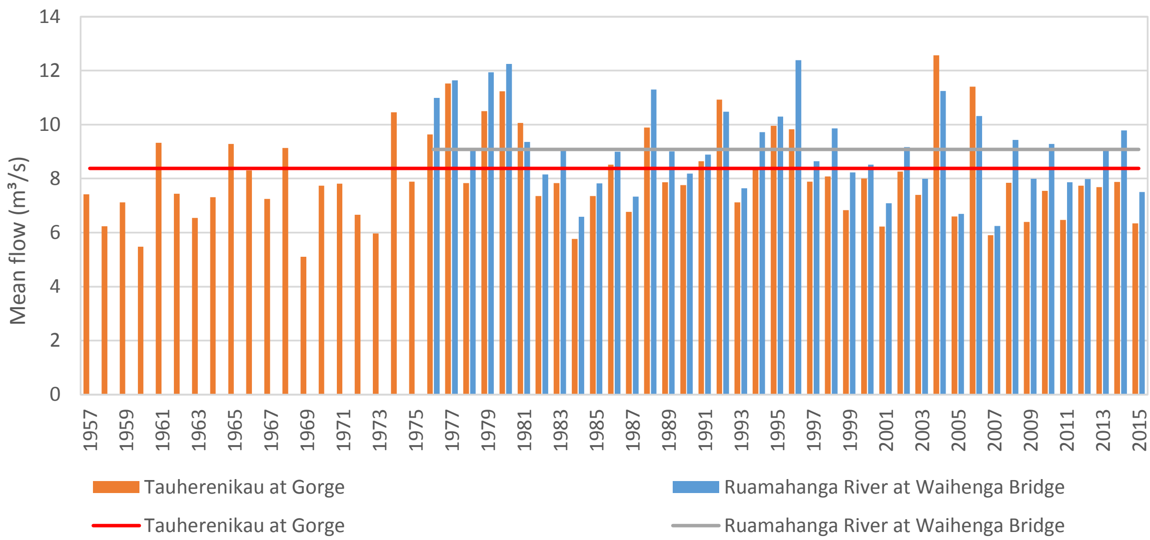


Figure 5.53: Mean annual flow at the Ruamahanga River at Waihenga Bridge and Tauherenikau River at Gorge (^10)

6 Results and Discussion

6.1 Wetland hydrology

Before any analysis on the potential effects of climate change on each wetland can be conducted, the hydrological inputs into each wetland need to be identified.

While data were collected at a 15-min resolution, most of the analysis focused on the daily average water level in each wetland. This allowed for a direct comparison and analysis with water levels, rainfall, pumping, and evapotranspiration (calculated at a daily resolution). Where appropriate (i.e. the assessment of diurnal fluctuations in water level), analysis was conducted on the raw, higher resolution data.

Plots of daily average water level, rainfall, pumping and potential evapotranspiration over the period water level data exists (25 Jun 2013 – 03 Sep 2014) are presented in Figure 6.1 and Figure 6.2. General observations, that will be addressed in more detail in the following section include:

- The water level in Mathews Lagoon is highly responsive to pumping from the Te Hopai Pump drain. Daily variations in pumping translate into noticeable variations in water level. It should be noted that the week prior to the commencement of the water level record, 112mm of rainfall was recorded over three days at the eastern lakeshore. This came on the back of a further 58mm of rain two days earlier. This translated into significant pumping, and is reflected by the high water level in Mathews Lagoon at the start of the record.
- The water level recorded in Mathews Lagoon becomes more stable when pumping is not occurring.

- A strong relationship between rainfall events and increases in pumping into Mathews Lagoon exists. No significant pumping occurred from mid-January to mid-March
- Boggy Pond has a more stable water level than the other two wetlands. While it exhibits a similar trend in a falling water level from November to February, its range is not as extreme. Boggy Pond's responsiveness to rainfall is more subdued than Wairio Stage 1.
- A diurnal fluctuation is present throughout the entire water level record at Boggy Pond.
- Wairio Stage 1 demonstrates a consistent drop in water level over periods of no rainfall, and is highly responsive to precipitation events.
- The water level in Wairio Stage 1 dropped below the water level sensor between 25 February and 16 April 2014.

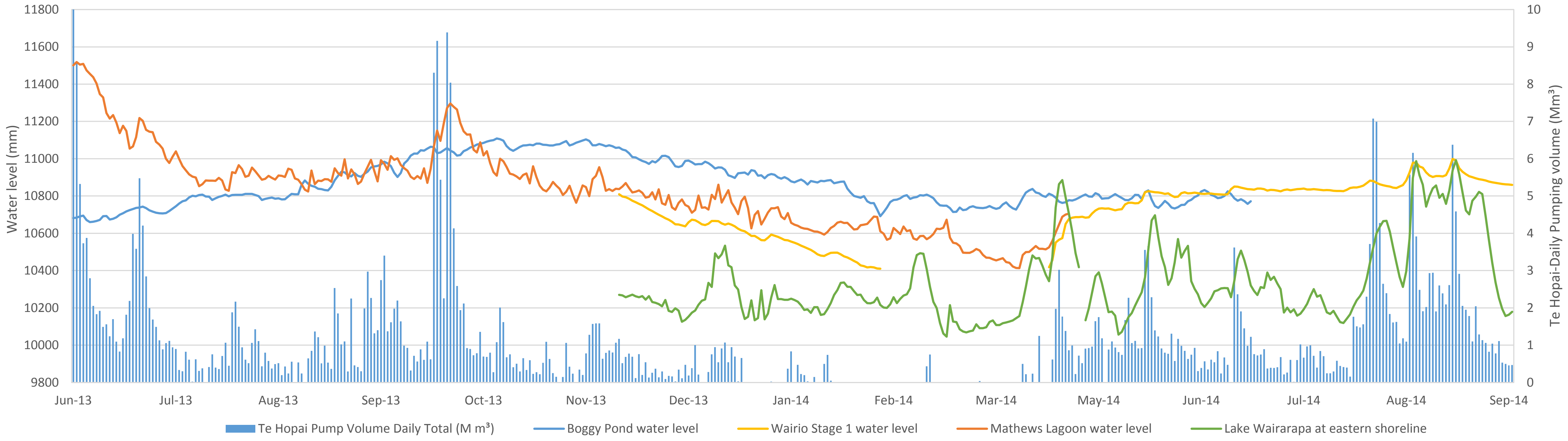


Figure 6.1: Daily average water levels for Boggy Pond, Mathews Lagoon, and Wairio Stage 1 and daily pumped volume from the Te Hopai Pump drainage scheme

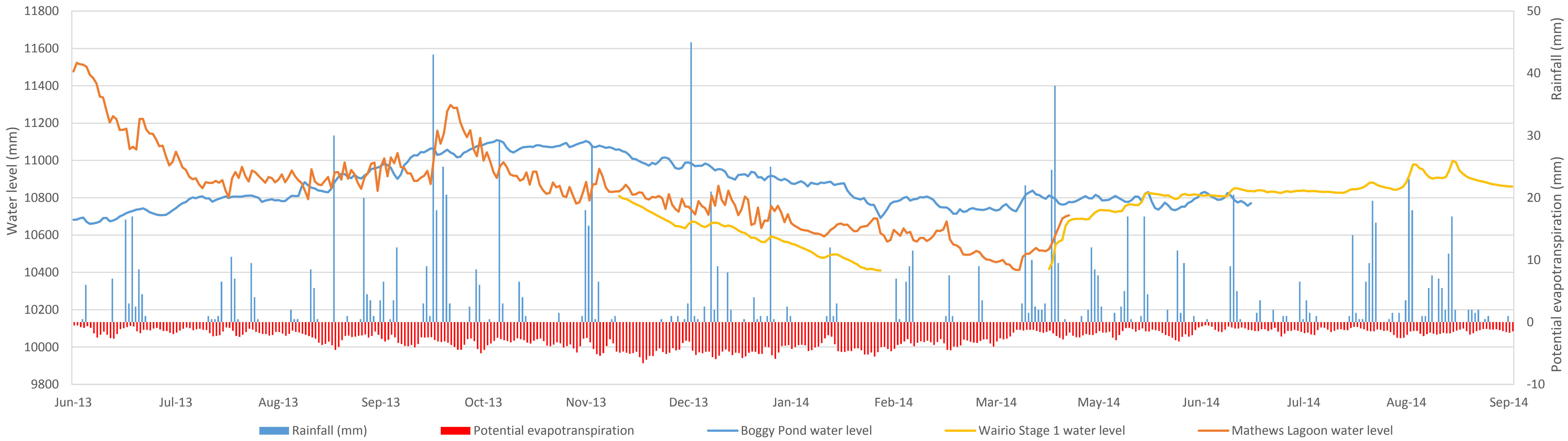


Figure 6.2: Daily average water levels for Boggy Pond, Mathews Lagoon, and Wairio Stage 1, potential evapotranspiration and rainfall

6.1.1 Mathews Lagoon

Water levels in Mathews Lagoon demonstrate a strong seasonal relationship which reflects water availability and evapotranspiration. Water levels throughout the record peaked at a Relative Level[3] RL of 11544mm, and dropped to 10417mm on 10 March 2014 (Table 6.1). The subsequent range in water levels recorded at this wetland (1127mm) is the greatest of all three wetlands.

Water levels exhibit a strong seasonal trend, remaining above RL 18000mm through until mid-December, at which point reductions in pumping and rainfall and increases in evapotranspiration culminate in a decline in water level averaging 2.3mm per day (Figure 6.3).

The highly variable nature of water level in this wetland is a result of pumping from the Te Hopai Pump Drain, and the presence of a surface water outflow point at the northern end of the pond. While the largest pumping event (25 June 2013) appeared to occur just prior to the installation of level sensors, its relative influence on water level cannot be determined as the initial level was not known. The second largest pumping event occurred between 12 and 20 October (an event total of 51.2, 000m³), and generated an increase in water level of 425mm. When pumping does not occur (i.e. between 10 Feb and 9 March 2014) the average weekly variability within the water level record drops from 59.9mm to 36.2mm.

This pumping is the dominant hydrological input into the wetland. Over the period June 2013-June 2014 water level data was available, indicating a combined total of 345,000m³ of water was pumped from the Te Hopai pump drainage scheme, which services an area of 1778ha, (6.6 times larger than the wetland itself) into this wetland. Over this period, 1146mm of rainfall was recorded at the eastern shoreline with pumping occurring 347 of the 427 days within the series (81% of the time). The rate of pumping exhibited significant

[3] Relative to the GWRC Datum

monthly variability, with pumping over the February and March period being 1.6% of what was pumped in October.

Table 6.1: Summary statistics for the water level record at Mathews Lagoon (mm)

	Min	Max	Range	Mean	Std Dev	L.Q.	Median	L.Q.
Water level	10417	11544	1127	10932	179	1082	10895	10990

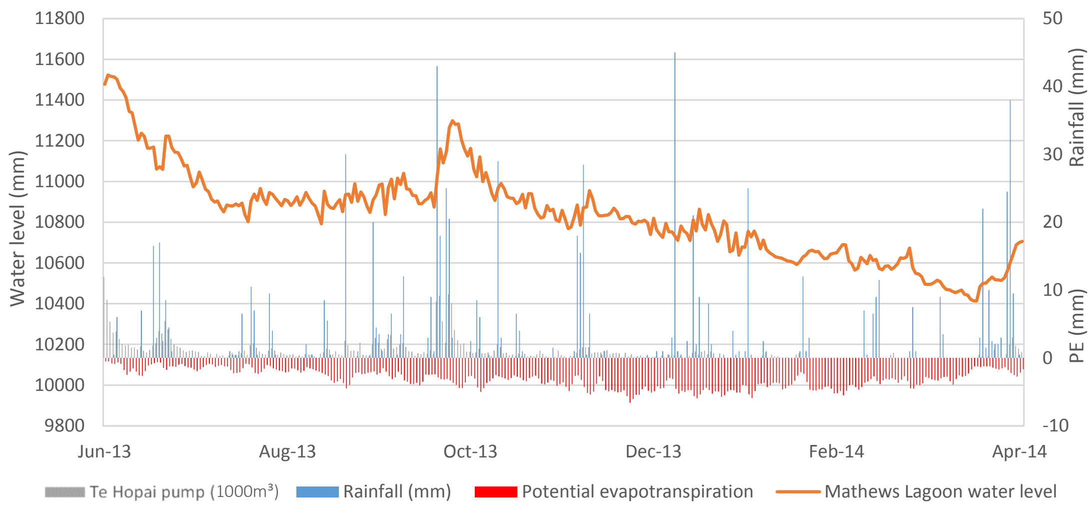


Figure 6.3: Water level fluctuations at Mathews Lagoon and dominant hydrological controls

Pumping in the 2013-2014 period was 42% greater (201,000m³) than what occurred in the following year. Seasonal rates of pumping were similar, with little to no pumping occurring over Jan-Mar (Figure 6.4). This difference in annual volume is reflected in the total rainfall that fell over each representative period. The annual rainfall for the 2013-2014 period was 1005mm, compared with 777mm, in the 2014-2015 period (23% less).

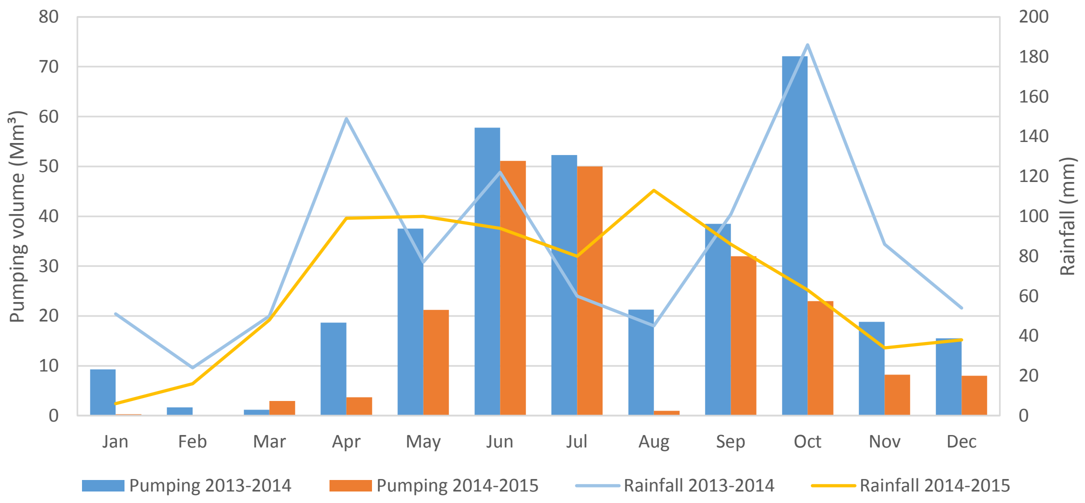


Figure 6.4: Relationship between pumping volume and rainfall at Te Hopai Basin

Pumping of the Te Hopai drainage network is driven by rainfall. A strong relationship exists between both the occurrence and the magnitude of pumping events and the duration and total volume in which pumping occurs in the available data (Figure 6.5). The frequency and magnitude of rainfall events in the lower valley is therefore significant.

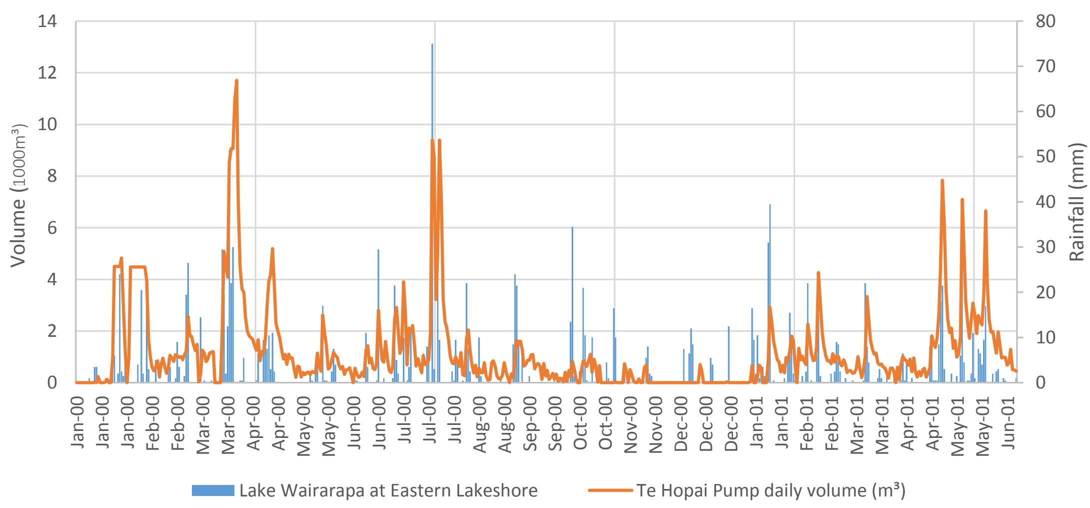


Figure 6.5: Relationship between pumping of the Te Hopai Basin and Rainfall

Comparative analysis of relative changes in water level in Mathews Lagoon and relative changes in available groundwater information identified no statistically significant relationship (the strongest relationship present is with groundwater bore BQ33 0013, with an $r^2 = 0.16$) (Figure 6.6). However the lack of relationship could be due to the frequency at which relative changes in level were assessed (daily) (Figure 6.7). Pressure responses through the bed of the wetlands with the groundwater system are likely to be moderated and attenuated to some degree. Bore results (discussed in Section 5.5) indicate a shallow clay pan exists in the area, and this could act as a confining aquitard between the wetland and deeper groundwater system.

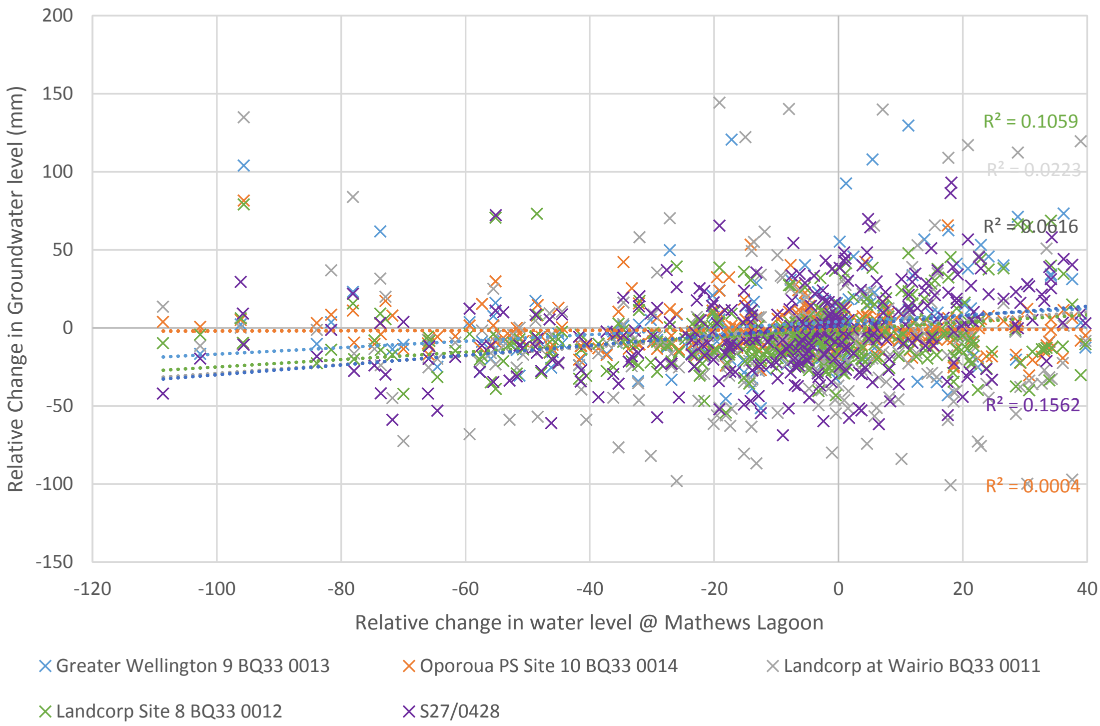


Figure 6.6: Correlation between relative changes in groundwater level and relative changes in water level at Mathews Lagoon

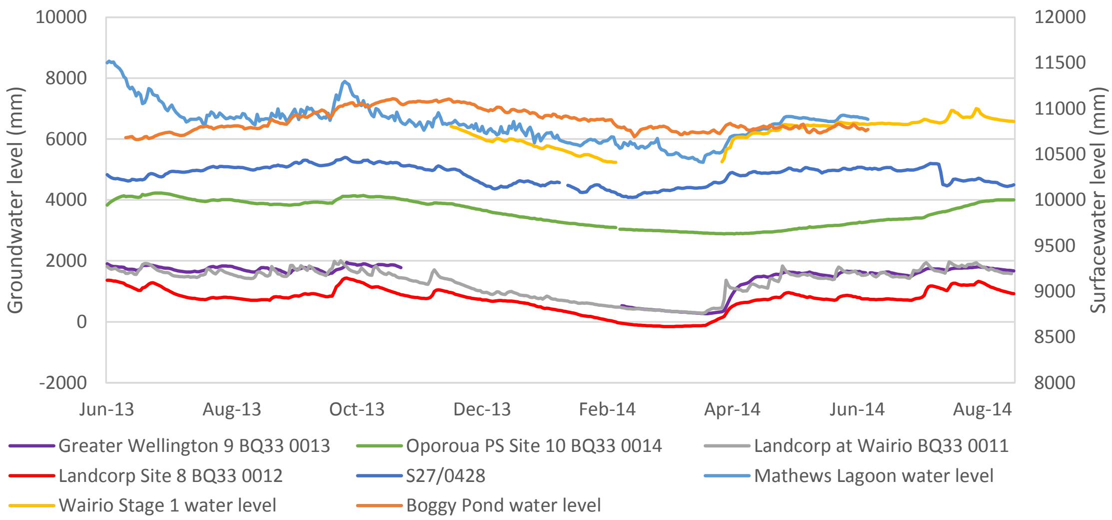


Figure 6.7: Daily comparisons between surface water and groundwater in selected bores around the wetland

Analysis of the raw water level record does indicate that a sustained input of shallow groundwater is present (Figure 6.8). Due to the level of noise present in the data, a range of moving averages were applied to the data to smooth the series (Figure 6.9). A three hour moving average was deemed most suitable at removing this noise while retaining the amplitude of daily oscillations.

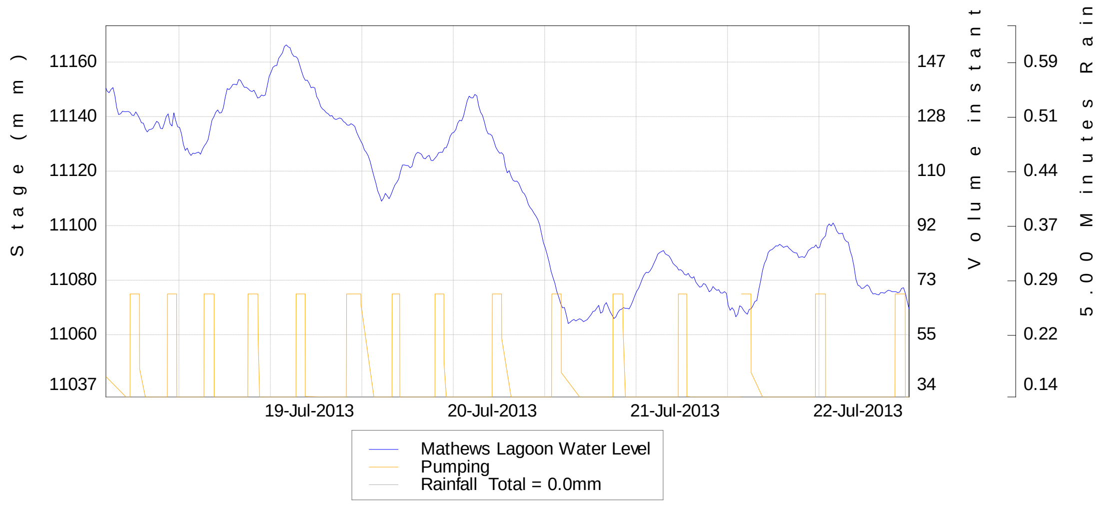


Figure 6.8: Water level fluctuation present in Mathews Lagoon relative to pumping

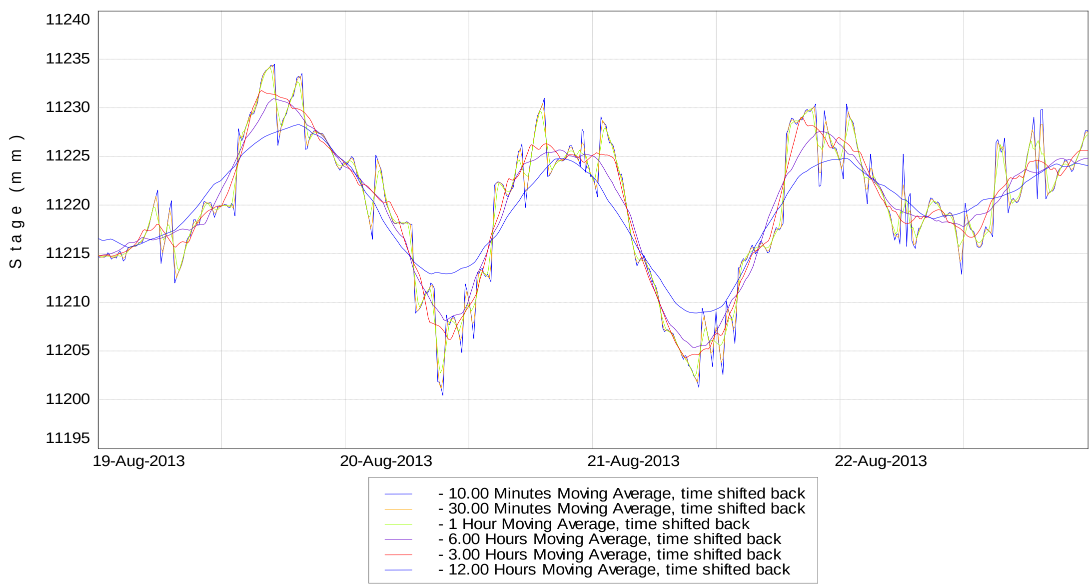


Figure 6.9: Influence of different moving means on water level oscillations at Mathews Lagoon

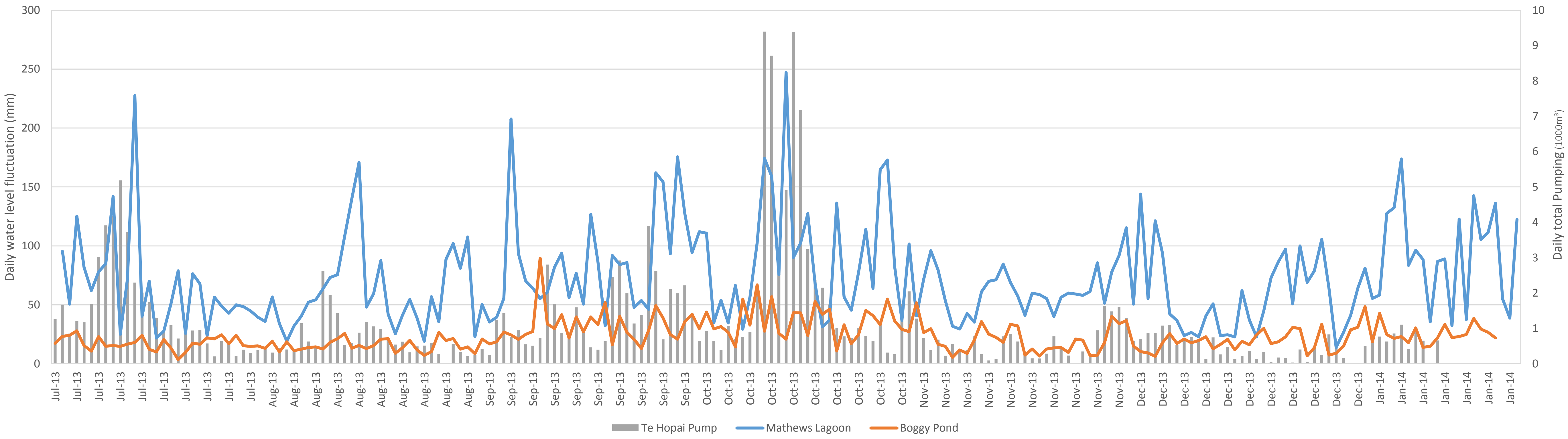


Figure 6.10: Relative change in water level for Mathews Lagoon and Boggy Pond relative to pumping from the Te Hopai Pump Scheme

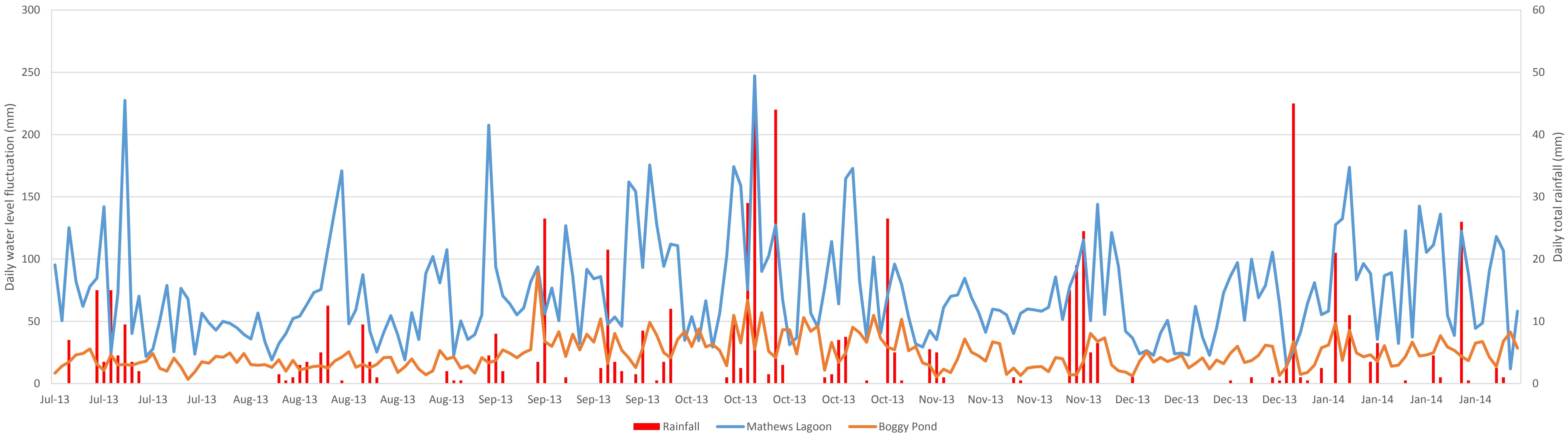


Figure 6.11: Relative change in water level for Mathews Lagoon and Boggy Pond relative to rainfall recorded at the lake's eastern shoreline

This groundwater signal is not obviously present in the data when pumping or rainfall occurs, however over summer (when no inputs are present) daily fluctuations in water level are observed. This indicates that significant evaporation is occurring, during this period, but recharge process are also present. The magnitude of these fluctuations are similar to those found in Boggy Pond (discussed in the following section).

Diurnal fluctuations in water levels in wetlands can be attributed to a number of variables, (eg. tides, groundwater fluctuations as a result of vegetation uptake, or pumping). In temperate climates and heavily vegetated areas (such as wetlands). This fluctuation is directly due to evapotranspiration, or an evapotranspiration-induced fluctuation in shallow groundwater. This may be driven by evaporation processes beyond the wetland margin, up-gradient of the groundwater contour. It is also possible that in the local area pumping of the shallow groundwater system for domestic water supply occurs. Six groundwater bores tapping shallow groundwater (<10m), registered with GWRC, are present up-gradient of these wetlands. Analysis of pumping could not be conducted as information on pumping rates was not available.

Outflows from this wetland are regulated through a culvert at the northern end of the wetland. Two control gates, located on the Oporua Spillway side of Parera Road, are controlled by a pressure relationship between the water levels in Mathews Lagoon and Lake Wairarapa. Depending on the lake level, higher water levels in Mathews Lagoon will flow out at a faster rate than when the water level is low.

This non-linear relationship between flow and variable water levels at both end of the culvert flow has been a significant constraint in the derivation of a reliable outflow series from this wetland. The resulting effect of this control can be observed in the water level record, where the rate of decline in water level is much greater (~28mm/day) when water levels are high in Mathews Lagoon (over

RL 10800mm), than when water levels are lower (~8mm/day below RL 10600mm). At present, sufficient information does not exist to quantify this regulation. This has been identified as an area of future work.

The use of daily average water levels has been appropriate in analysis of the increase and decrease in water levels in Mathews Lagoon relative to pumping rates, rainfall and evapotranspiration. However, the observed diurnal signal in the water level record required analysis at a higher frequency.

Within his study of nutrient regimes in Mathews Lagoon, Shi (2014) hypothesised that flows may prefer a path around the edge of the wetland, where a formed channel along the common stop bank exists. Subsequent inputs up to a certain volume, depending on the initial water level, may travel via this flow path before becoming a signal in the main water body where the water level sensor was placed. The general responsiveness of water level recorded, to pumping events does not support this theory (Figure 6.10), as high resolution responses in water level were comparatively similar in their response, over a range of pumping volumes.

Issues with Q.A of the data collected by Shi (2014) also places constraints on more detailed analysis of water level fluctuations. Water level sensors were installed inside a slotted pvc pipe but were not secured in place. This left them dangled in the water column. Movement of the pipe with wind, expansion and contraction of the string as a result of temperature, saturation and fatigue, and the inability to return the sensor to the same level following periodic data retrieval has led to significant noise within the data set, however, some of this noise is filtered out over both the 3hour moving average used for analysis of the diurnal fluctuations and the mean daily lake level used for the daily analysis.

6.1.2 Boggy Pond

Boggy Pond is situated next to Mathews Lagoon and is separated by a common stop bank. Anecdotal evidence suggests that very limited flow (a trickle can be heard) occurs between the two wetlands through the old culvert, despite the attempt to seal it in 1989.

The water level record for Boggy Pond demonstrates a far more stable hydrology than Mathews Lagoon and Wairio Stage 1. The total variation in water level observed over the 2013-2014 period is 477mm (Table 6.2).

Table 6.2: Summary statistics for the water level record at Boggy Pond (mm)

	Min	Max	Range	Mean	Std Dev	L.Q.	Median	L.Q.
Water level	10645	11121	477	10867	123.4	107756	10816	10972

Boggy Pond experiences a similar trend in water level decline to Mathews Lagoon over the November to March period, however this decline does not begin until the start of November (a decline in water level appears to start in October at Mathews Lagoon). No surface water outflow exists from this wetland and therefore the only possible loss of water is through evapotranspiration or groundwater seepage. However, because the wetlands water level rises through periods of no rainfall, losses to groundwater cannot be overly substantial. Therefore, evaporation is the control on the loss of water from this wetland. Evaporation begins to be have a dominant control on water level from November, when the daily average rate of evaporation exceeds 3.5mm/day (Figure 6.2).

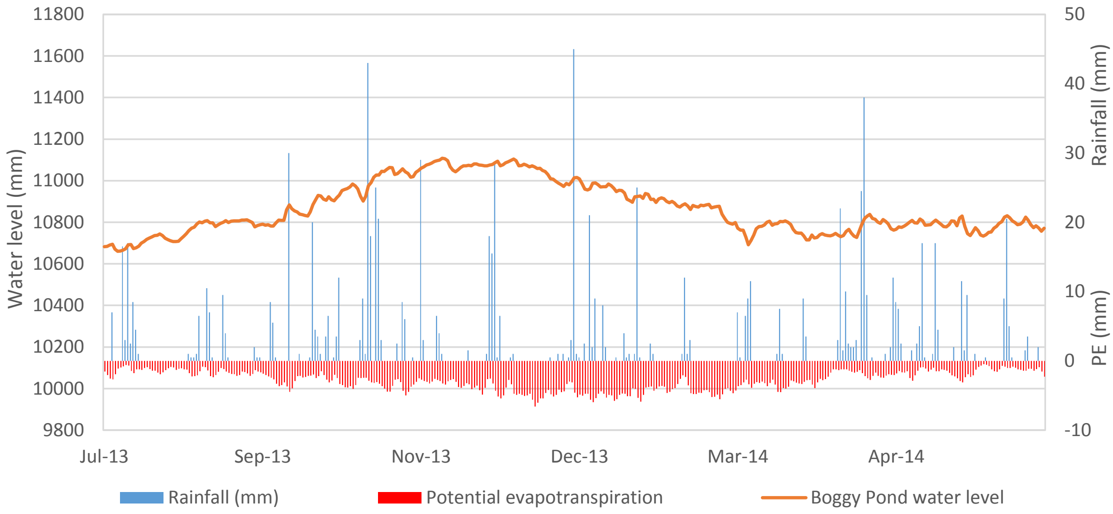


Figure 6.12: Water level fluctuations at Boggy Pond and dominant hydrological controls

Interestingly, periods of rainfall do not produce significant signatures in the water level record. This differs from both Wairio Stage 1 and Mathews Lagoon where rainfall events have a pronounced influence on water level. This lack of signature is due to the wetlands bathymetry and wetland structure. Boggy Pond consists of a large, well connected network of shallow ponds, pools, vegetated marshes, and swamps. Subsequently, rainfall inputs into the system become subdued as water fills, replenishes and moves through this shallow, connected system.

The stability of this wetland, and its continued increase in water level over periods of no rainfall indicate that there must be a continued input of water more substantial than what may enter the system through the old culvert. Correlations between relative daily changes in water level at Boggy Pond, and the five groundwater bores in close proximity identified no significant correlation with groundwater (the strongest being an R^2 of 0.2 at S27/0428).

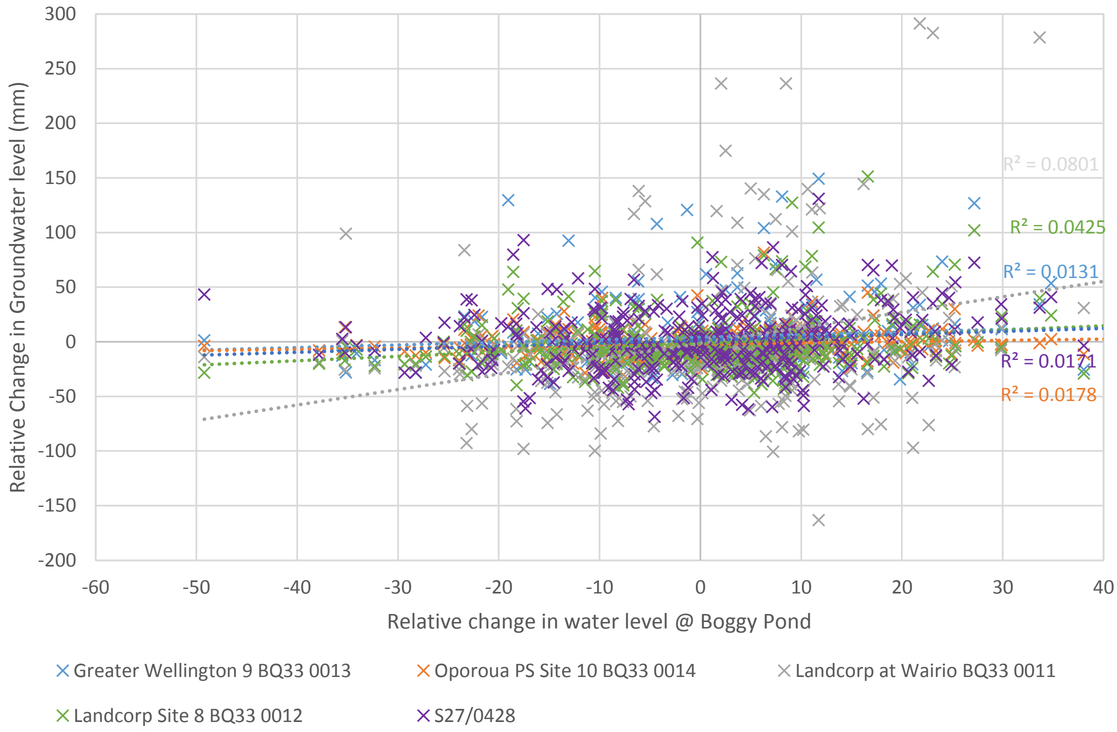


Figure 6.13: Correlation between relative changes in groundwater level and relative changes in water level at Boggy Pond

As with Mathews Lagoon analysis of the raw water level record for Boggy Pond at a finer resolution does show a diurnal fluctuation in the wetlands water level. This signature is present through the entire period of record and isn't subdued by rainfall. The steady nature of this daily oscillation in water level corresponds with the theoretical daily uptake of water from plants, peaking around midday, when the solar radiation intensity is highest (Figure 6.14). This fluctuation is more pronounced during summer than over the winter period. This supports the hypothesis that it is a result of evapotranspiration. The largest variation that occurs in the record is ~50mm over March. Over the winter months, this oscillation is much smaller, ~20mm. The persistent nature of this indicates a steady input of groundwater, either from lateral groundwater movement from the East, or from a deeper, artesian spring. Artesian springs are known to exist in Lake Wairarapa (Perrie & Milne, 2012), and some bores surrounding the wetland, (with depths ranging from 5-30m) rely on artesian pressure for stock consumption and domestic water supply.

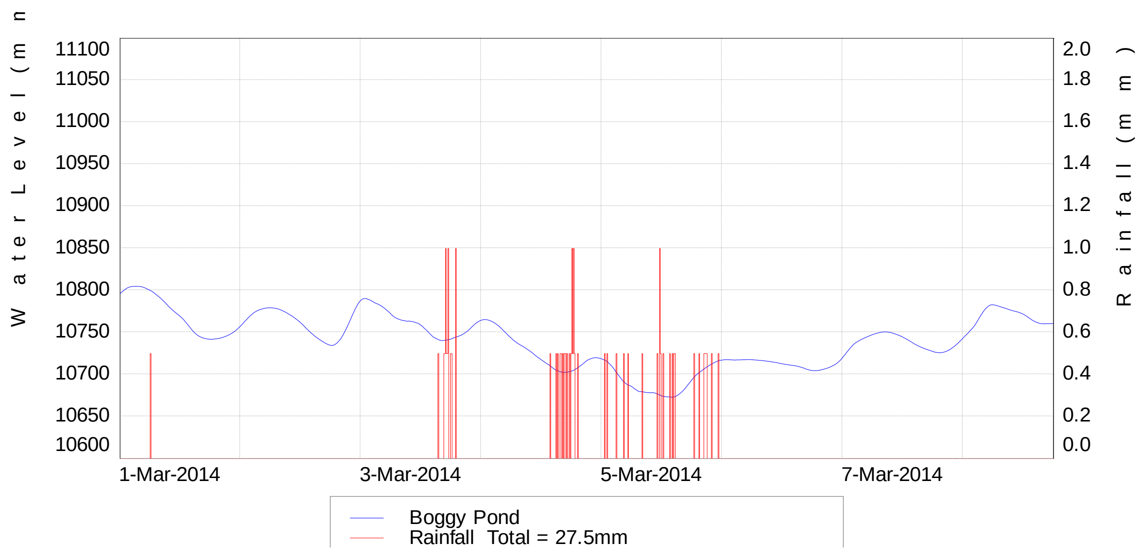


Figure 6.14: Diurnal fluctuation in water level observed at Boggy Pond

It was considered that this sustained input may instead, be a result of a pressure relationship between Boggy Pond and water levels in Mathews Lagoon, attenuated or moderated through the stop bank or through the subsurface. Analysis of the daily difference in maximum and minimum water levels, over days where no rainfall occurred yielded poor relationships with a range of possible controls (Figure 6.15 to Figure 6.18). Comparison between the amplitude of the fluctuation and mean water level in Boggy Pond itself, yielded an r^2 of 0.001, while comparisons with water level in Mathews Lagoon, mean daily PE, and pumping into Mathews Lagoon produced relationships of, 0.001, 0.05, and 0.07, respectively.

This does not suggest no relationship exists between either of these variables, it just identifies that the attenuation and moderation of the source behind this input is not identifiable at a comparative daily resolution. it is likely that the source of this oscillation is driven by shallow groundwater (the top few metres). This in turn may be responsive to evapotranspiration from the surrounding land and, potentially lake level fluctuations. This has been identified an avenue for future research.

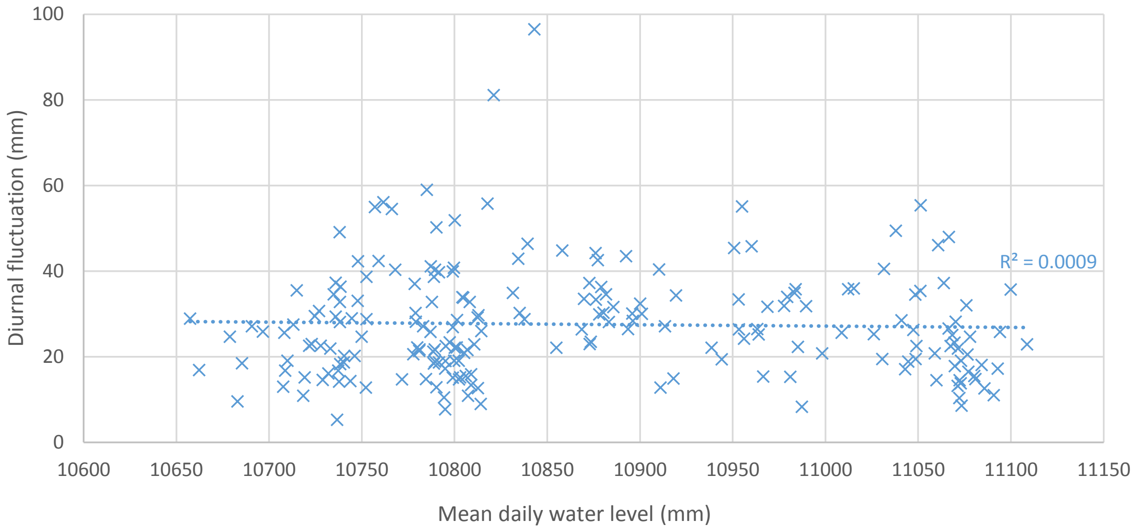


Figure 6.15: Relationship between diurnal fluctuation and mean water level in Boggy Pond

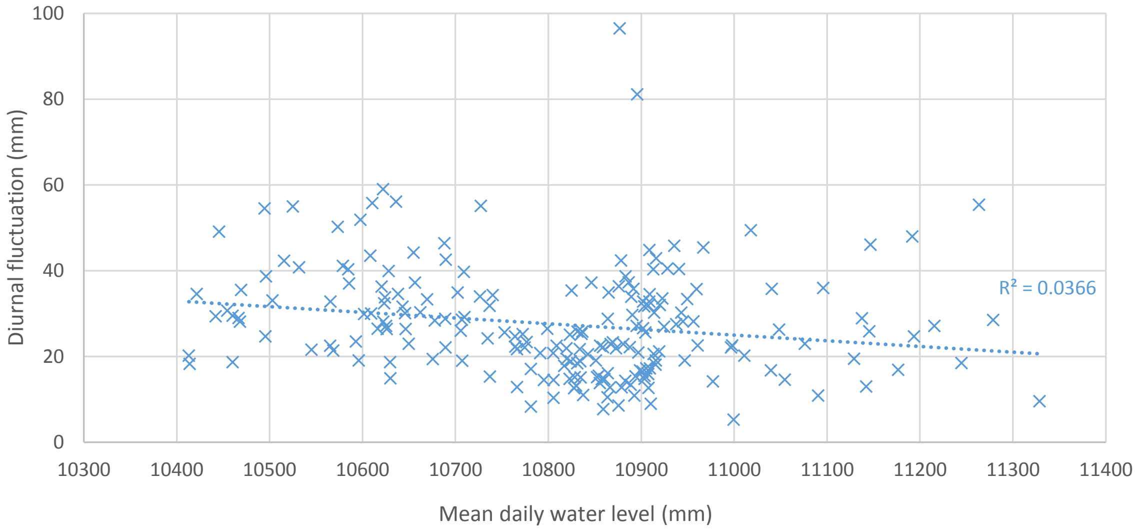


Figure 6.16: Relationship between diurnal fluctuation and mean water level in Mathews Lagoon

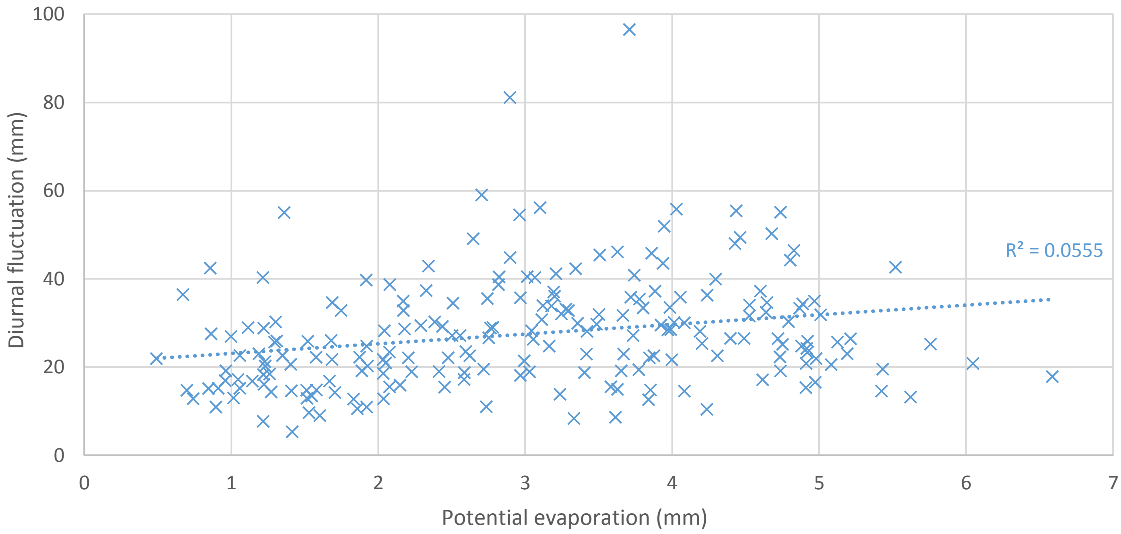


Figure 6.17: Relationship between diurnal fluctuation and potential evaporation

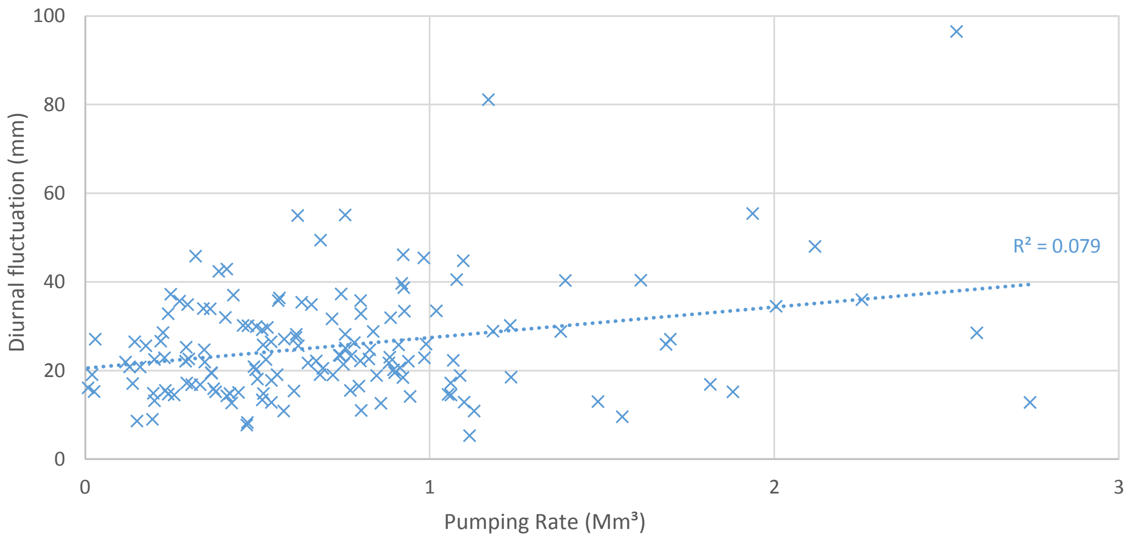


Figure 6.18: Relationship between diurnal fluctuation and potential evaporation

6.1.3 Wairio Stage 1

Wairio Stage 1 exhibits a markedly different hydrology to both Mathews Lagoon and Boggy Pond. It is important to note that this wetland was artificially created in the summer of 2012/13 to provide open water habitat for waterfowl. Historically this area was a Kahikatea marsh/swamp forest (and therefore may not be suitable for the permanent presence of water, now that lake levels are extensively managed.

The rate of decline in this wetland's water level over summer demonstrates that if any input from groundwater does occur, it does not occur at a rate that can keep up with evapotranspiration. Subsequently, over the summer of 2013-2014 water levels fell below the water level sensor (RL 10388mm) for a period of 50 days. During this time, this wetland became dry, which was confirmed by a site visit on the 16th March (Figure 6.19).

Figure 6.19: The exposed water level recorder in Wairio Stage 1, 16-March 2014

Table 6.3: Summary statistics for the water level record at Wairio Stage 1

	Min	Max	Range	Mean	Std Dev	L.Q.	Median	L.Q.
Water level (mm)	10388	10844	455	10599	159	10410	10624	10752

The range in water levels at this wetland (605mm) (a recorded level change on 455mm + 150mm between the sensor and the wetland bed) is greater than that of Boggy Pond but more subdued than Mathews Lagoon (Figure 6.20). This is reflective of its bathymetry, rainfall into the system does not "spill out" over an area until it reaches an RL 10800mm where water backs up to the north in an area of low lying land.

Changes in the upper catchment areas of this wetland over the period of study have significantly influenced the hydrology of the system since water levels were recorded. Publically available satellite images identify that since construction in September 2014 the upper catchment area has been modified in a number of ways.

- A number of new stop banks have been constructed to pond water into larger areas in the north of this watershed
- An open channel to the lake once existed to provide an outlet for water entering the area from the north. This has been enclosed as part of the fore-mentioned stop banking work.

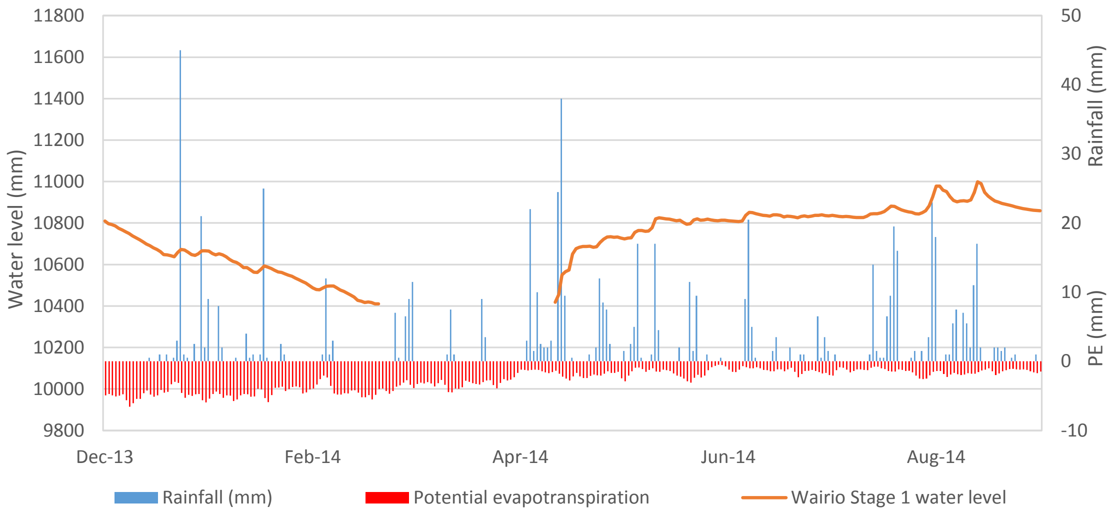


Figure 6.20: Water level fluctuations at Wairio Stage 1 and dominant hydrological controls

This wetland's water level is highly responsive to precipitation events. A correlation between relative changes in water level with rainfall depth identifies an r^2 of 0.4, (Figure 6.21). Considering the nature of the data, this is considered significant. The largest increase in water level was 95mm following 38mm of rainfall. Significant increase in water levels were recorded following rainfall of 72.5mm on the 17th and 18th of April, this raised the level of the wetland by a total of 258mm. The rate of increase in water level at this pond tapers off at ~RL 10800mm, where rainfall events of ~20mm lead to consistent increases in water level of ~40mm.

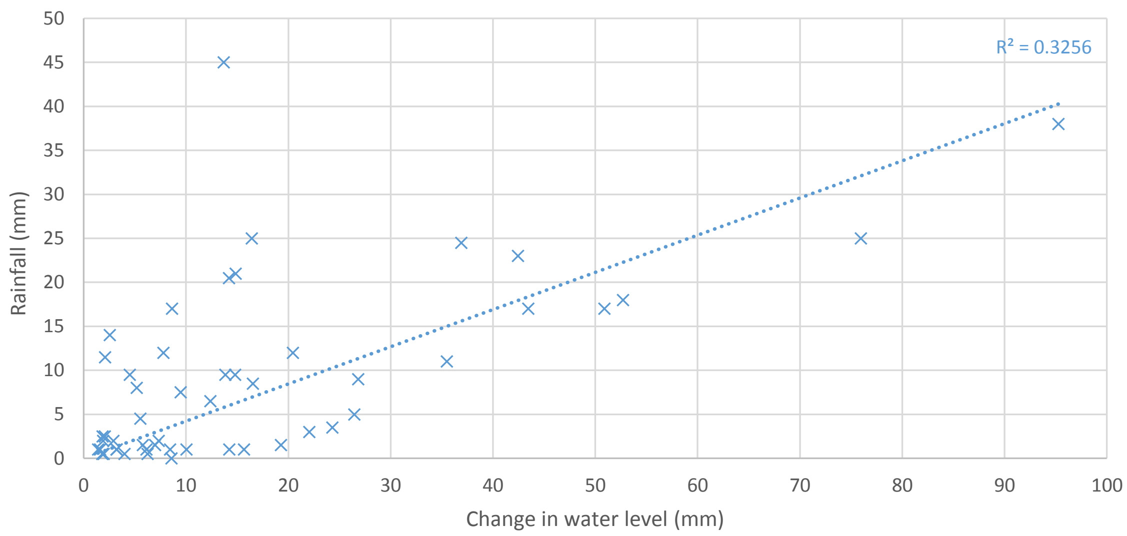


Figure 6.21: Relationship between rainfall and increases in water level at Wairio Stage 1. The change in water level is twice that of the rainfall. This is a result of the large catchment area (134ha) which services the relatively small wetland (4ha)

A spike in water levels in Wairio Stage 1 coincided both in timing and relative level, with a spike in the water level recorded at the eastern lakeshore (Figure 6.22). In general, no significant relationship exists between relative changes in water level between these two systems (Figure 6.23), however this does indicate that during certain periods, high lake levels amplified by wind back fill the channel north of this wetland and subsequently flow into this area. This was blocked off in 2015 to facilitate the trapping of more water.

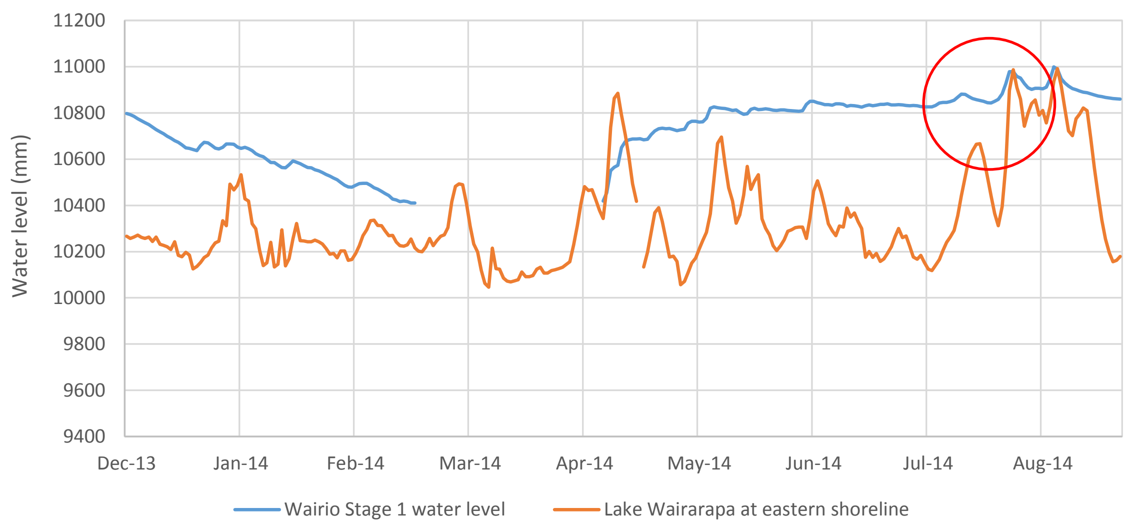


Figure 6.22: Water levels in Wairio Stage 1, and eastern shoreline of Lake Wairarapa

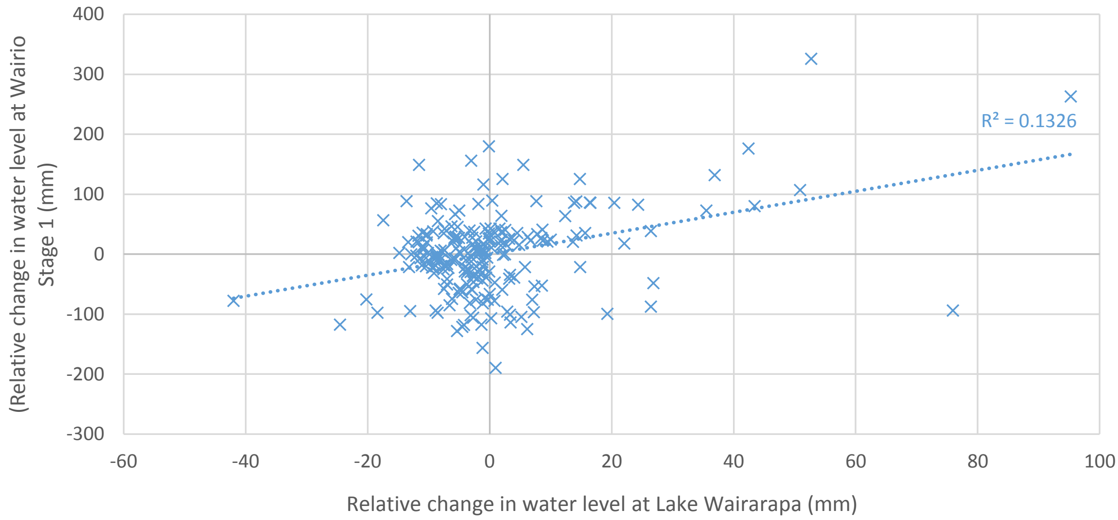


Figure 6.23: Correlation between relative changes in water level at Wairio Stage 1 and Lake Wairarapa from 07-Dec 2013 to 03-Sep-2013

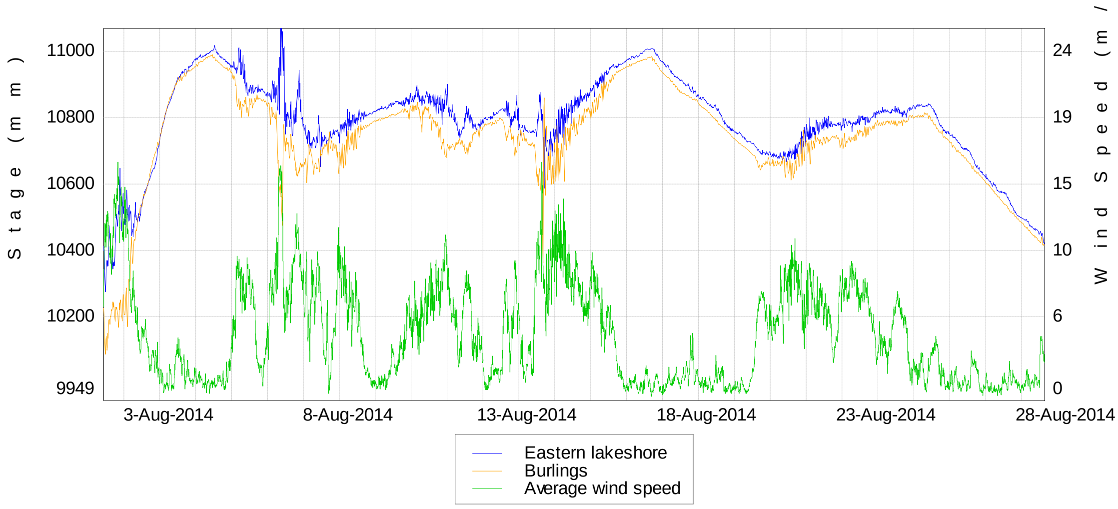


Figure 6.24: Lake Wairarapa water level over period of converging levels, and average wind speed over Lake Wairarapa

A stronger statistical relationship between relative changes in water level and groundwater level, over all groundwater records, exists in this wetland than those identified in Mathews Lagoon and Boggy Pond (Figure 6.25 and Table 6.4). However, nothing can inferred from this, as all groundwater bores experienced seasonal decline over this summer period. Because the water level in this wetland also experienced a relatively uniform decline, this translates into a common relationship between the records that are both driven in the same direction by seasonal patterns, not each other.

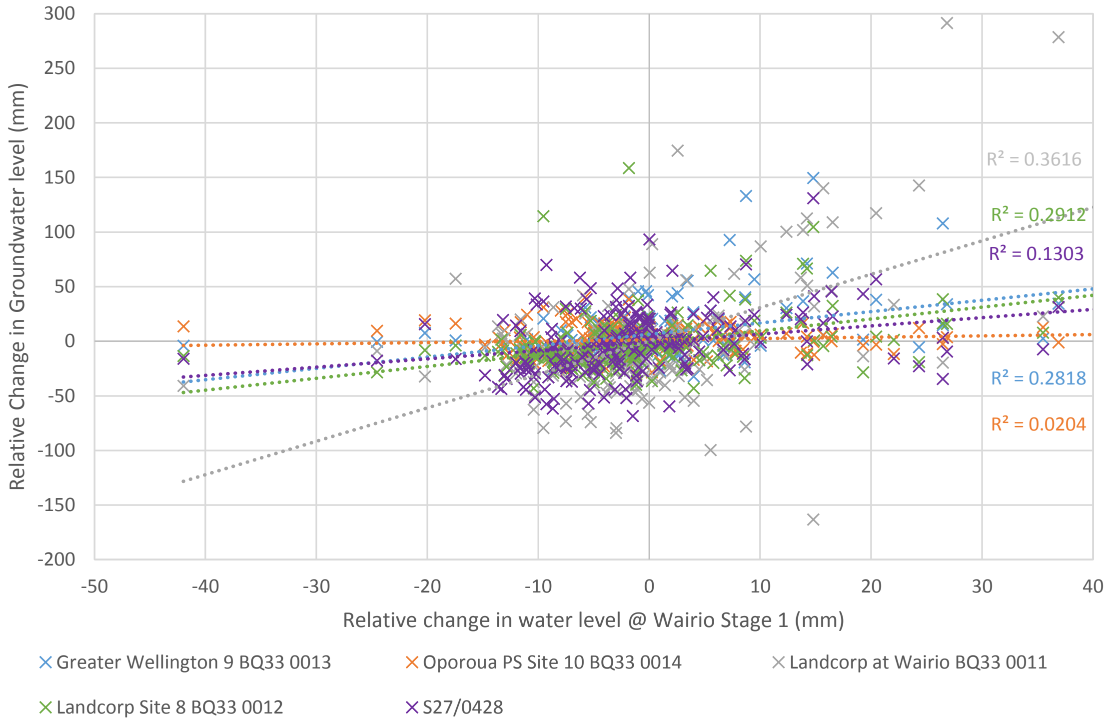


Figure 6.25: Correlation between relative changes in groundwater level and relative changes in water level at Wairio Stage 1

Table 6.4: Relationships between wetland water levels and groundwater bores

Groundwater bore	Relationship (r^2)		
	Wairio Stage 1	Mathews Lagoon	Boggy Pond
Greater Wellington Site 9 BQ33 0013	0.30	0.16	< 0.01
Oporoua PS Site 10 BQ33 0014	0.02	< 0.01	0.02
Landcorp at Wairio BQ33 0011	0.36	0.02	0.08
Landcorp Site 8 BQ33 0012	0.30	0.11	0.04
S27/0428	0.13	0.046	0.20

6.1.4 Lake water levels and wind

Since a surface water interaction has been shown to play a role in the water level of Wairio Stage 1, the analysis of the eastern shoreline lake level becomes particularly relevant. While the event that created a pulse into the wetland was the result of high lake levels (the highest over the entire dataset at 11020mm), the data at that time also demonstrates that wind-induced fluctuations in water level can occur that further amplify local lake level. Over this period of high lake level, a series of wind gusts (16.25m/s) achieved a peak lake level of 11110mm. These gusts were not the largest (largest recorded being 23.75m/s), however they occured when the lake level was high.

Records from each lake shoreline identify a strong relationship between wind speed and lake level differential from shoreline to shoreline (Figure 6.26). This difference increases with wind speed (Figure 6.27). The quantification of the relationship was conducted on 30 min smoothed data, detailed in Section 6.1.1, which identified the largest difference between lake levels as 715mm. Details of the largest three level differentials are detailed in Table 6.5.

Table 6.5: Lake level differences with wind

Date	Lake level difference -averaged over period (mm)	Wind speed (m/s)	Duration (hours)	Max level in period (mm)
25/05/2014	675	18.55	8	715
29/10/2014	627	17.84	6	657
19/11/2015	612	18.65	2	656

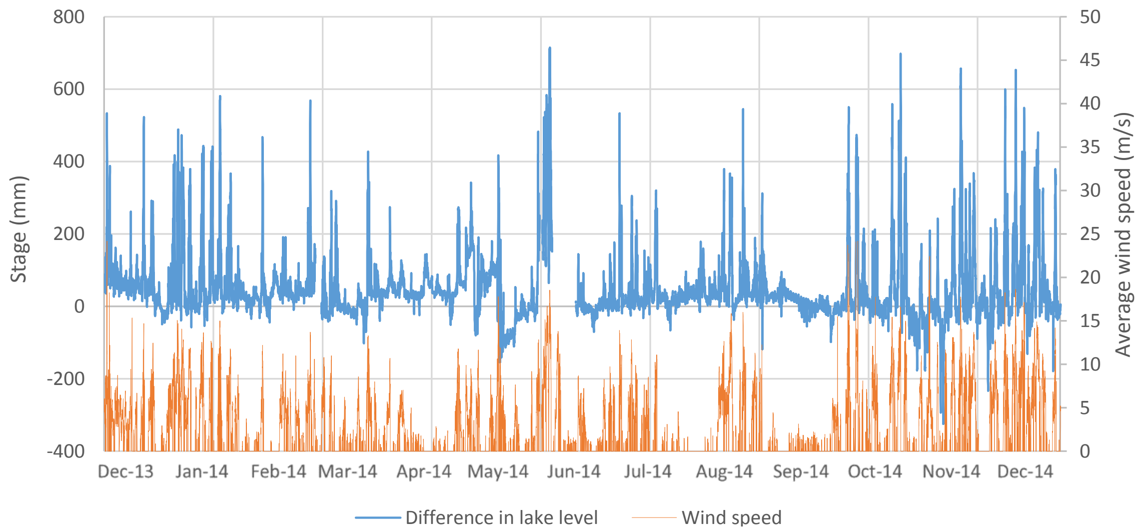


Figure 6.26: Average wind speed relative to difference in lake level eastern and western shoreline

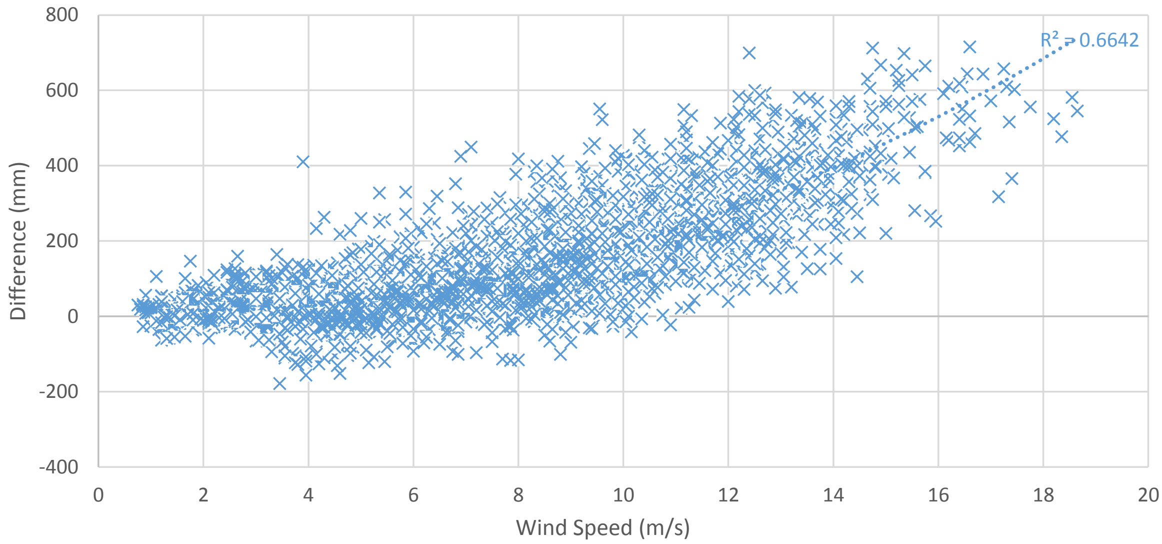


Figure 6.27: Relationship between wind speed and lake level difference at Lake Wairarapa

6.1.5 Commonality

All wetlands exhibit a similar trend in the long term variability of their water level. This is driven by evapotranspiration and the seasonal reduction in rainfall (either directly or indirectly). Potential evapotranspiration over these wetlands has been treated consistently.

Differences in the responsiveness of each wetland to precipitation can be attributed to the bathymetry of each system.

Observations during site visits identified that when water levels are low, a significant migration in the surface area of the wetland occurs in Boggy Pond Estimates derived from publically available aerial imagery have summer periods have open water areas ~40% less than in winter with significant die back of wetland vegetation occurring.

Wairio Stage 1 however, is an artificially created area with a steep gradient in its embankment. This leads to little change in wetland extent, and little migration of exposed banks. Variation between evaporation from open water and transpiration from plants is therefore minimal. Mathews Lagoon also has a more controlled surface area extent, and a deeper bathymetry than Boggy Pond (Shi, 2014).

6.2 Rainfall distribution over wetland system

An initial site visit to the wetlands at the begining of this study identified the role wind played in dispalcing water off the Lake over the wetland system. Rainfall at the time was not occuring on the Western shoreline, or inland, but was in fact a product of shear stress on the surface of the lake tearing water off and depositing it over the wetland in an almost horizontal fashon. The influence this will have on rainfall at each wetland is significant, especailly when one considers the inherent errors associated with collecting rainfall in the presence of wind. The methodology used to identify the significance of this has been detailed in Section 5.2.

Rainfall from each pit gauge was collected as frequently as possible (within budget and time constraints). Telemetered data from the GWRC operated rainfall site on the eastern lakeshore was used to assess when rainfall events had occurred and a site visit was scheduled. Prior to the arrival of predicted storm events a site maintenance visit was conducted to empty the collectors and clear the sites of regrowth. In total 28 rainfall events were collected with a control gauge catch ranging from 0-60mm. Rainfall totals caught at each gauge can be found in Table 6.6.

Table 6.6: Rainfall collected in pit gauges (mm)

Period	GWRC Met Site Total	Control Gauge Total	Lake	Wairio	Boggy Pond	Mathews Lagoon
30-14 Jul 2014	13	13	13	13	12	12
15-17 Jul 2014	16.5	17	17	17	16	16
18-19 Jul 2014	1	2	2	1	2	1
20-23 Jul 2014	51.5	60	62	59	59	58
24-31 Jul 2014	3.5	4	4	4	3	3
01-04 Aug2014	44.5	50	52	50	52	50
04-10 Aug 2014	15	22	23	20	21	21
11-12 Aug 2014	12.5	16	17	15	14	15

13-18 Aug 2014	32	39	41	38	34	32
19-04 Sep 2014	12.5	10	12	6	12	13
05-06 Sep 2014	14	16	19	12	15	15
07-12 Sep 2014	0	0	0	0	0	0
13-15 Sep 2014	12	14	13	12	9	13
16-19 Sep 2014	12	17	20	15	14	12
20-22 Sep 2014	18.5	23	28	24	19	17
23-26 Sep 2014	0	0	0	0	0	0
27-02 Oct 2014	28	33	34	31	32	31
03-05 Oct 2014	3	7	8	4	2	3
06-07 Oct 2014	25.5	30	33	30	27	29
08-18 Oct 2014	1	1.5	2	1	1	1
19-25 Oct 2014	5.5	6	7	5	4	5
26-03 Nov 2014	33	34	23	28	28	24
04-12 Nov 2014	10.5	12	13	10	6	6
13-17 Nov 2014	14.5	12	20	12	3	10
18-27 Nov 2014	2	4	4	3	1	2
28-07 Dec 2014	13.5	16	18	14	13	7
08-09 Dec 2014	0	0	0	0	0	0
10-12 Dec 2014	8.5	9	9	8	8	9
13-19 Dec 2014	6.5	7	7	7	7	6
20-23 Dec 2014	7.5	8	8	8	7	7

6.2.1 Analysis

Rainfall recorded by GWRC was plotted and visually inspected for errors. Manual tips were deleted when a GWRC field officer inspected the site or erroneous data was present (isolated spikes in the rainfall record).

The aim of the data analysis was to determine:

- What is the spatial variation in rainfall over the wetland?
- What is the relationship between the GWRC tipping bucket gauge and the in-ground control gauge? and;
- Were variations in the distribution of this rainfall greater during high wind speed events?

6.2.2 Rainfall distribution over the wetland system

Comparison of rainfall totals caught in each gauge are presented cumulatively in Figure 6.28, as a departure from the control pit gauge in Figure 6.29 and as as totals in Figure 6.30. Rainfall totals for each gauge are presented in Table 6.7. There is considerable variation in catch through the wetland system, most noticeably between the lakeshore gauge (509mm), and Mathews Lagoon (418mm). However, rainfall collected at Mathews Lagoon was identical in volume to that caught at the GWRC meteorological gauge.

Considerable variability in the rainfall caught at each wetland over each event occurs (Figure 6.29), but indicate a trend that the further from the lake the gauge is, the less rainfall it catches. It appears however that the pit gauges caught more rainfall during the August/ October period, the OTA tipping bucket gauge catches up to Boggy Pond, Wairio and Mathews Lagoon gauges as their catch rate reduces relative to the OTA gauge (Figure 6.28). Wind speeds and maximum wind gusts over this period were, on average 1m/s slower than the August October period and exhibited less variance (data can be found in Appendix D).

Table 6.7: Total rainfall caught at each gauge over the study period (mm)

Gauge	GWRC met site	Control	Lake	Wairio	Boggy Pond	Mathews Lagoon
Total Catch	418	483	509	447	421	418

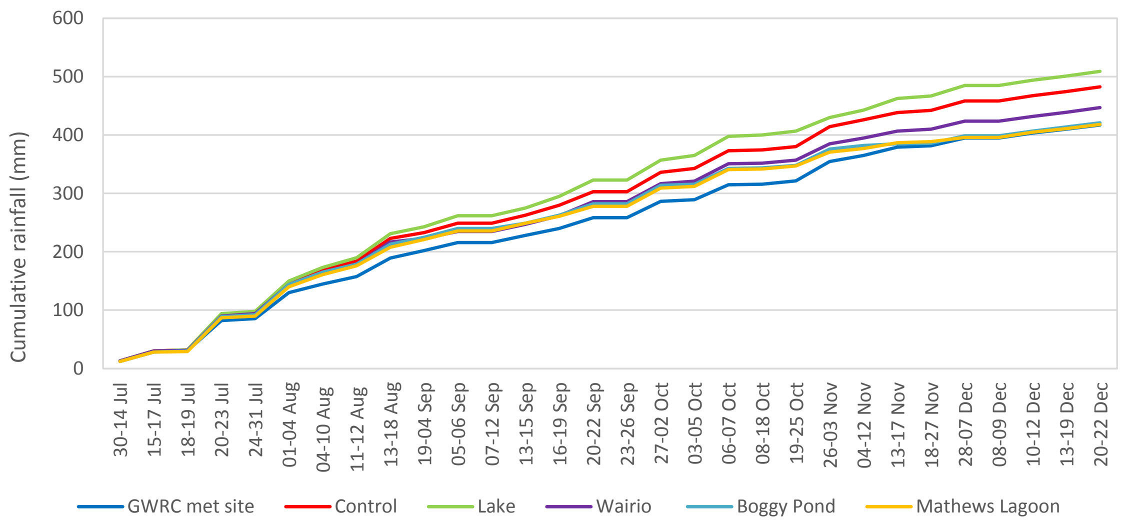


Figure 6.28: Cumulative rainfall over the wetland system for all gauges (mm)

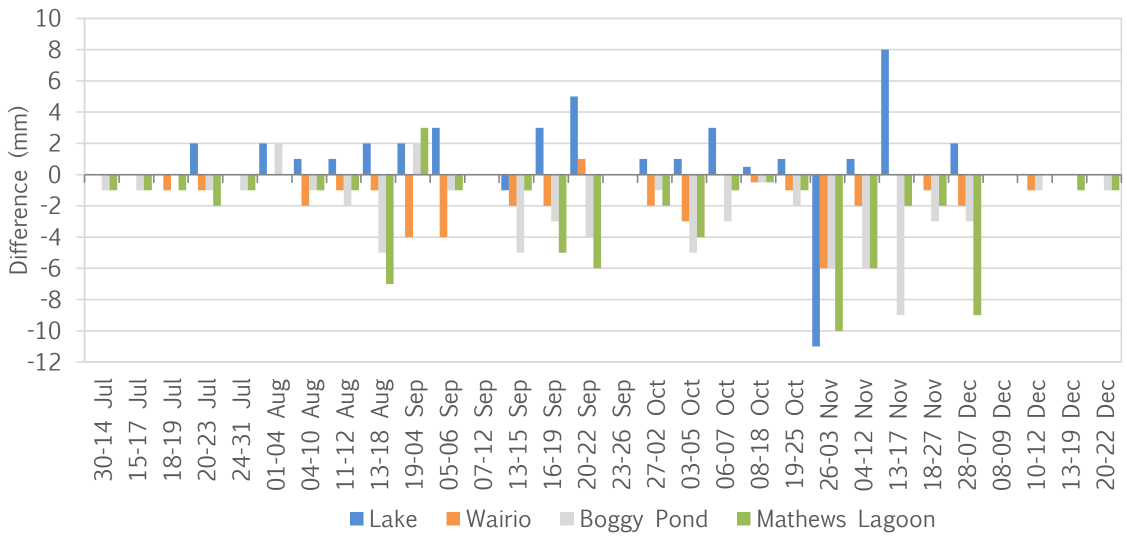


Figure 6.29: Rainfall departure from control gauge (mm)

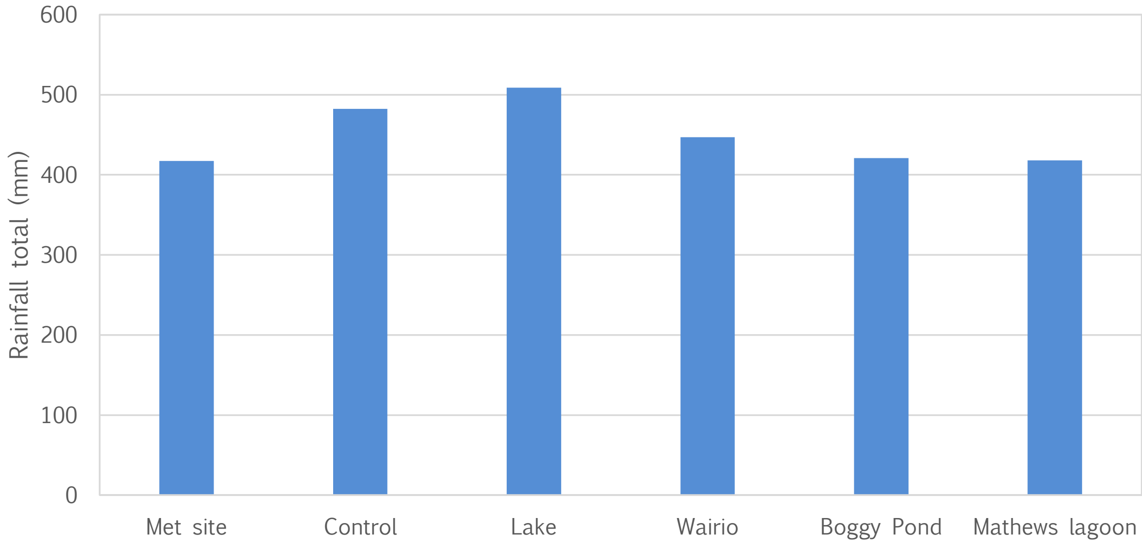


Figure 6.30: A comparison of total rainfall caught in each pit gauge and the GWRC Met site (mm)

6.2.3 Gauge performance and variation in catch during storms

Assessment of catch performance and rainfall distribution as a function of wind speed required considerable management of data. Plots were therefore created for each period between site visits that presented the recorded data at the GWRC meteorological site, including: rainfall, average wind speed, maximum wind gusts, and the recorded wind direction, conducive to driving rainfall over the wetland system (i.e. the rainfall event of 20-23 December in Figure 6.31). Wind rose plots were also created for each period. These graphs can be found in Appendix D.

The primary focus of these plots was to identify when rainfall events occurred within the period of time between site visits, and periods where wind speeds exceeded both 5.5m/s (the speed in which wind starts to influence rainfall under catch) and 13.5m/s (as indicated by the Beaufort scale, (Table 6.8) as the wind speed at which spray from crested waves would begin to be carried).

Visual inspection of these graphs was conducted in an attempt to refine the data over each collection period to determine the relationship between rainfall and wind speed. The GWRC Met site was used to identify when rainfall was likely to have occurred. Collection periods that exhibited only a single rainfall event with no wind speed over 13.5m/s (other than at the time of rainfall) were processed so all continuous non-rainfall days were removed. It was assumed that rainfall collected in each pit gauges would have occurred over a single event or during high wind speeds (Figure 6.31). Periods that consisted of high wind speed events or multiple rainfall events between collection periods were not refined as no delineation between rainfall events and total catch could be conducted.

Table 6.8: The Beaufort scale of wind induced effects on surface water

Beaufort scale	Description	Wind speed (m/s)	Lake condition
0	Calm	< 0.3	Flat
1	Light air	0.3 - 1.5	Ripples without crests
2	Light breeze	1.5 - 3.3	Small waves, crests not breaking
3	Gentle breeze	3.3 - 5.5	Crests begin to break
4	Moderate breeze	5.5 - 8	Small waves with breaking crests, whitecaps
5	Fresh breeze	8 - 10.8	Moderate waves, whitecaps, small amounts of spray
6	Strong breeze	10.8 - 13.9	Long waves forming, airborne spray is present
7	High wind	13.9 - 17.2	Sea heaping, foam from breaking waves, moderate amounts of spray.
8	Gale	17.2 - 20.7	Moderately high waves with breaking crests, considerable airborne spray
9	Strong gale	20.7 - 24.5	High waves whose crests role over. Large amounts of airborne spray
10	Storm	24.5 - 28.4	Very high waves, foam patches. Large amounts of airborne spray reduce visibility
11	Violent storm	28.4 - 32.6	Exceptionally high waves. Very large amounts of airborne spray
12	Hurricane	>32.6	Sea completely filled with driven spray, air filled with driving spray reducing visibility

Note, This table has been adapted from NOAA(a) 2016.

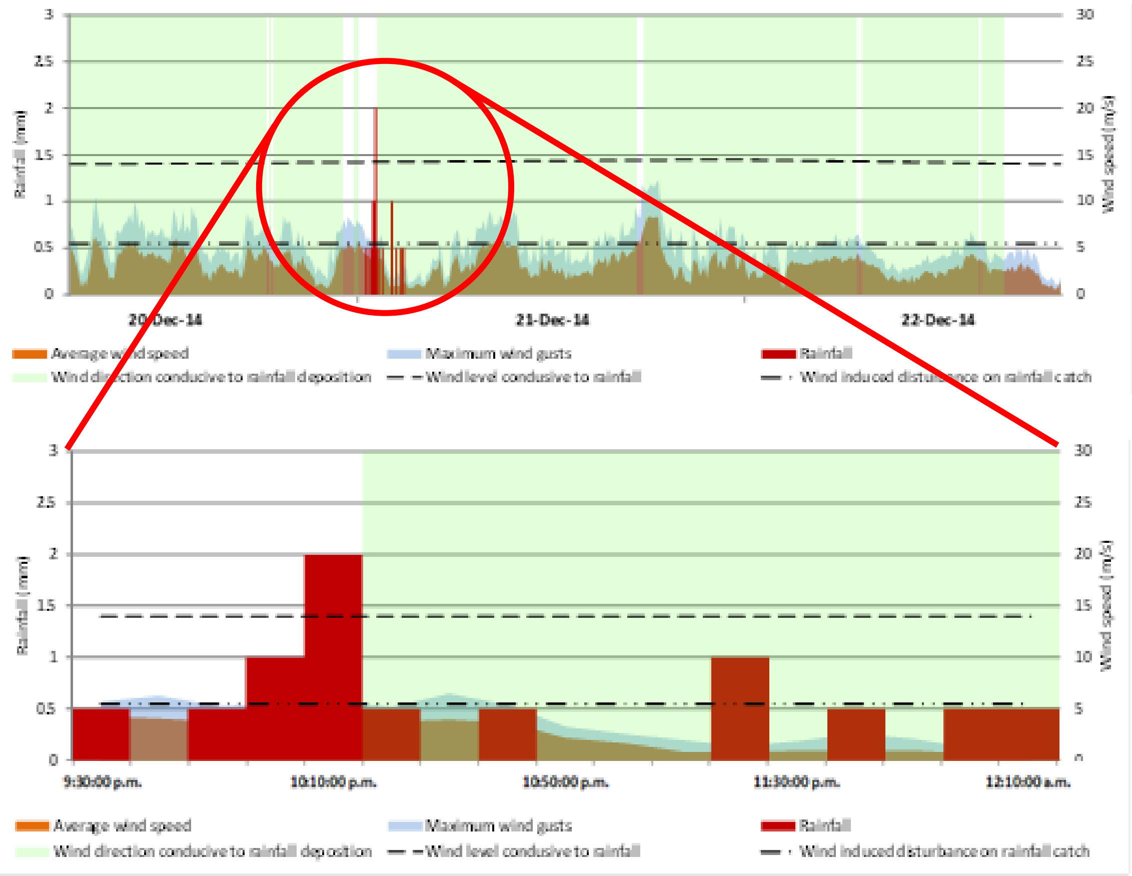


Figure 6.31: Data collection period (20-22 Dec 2014) and its corresponding "refined period of record".

Refinement of the data collected between visits was required to better identify if deviation in rainfall catch occurred during higher wind speed events, and to identify any difference in catch between the control gauge and the GWRC OTA tipping bucket gauge. In total, only 10 of the 28 periods could be refined to a single rainfall event. The refinement of these periods proved useful, and produced stronger statistical relationships for two of the goals of this sub-study (Figure 6.32 and Figure 6.33).

Analysis of the available data sought to quantify the average wind speed, gustiness, standard deviation and sample variance of each event (Appendix E). A statistically significant relationship exists between the deviation in catch across the wetland complex and the deviation in catch between the OTA tipping bucket gauge and the control gauge, (r^2=0.62 and r^2=0.73 respectively). Considering the nature of the data, this is considered to be excellent. Results are consistent with other studies (discussed in Section 5.2.1) and demonstrate that a) the tipping bucket gauge is under-catching rainfall by 15% (Table 6.7) and this is likely occurring during higher wind speed events, and b), greater variation in catch appears to occur across the wetland during more turbulent conditions. Unfortunately, quantifying whether specific events occurred that were caused by rainfall sourced specifically from the lake was not possible. On all occasions any significant volume of rainfall fell on the eastern shore (above 2mm), rainfall also occurred on the western shoreline.

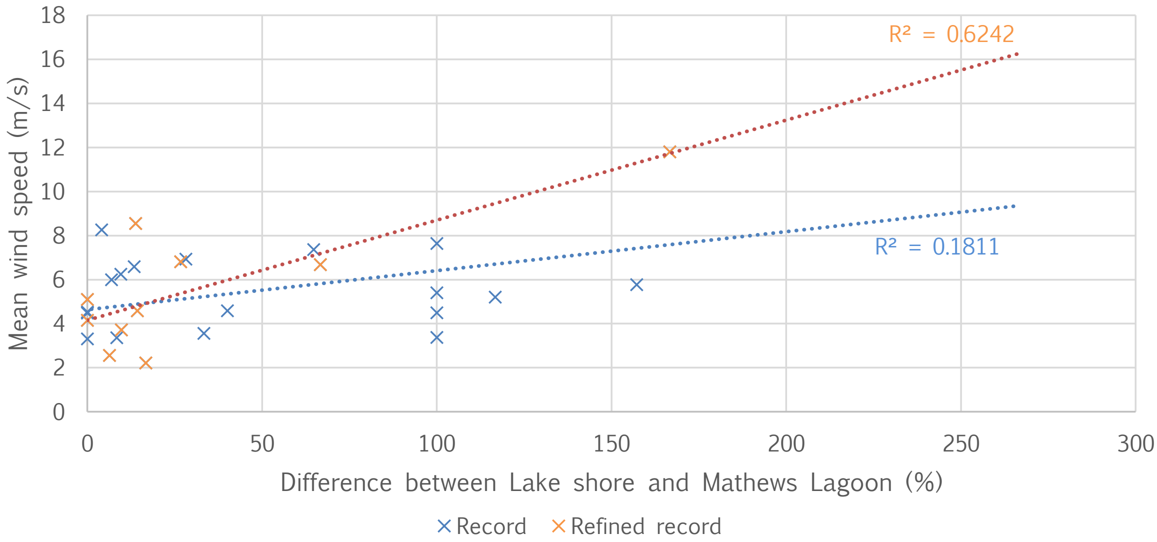


Figure 6.32: Relationship between lakeshore and Mathews Lagoon over the record period, and refined record period.

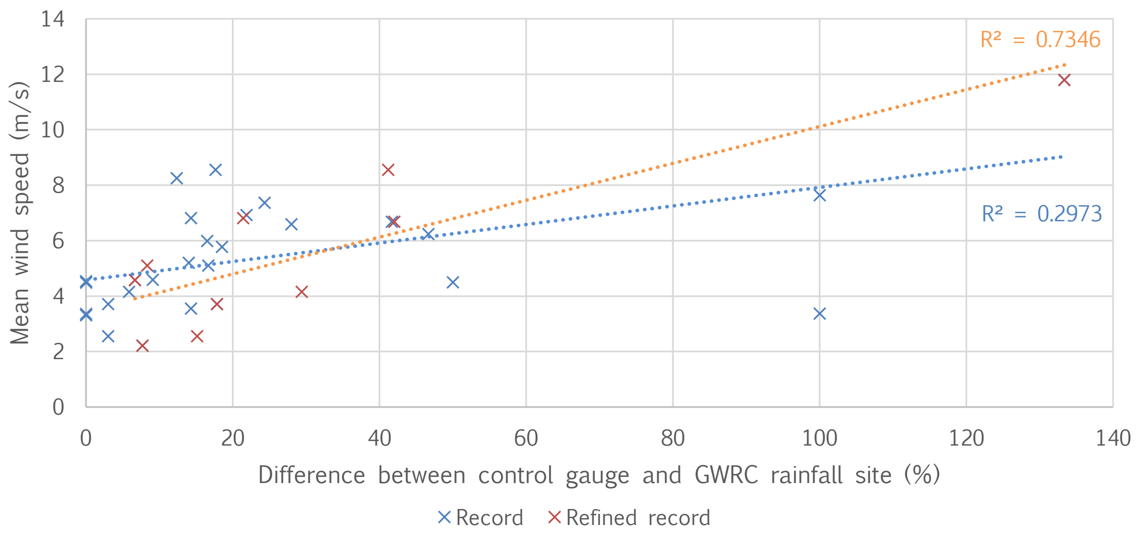


Figure 6.33: Differences between rainfall caught at the control gauge and the GWRC Met site (OTA tipping bucket)

Based on this study, applying standard adjustments for future rainfall based on the record collected automatically at the OTA tipping bucket gauge, to each wetland may not be appropriate. While adjustments to rainfall over the period could be made (Table 6.9), the OTA gauge itself catches 15% less rainfall than the control gauge. The OTA tipping bucket gauge is therefore representative of the likely rainfall to occur over the wetland system, especially when accounting for the nature of rainfall. It should be noted however that the number of events conducive to the identification of the aims of this study were limited, and the resource limitations prevented the collection of more significant and accurate data.

This study has however allowed for a general conclusion that with climate change, increases in the storminess of rainfall events (especially with increases in wind speed) could cause greater variation in rainfall over the system, which will be under recorded by the meteorological gauges currently installed.

Table 6.9: Rainfall adjustments for each wetland

Wetlands	Adjustment to rainfall from GWRC OTA tipping bucket gauge (%)
Lake Shore	+5%
Wairio	-8%
Boggy Pond	-15%
Mathews Lagoon	-15%

6.3 Evapotranspiration

Water level analysis of the three wetlands has highlighted the relative importance of evapotranspiration on all three wetlands. Evapotranspiration is the dominant process of removal of water from both Boggy Pond and Wairio Stage 1 over summer, and is an important component in water removal in Mathews Lagoon when flows out of the outlet culvert are not extreme.

Discussion has already been conducted around the variables used to derive a suitable evapotranspiration equation, their source and the limitations present with the available data (Section 5.6.1). This initial discussion has allowed for what is considered a robust estimation of PE for 2013 to be used in the assessment of relative changes in the drought period, and a representative estimate of PE for a grounded 1986-2005 period to be adjusted for predicted changes in climate. The only difference between these two models has been adjustments to monthly temperatures (detailed in Section 0). The result is a grounded (in the 1986-2005 period) model with a slightly lower annual mean evaporation rate (Table 6.10).

Table 6.10: Min, mean and maximum rates of potential evaporation over the 2013, and grounded PE models

	Min (mm)	Max (mm)	Mean (mm)
2013	0.51	6.87	2.88
2013 grounded	0.46	6.85	2.87

Climate change adjustments, based on the variable discussed in Section 5.6 have been used to derive evapotranspiration rates from this grounded model out to 2040 and 2090 over all four RCPs (Table 6.11 and Table 6.12).

Table 6.11: Summary statistics for annual potential evaporation rates, grounded in the 1985-2005 period out to 2040 (all results are in mm)

Model (mm)		Min	Max	Mean	Std dev	L.Q.	Median	U.Q.
RCP 2.6	Min	0.47	6.90	2.92	1.52	1.58	2.79	4.09
	Mean	0.48	7.00	2.97	1.55	1.61	2.84	4.16
	Max	0.49	7.09	3.01	1.57	1.63	2.87	4.21
	RANGE	0.02	0.19	0.09	0.04	0.05	0.08	0.12
RCP 4.5	Min	0.48	6.98	2.96	1.54	1.61	2.82	4.14
	Mean	0.49	7.07	3.01	1.56	1.63	2.87	4.20
	Max	0.50	7.17	3.05	1.58	1.66	2.91	4.26
	RANGE	0.02	0.19	0.09	0.05	0.05	0.08	0.12
RCP 6.0	Min	0.49	7.04	2.97	1.55	1.61	2.84	4.16
	Mean	0.50	7.13	3.03	1.57	1.65	2.89	4.23
	Max	0.51	7.24	3.08	1.60	1.68	2.93	4.30
	RANGE	0.02	0.21	0.10	0.05	0.06	0.10	0.14
RCP 8.5	Min	0.50	7.13	3.00	1.56	1.63	2.85	4.18
	Mean	0.51	7.24	3.05	1.59	1.66	2.90	4.26
	Max	0.52	7.36	3.10	1.62	1.68	2.94	4.33
	RANGE	0.02	0.23	0.10	0.06	0.06	0.09	0.14

Table 6.12: Summary statistics for annual evaporation rates, grounded in the 1985-2005 period out to 2090 (all results are in mm)

Model (mm)		Min	Max	Mean	Std dev	L.Q.	Median	U.Q.
RCP 2.6	Min	0.49	6.90	2.92	1.52	1.59	2.79	4.09
	Mean	0.49	7.00	2.97	1.54	1.62	2.84	4.15
	Max	0.51	7.13	3.04	1.57	1.66	2.90	4.24
	RANGE	0.02	0.22	0.12	0.05	0.07	0.12	0.16
RCP 4.5	Min	0.51	7.00	2.99	1.54	1.64	2.85	4.16
	Mean	0.52	7.13	3.06	1.57	1.68	2.93	4.25
	Max	0.53	7.36	3.15	1.63	1.72	3.00	4.38
	RANGE	0.03	0.36	0.16	0.09	0.08	0.15	0.21
RCP 6.0	Min	0.52	7.21	3.07	1.59	1.68	2.92	4.28
	Mean	0.54	7.39	3.16	1.63	1.73	3.01	4.40
	Max	0.57	7.71	3.29	1.71	1.80	3.12	4.57
	RANGE	0.04	0.50	0.22	0.12	0.12	0.20	0.29
RCP 8.5	Min	0.57	7.71	3.25	1.69	1.78	3.08	4.52
	Mean	0.59	7.89	3.35	1.73	1.84	3.18	4.64
	Max	0.62	8.21	3.49	1.81	1.91	3.31	4.83
	RANGE	0.04	0.50	0.23	0.12	0.13	0.22	0.31

Variability in possible range within each scenario became more pronounced over the 2081-2100 period. This was expected, as an increase in variation will manifest through, the larger percentage adjustments used for relative humidity, wind speeds, and solar radiation in each scenario. The ranges in the variations for the RCP8.5 scenarios between the two periods are presented in Figure 6.34. Variation within each scenario was not significant, adjustments demonstrate very little variability from the predicted mean change in temperature (the largest deviation from the mean was present in RCP 8.5, (2090) and accounted for less than 3% of the mean evaporation). Analysis on the mean scenarios is therefore considered to be suitably representative of the variation within the respective RCP scenario. The mean monthly rate of PE, derived from the evaporation equation are presented in Figure 6.35 & Figure 6.36. They demonstrate a uniform, and comparative amplification in each months average evaporation total.

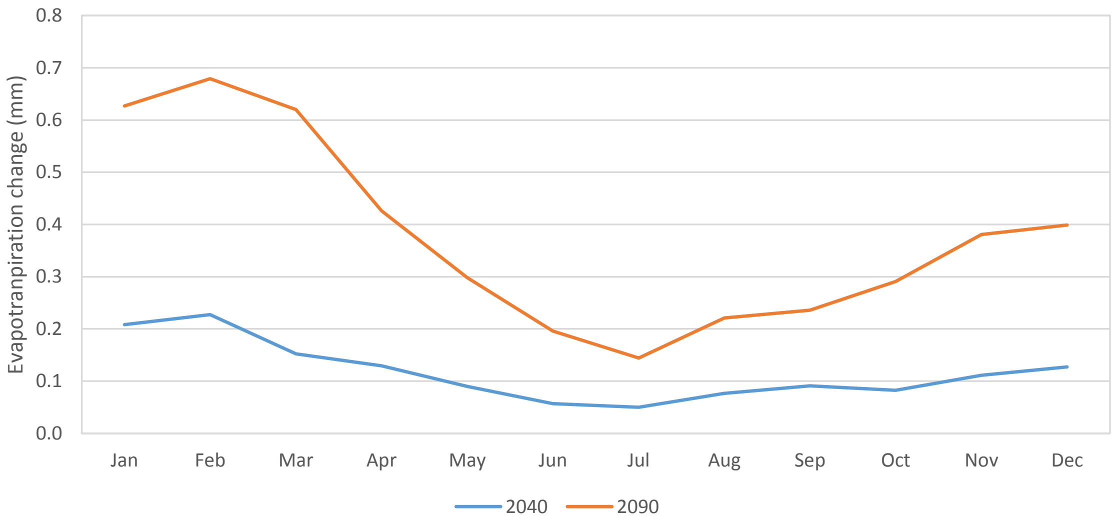


Figure 6.34: Variation observed in monthly min and max evapotranspiration scenario (8.5) for 2040 and 2090

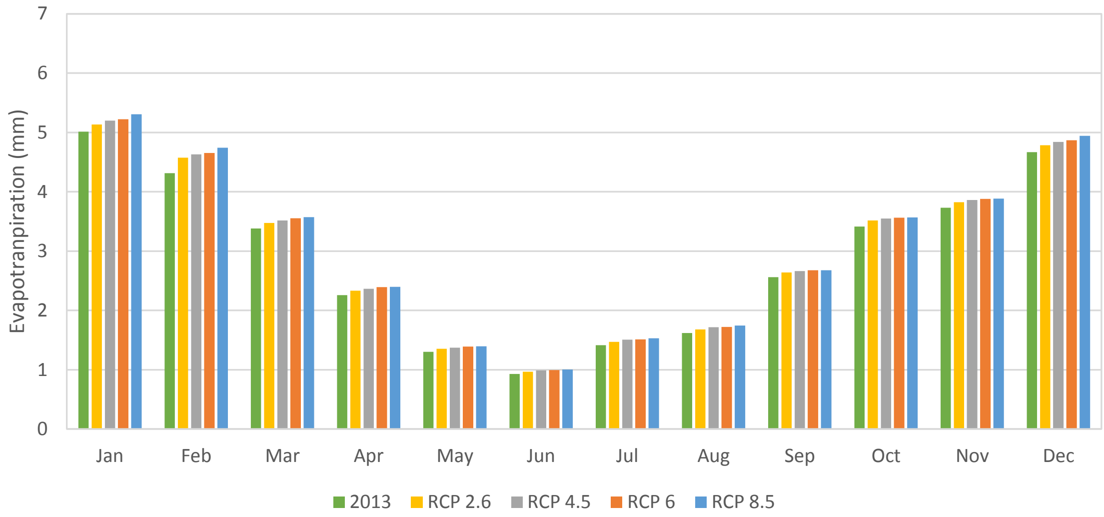


Figure 6.35: Mean monthly rate of potential evapotranspiration (2040)

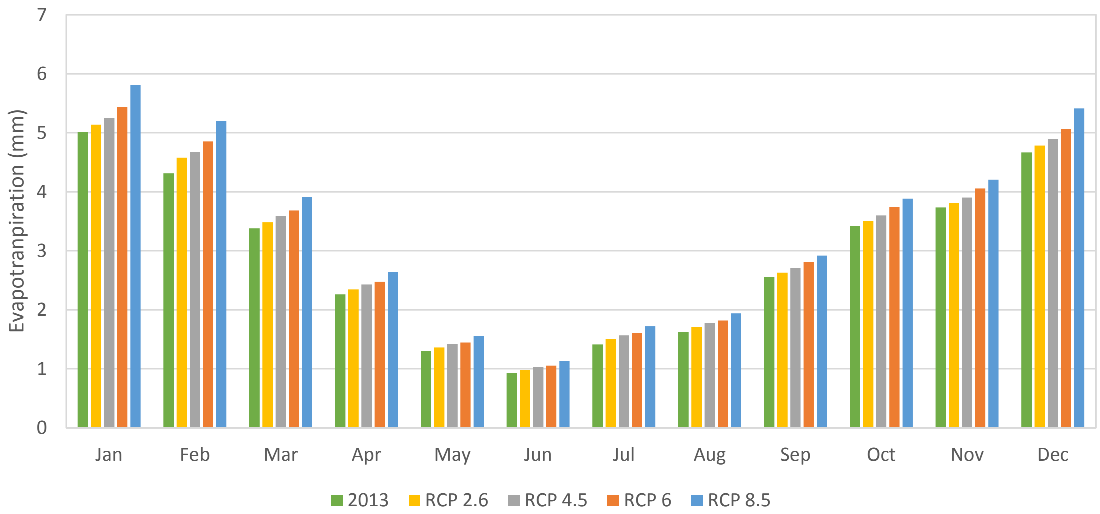


Figure 6.36: Mean monthly rate of potential evapotranspiration (2090)

Results demonstrate a relative increase in PE that becomes more pronounced with increases in temperature. Percentage increases for each month, relative to the 2013 base year, are presented in Table 6.13. Annual increases in evapotranspiration rates range from 3-7% out to 2040 and between 4-17% out to 2090. The greatest average monthly increases in temperature occur during February.

Table 6.13: Expected amount of potential evapotranspiration as a % of the 2013 grounded model

	2040				2090			
	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
Jan	102%	104%	104%	106%	102%	105%	108%	116%
Feb	106%	107%	108%	110%	106%	108%	112%	121%
Mar	103%	104%	105%	106%	103%	106%	109%	116%
Apr	103%	105%	106%	106%	104%	107%	110%	117%
May	104%	105%	107%	107%	104%	109%	111%	119%
Jun	104%	106%	107%	108%	106%	111%	113%	121%
Jul	104%	107%	107%	108%	106%	111%	113%	119%
Aug	104%	106%	106%	108%	105%	109%	112%	120%
Sep	103%	104%	105%	105%	103%	106%	110%	114%
Oct	103%	104%	104%	105%	103%	105%	110%	114%
Nov	103%	103%	104%	104%	102%	105%	109%	113%
Dec	102%	104%	104%	106%	102%	105%	109%	116%
Annual	103%	105%	106%	107%	104%	107%	111%	117%

Of particular interest was whether these increases in PE would translate into an extension of the critical drought period, by enhancing evaporation to a degree that negated predicted increases in rainfall. Increases in evapotranspiration will lead to a faster reduction in water level, however increases in precipitation may offset this. An extension of the drought period, and a potential increase in the intensity of drought may affect the timing of pumping from Te Hopai drainage scheme as more rainfall may be required to replenish the soil moisture deficit before rainfall became runoff.

The critical drought period for these wetlands is between December and April (Figure 6.35 and Figure 6.36). Figure 6.39 and Figure 6.40 show the predicted increase in PE, under all four RCP pathways, out to 2040 and 2090. As demonstrated with the monthly averages, the variation in evaporation, is not significant when averaged over the month, however daily increases under RCP

8.5 scenario can exceed current PE rates by 1.9mm. Daily increases in PE out to 2090 can be more significant, especially over the December to March period, with an increase of 2.5mm.

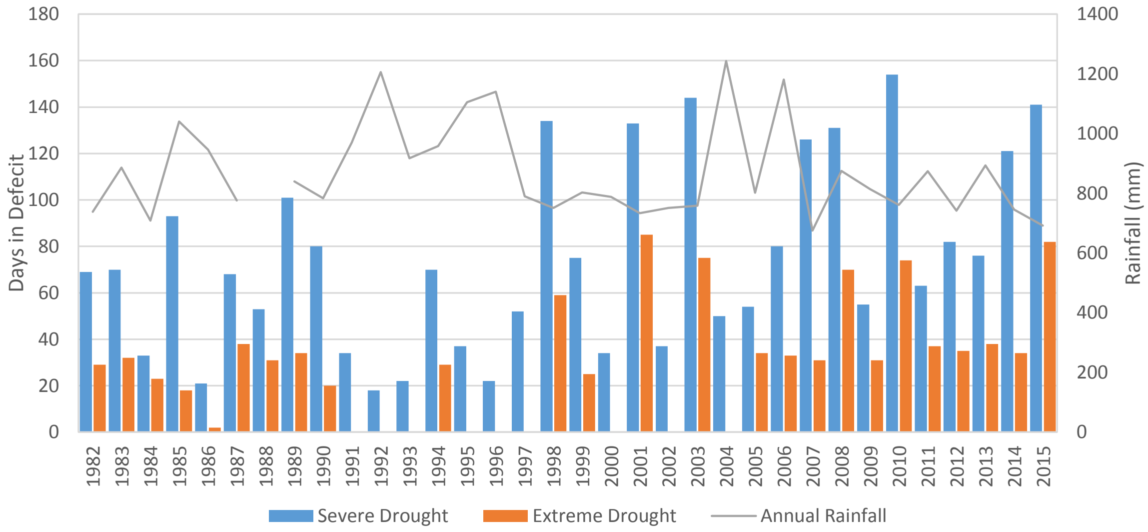


Figure 6.37: Days spent in drought, per year at Kahutara for over the period 1982-2015

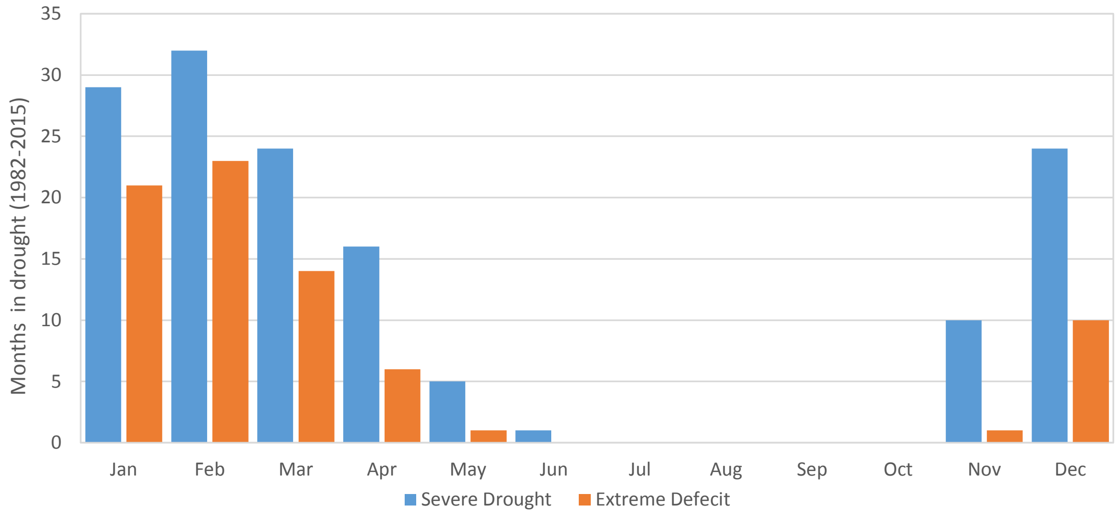


Figure 6.38: Months spent in drought, at Kahutara for over the period 1982-2015

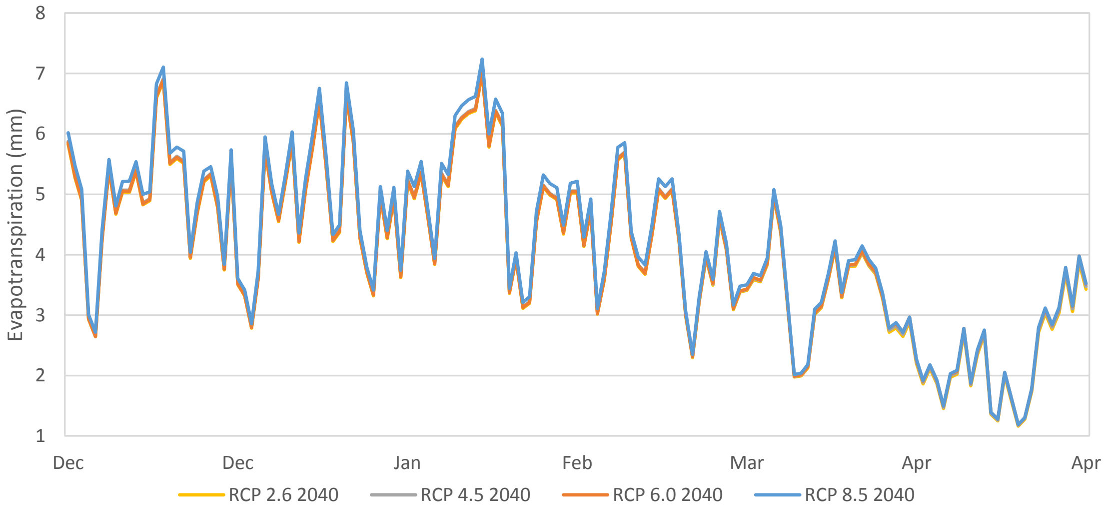


Figure 6.39: Evapotranspiration rates for four RCP pathways for 2040 over critical drought months

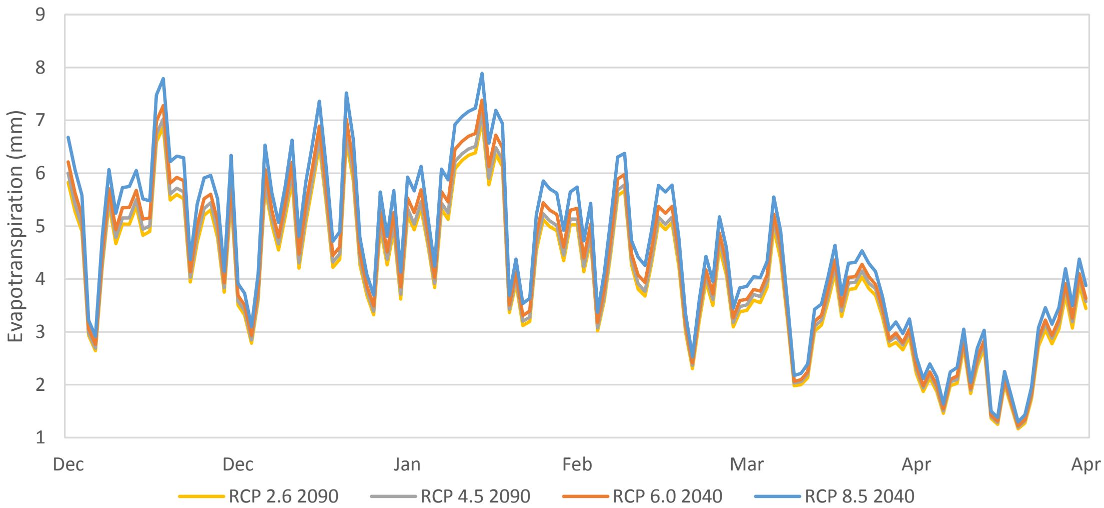


Figure 6.40: Evapotranspiration rates for four RCP pathways for 2090 over critical drought period

A soil moisture deficit equation was constructed, (discussed in Section 5.13.1), and used in conjunction with increases in PE and a rainfall pattern grounded in 2013. Results identify that increases in evapotranspiration, over all scenarios does not translate into an increase at the conclusion of the critical drought period. Under the mitigation scenario (RCP 2.6) the drought period is predicted to end a day shorter on average.

This analysis is limited in that adjustments to precipitation, based on the generalised temperature adjustment from the downscaled climate models, only allow for adjustments in the volume of rainfall, not its distribution. Rainfall events throughout the year are critical in maintaining stable soil moisture levels (and in the case of Wairio Stage 1, stable water levels). Changes to the frequency of rainfall, especially smaller, more frequent rainfall events, is going to be the critical control on the drought period. This is accounted for in the downscaled regional models but are lost when this is normalised to an area adjusted temperature. The use of the actual downscaled model runs could therefore be used to drive analysis of the potential variation in rainfall frequency.

The soil moisture equation does identify, that under the 2013 rainfall pattern used, drought through the spring is likely to increase in its relative intensity. Assuming that plant growth becomes supressed when the SMD becomes half the available soil moisture capacity of the soil, the time spent a state of drought in the Te Hopai basin may increase by up to a few days (2040) and over two weeks (2090). The relative intensity of the soil moisture deficit experienced at the end of April, will also increase by up to 7.5 and 11.4%/ (2040 and 2090 respectively).

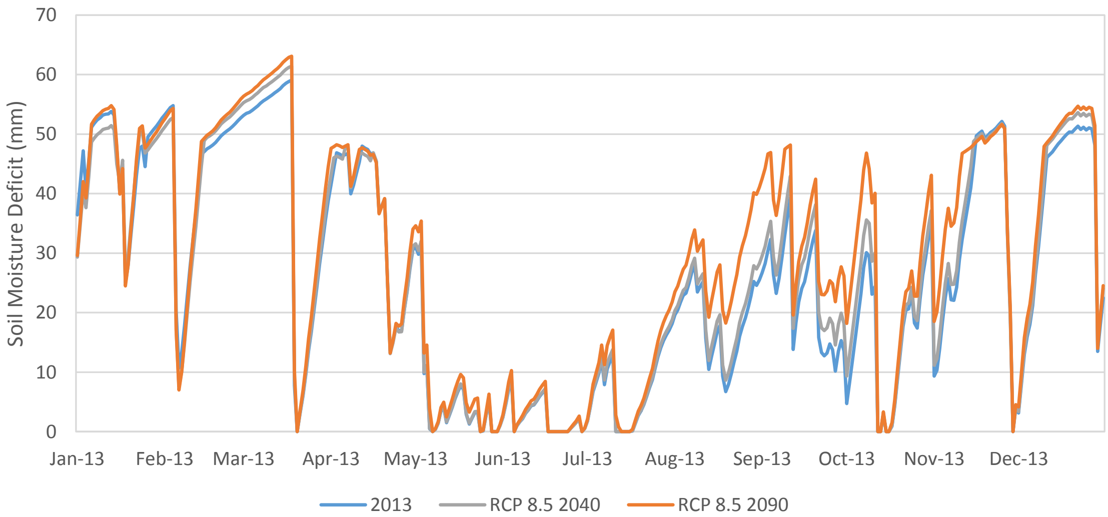


Figure 6.41: Changes in the soil moisture deficit using PE (AE) and adjusted rainfall for 2013, 2040 and 2090 (RCP 8.5)

Table 6.14: Initial and final SMD conditions used in the SMD equation, and results at the end of the critical drought period (April) (mm)

Model run	Warm up		Final Run		
	Initial SMD	SMD at Dec 31	Initial SMD	SMD at April 30th	Drought period ends
2013 grounded	0	31	31	30.6	7 may
2040					
RCP 2.5	0	23.3	23.3	30.4	7 may
RCP 4.0	0	24.7	24.7	32.7	7 may
RCP 6.0	0	24.1	24.1	31.2	7 may
RCP 8.5	0	26.7	26.7	32.9	7 may
Maximum increase from 2013 grounded SMD				2.3mm	
2090					
RCP 2.5	0	25.0	25.0	30.0	6 may
RCP 4.0	0	24.5	24.5	32.5	7 may
RCP 6.0	0	27.7	27.7	32.0	7 may
RCP 8.5	0	24.6	24.6	34.1	7 may
Maximum increase from 2013 grounded SMD				3.5mm	

6.4 Effects of climate change on each wetland

Analysis of hydrology of the wetlands has allowed for the refinement of the theoretical water mass balance equations presented in Section 5.6. Refined mass balance equations based off this analysis are presented in Figure 6.42 to Figure 6.44. Assessment of these refined water balance schematics identify that each wetland will respond differently to predicted increases in evapotranspiration, and rainfall.

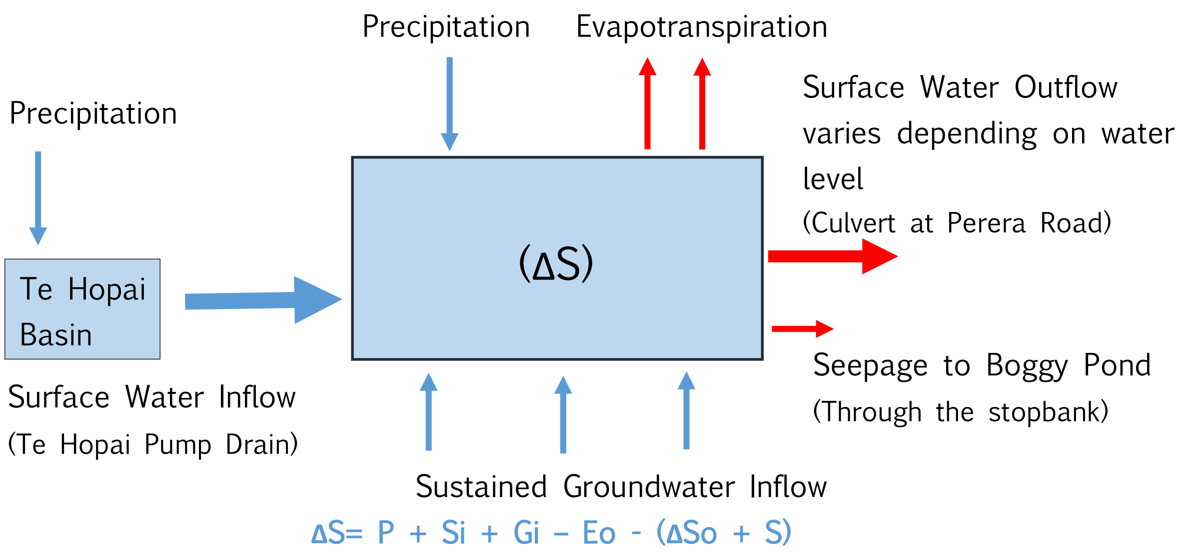


Figure 6.42: Refined water balance schematic and equation for Mathews Lagoon

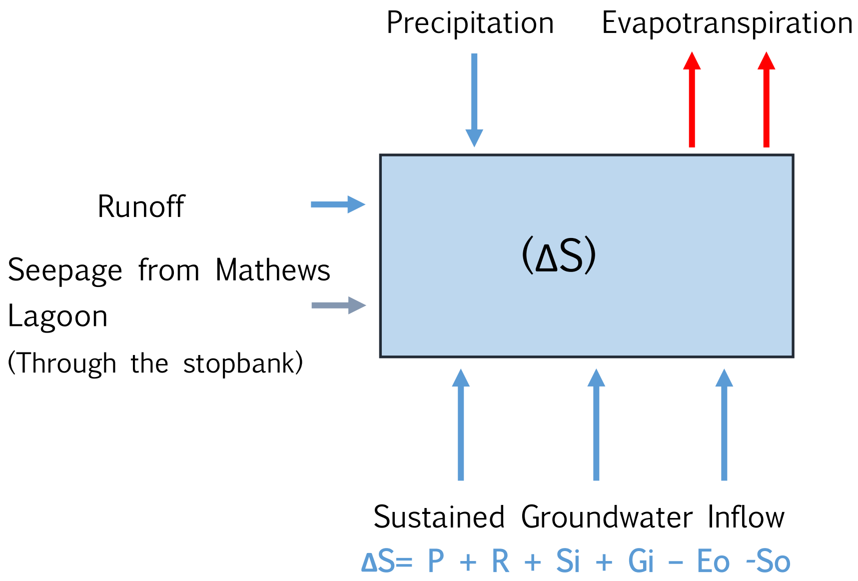


Figure 6.43: Refined water balance schematic and equation for Boggy Pond

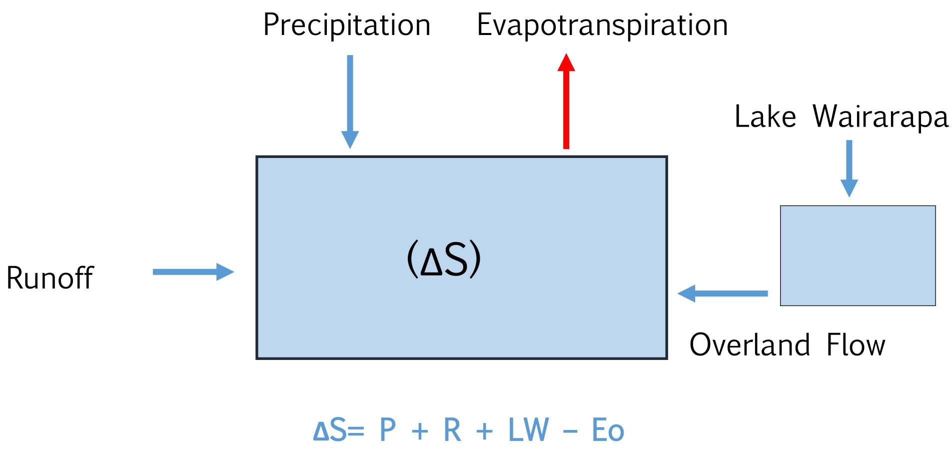


Figure 6.44: Refined water balance schematic for Wairio Stage 1 wetlands

Where:

- ΔS = change in storage volume
- P = net precipitation
- S_i = surface water inflow
- S = Seepage
- G_i = ground water inflow
- Eo = evapotranspiration
- I = infiltration
- S_o = surface water outflow
- G_o = ground water outflow

A critical limitation to this study has been the inability to adjust the temporal pattern of rainfall to reflect likely future changes in precipitation patterns. However, volumetric adjustment provided by MfE (2016) to rainfall, based off predicted increases in mean temperature, do allow for the some consideration into the likely increase in rainfall volume that may be experienced for larger, less frequent precipitation events.

Frequency analysis (described in Section 5.12.6) conducted on the synthetic record at Kahutara (Figure 6.45) has identified the annual maximum rainfall as being 40mm. The largest daily rainfall event that occurred over the record period was 45mm, and has a return period of approximately three years. This event (coupled with pumping of the Te Hopai pump drain) produced an increase in water level of 78mm in Mathews Lagoon 22mm in Boggy Pond, and 35mm at Wairio Stage 1. The reflective difference (assuming a stable and consistent rainfall over each wetland area) in water level between Boggy Pond and Wairio Stage 1 can be attributed to the bathymetries of each wetland. Quantification of the relative effect of different rainfall on all of the wetlands was not achieved, as no relationship between relative water level changes and rainfall inputs could be achieved.

Using the mean annual temperature predictions for all climate scenarios, identified in MfE (2016), and the adjustment factors for various design rainfall depths from MfE (2010) the intensity of largest annual rainfall event experienced year on year, may increase by ~1 to 5% by 2040 and ~5-13% by 2090. The intensity of less frequent events (i.e 100 year ARI) might be expected to increase by up to 9% (2040) and 25% (2090) (Table 6.15 and Table 6.16). These increases will translate into more pronounced increases in water level at Wairio Stage 1 and through pumping, a larger pulse in Mathews Lagoon. Boggy Pond's response is likely to be more subdued. At higher lake levels this will become less pronounced.

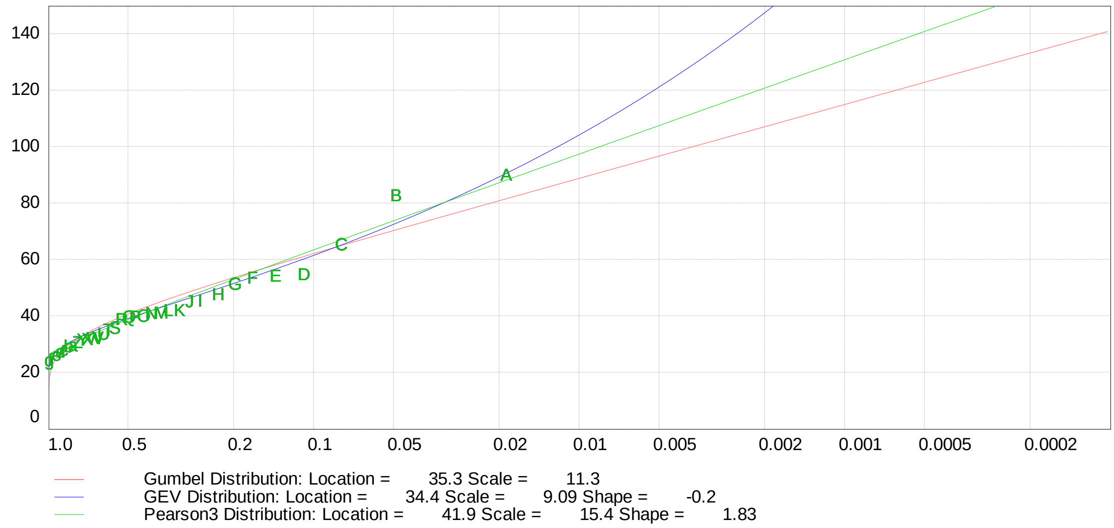


Figure 6.45: Frequency analysis conducted on annual maxima synthetic rainfall series at Kahutara

Table 6.15: Rainfall depth increases for the mean temperature increases of four RCP scenarios out to 2040

Scenario	Adjustment (°C)	Annual Recurrence Interval (years)					
		2.33	5	10	20	50	100
Adjustment		4.3	5.4	6.3	7.2	8.0	8.0
Current	0	40	52	62	73	86	96
RCP 2.6	0.7	41	54	65	77	91	101
RCP 4.5	0.9	42	55	66	78	92	103
RCP 6.0	0.8	41	54	65	77	92	102
RCP 8.5	1.1	42	55	66	79	94	104
Max Increase from current		2	3	4	6	8	8

Table 6.16: Rainfall depth increases for the mean temperature increases of four RCP scenarios out to 2090

Scenario	Adjustment (°C)	Annual Recurrence Interval (years)					
		2.33	5	10	20	50	100
Adjustment		4.3	5.4	6.3	7.2	8.0	8.0
Current	0	40	52	62	73	86	96
RCP 2.6	0.7	41	54	65	77	91	101
RCP 4.5	1.4	42	56	67	80	96	107
RCP 6.0	1.8	43	57	69	82	98	110
RCP 8.5	3	45	60	74	89	107	119
Max Increase from current		5	8	12	16	21	23

Changes in the pattern of precipitation will effect changes in the pumping regime at Te Hopai. This may have less of a direct impact on Mathews Lagoon, in that pumping of the drainage system already acts somewhat as a buffer on the instantaneous input of water into the wetland. High inflow rates also tend to pulse through the system relatively quickly, as the wetland reaches an equilibrium with the discharge rate moderated through the culvert.

The resulting effect that can be inferred from the available data is that this will generate greater increases in pulses of water into Mathews Lagoon, rapidly elevating water levels. However, without the more frequent events, less consistent pumping will likely manifest as a lowering of the mean water level. Changes in precipitation may also lead to an extension of the critical drought period (identified in this study to be December through March). Should pumping cease over this period earlier, or start back up later in the season a drop in water level of between 8 and 16mm per day could be expected.

Climate change is expected to increase the frequency of wind speeds conducive to the removal and deposition of water from the surface of Lake Wairarapa to the eastern shoreline. Results from the nested pit gauges has identified that this will likely benefit (depending on the antecedent conditions) Wairio Stage 1. However it is less likely to significantly increase inputs of rainfall over Boggy Pond or Mathews Lagoon.

More frequent high wind speeds will have an increased effect on the presence of the lake on the eastern shoreline. Recent research by Marapawa (2016) indicates a relationship between lake level and soil moisture may exist in the area. Increased time spent pushed up against this shoreline may benefit this wetland as the hydraulic signal should translate into the wetland. This level of relationship is too fine to have been assessed during this study.

7 Conclusion

This thesis sought to identify and refine the understanding of the hydrology of three wetlands, Mathews Lagoon, Boggy Pond and Wairio Stage 1, and identify how they may respond to predicted changes in regional climate.

In order to achieve this, analysis of each wetlands hydrology, and the regional climate was required. Four objectives were identified in Chapter One, these have been answered with varying degrees of certainty, using the most recent predicted changes in climate, downscaled from the IPCC 5th assessment report.

7.1 Overall conclusions

What relationships do these wetlands have with local groundwater and surface water environments, and what is the level of connectivity between each wetland?

Analysis of water levels in each of the three wetland have identified markedly differing hydrologys, with no significant interaction between them.

- Mathews Lagoon is heavily reliant on pumping from the Te Hopai drainage network. This pumping is responsible for considerable fluctuations in the wetlands water level (1127mm). Inputs from these pumps have been calibrated recently and subsequent inflows are considered accurate. A steady inflow of groundwater is also present in this wetland, however this inflow is not sufficient to maintain a steady water level in this wetland. The signal is often distorted, amplified or subdued through the record. Only when water levels are low during summer does the signal become discernible.

  The dominant outflow from this wetland is via a culvert at the wetland northern margin. Two floodgates regulate flows through a pressure relationship between the water level head in the wetland, and the level of Lake Wairarapa. Due to the complicated nature of this relationship, the equipment required to adequately derive a suitable relationship, and the issues in measuring flows in this area, no reliable outflow series has yet been created.

- Boggy Pond exhibits a tempered water level with a range of only 477mm. This wetland exhibits a continual rise in water level until November when evapotranspiration intensifies, causing a lowering of level. This increase in water level, and the presence of a pronounced diurnal fluctuation has led to the conclusion that groundwater inflows is a significant inflow to this wetland. This wetland does not respond to rainfall as significantly as Mathews Lagoon or Boggy Pond.
- Wairio Stage 1 appears completely reliant on rainfall to maintain a presence of water. Over summer, the reduction in rainfall is insufficient to counterbalance losses from evapotranspiration. Subsequently, this dried up over the summer of 2013-2014. The water level in this wetland is extremely responsive to rainfall. On one occasion, a channel north of this wetland, which had a direct connection with Lake Wairarapa, flooded. This created a pulse of water into the wetland that matched the water level in Lake Wairarapa. This channel has since been filled in.

How sensitive to changes in precipitation and evapotranspiration is each wetland?

The sensitivity of each wetland to changes in precipitation and evaporation is different for each wetland.

- Wairio Stage 1 will be the most susceptible wetland of the three studied. It already is unable to sustain a permeant presence of water over the summer. Changes to the upper catchment area of this wetland may mitigate this in the future.
- The presence of groundwater as the major input into Boggy Pond makes it the least susceptible to climate change. The bathymetry of the wetland however means significant areas of wetland bed are exposed over a

relatively small range in water level. Extensive riparian areas will be in a state of drought for longer if water levels decrease from the current norm too much.

- Mathews Lagoon is highly dependent on pumping from the Te Hopai Pump drain. While it too has inputs from groundwater, its relative ability to maintain a stable water levels is impeded by the outflow culvert. Loss of water during dryer periods in the future could be mitigate by blocking outflows prior to summer. The main risk with this wetland is how changes in the distribution of rainfall will play out in the pumping regime of the Te Hopai Pump drainage scheme. Intensification of drought may reduce the volume and duration of pumping, critical in the maintenance of the current hydraulic regime.

How sensitive is evapotranspiration to predicted changes in radiation, temperature humidity, and wind speed out to 2040 and 2090?

The acquisition and assessment of meteorological data required to produce a potential evapotranspiration from a FAO Penman Montieth equation was completed. Forcing of this equation, and climate adjustments, in line with regional predictions identified that;

- Evapotranspiration is most responsive to changes in radiation intensity and least sensitive to increases in wind speed.
- Under the four Representative Concentration Pathways, downscaled by MfE (2016) from the IPCC 5th assessment report, increases in average potential evapotranspiration of between 3 - 7% out to 2040 and 4 - 17% out to 2090 can be expected.
- The largest monthly increase in potential evaporation is likely to occur in February where an increase of up to 21% can be expected under the RCP 8.5 scenario out to 2090.

How is rainfall, both locally and across each wetland system, likely to change with predicted changes in climate?

The design, construction and monitoring of a network of five pit gauges was used to determine the spatial distribution of rainfall over the wetland system. Results have identified that:

- Variation in rainfall is observed over the wetland area, with rainfall on the eastern shoreline of Lake Wairarapa being 18% higher over the study period than that caught in Mathews Lagoon.
- The variation in catch can be partially attributed to wind speed
- The GWRC operated OPTA tipping bucket gauge appears to under catch the true rainfall by up to 15%.
- Rainfall is predicted to increase in its intensity, but decrease in its frequency over the Wairarapa Region. This will become more pronounced in areas of that already exhibit low rainfall, like the lower valley where these wetlands are located.
- It can be expected that greater bursts of rain will occur over the winter and spring period, volumetric increases can be quantified based on MfE projections. The distribution of smaller rainfall events, critical in the maintenance of stable water levels in these wetlands will like around the critical drought period will likely substantially affect each wetland's

7.2 Recommendations for future work

While this thesis has refined the understanding around the hydrology of these wetlands, and has identified potential climatic responses, it has identified a need for further work. This work falls into two categories. 1), a better quantification of the hydrodynamic process that operate in the wetlands, and 2), the need for better understanding of how changes in climate will affect the temporal distribution of rainfall.

- It is recommended that water level data continue to be collected to generate a longer time series that can better reflect how these wetlands will respond to year to year changes in precipitation.
- Investment into the generation of a reliable rating curve for the Mathews Lagoon outflow should be a priority. The outflow series will need to take into account the pressure difference inherent in the control of the outflow culvert by relative changes in water level at Lake Wairarapa. To achieve this, water levels on both sides of the culvert should be measured, and a series of regular gauging's be conducted on the lake side. By generating a reliable rating curve, the quantification of the relative importance groundwater plays in this wetland can be achieved. Inflows into this wetland are based of the running time of pumps, and have been calibrated recently, they are therefore deemed suitably accurate.
- The defining limitation of this study has been its inability to determine how increases in evapotranspiration may affect or extend the period of time spent in drought by using the generalised regional predictions. The use of the actual downscaled climate models, which factor in temporal changes in precipitation, wind speeds, and temperature could be a way forward in better quantifying the relative effects changes in precipitation patterns may have.

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