Hydrological and chemical characteristics of Matthews Lagoon and Boggy Pond, Wairarapa:

Essential information for the decision making process of wetland restoration

BY

CHENG SHI

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School of Biological Sciences,

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Abstract

Wetlands are areas where lands transition to water bodies. Because of this special geomorphological setting, wetlands play important roles in flood control, nutrient retention, and water storage. In New Zealand, less than ten percent of the original wetlands have survived since human settlement. Many of the remaining wetlands are still under threat from water quality degradation, invasive species, and changes in hydrological regime. Wetland restoration is the process of bringing the structure and function of a wetland back to its original state. Although specific objectives may vary between different projects, three major objectives of wetland restoration are restoration of wetland function, restoration of wetland structure, and restoration of traditional landscape and land-use practices. In order to ensure the success of a wetland restoration project, a good understanding of the hydrological process in the wetland is the first step.

Boggy Pond and Matthews Lagoon are located at the eastern edge of Lake Wairarapa in the Wellington Region. They formed as a result of the deposition of sanddunes on the eastern shore and changes in river courses between floods. They were modified by a series of engineering works under the lower Wairarapa valley development scheme in the 1980s. As a result, Matthews Lagoon now receives agricultural outputs from surrounding farms; it is affected by water pollution and invasive plant species. Boggy Pond is cut off from Lake Wairarapa and surrounding wetlands by a road and stopbank, leaving a more stable water level compared to its original state. To analyse the water and nutrient balance in these two wetlands, factors such as surface flows, surface water levels, groundwater levels, rainfall, climate data, and water quality were assessed at various monitoring stations in this study.

It is believed that Matthews Lagoon and Boggy Pond have completely different water regimes. Matthews Lagoon receives surface inflow from the Te Hopai drainage scheme and discharges to Oporua floodway, but Boggy Pond only has rainfall as the water input. The results from the water balance analysis seem to support this assumption. An unexpected finding in Matthews Lagoon suggests that water might

bypass the main wetland, creating a shortcut between the inlet and outlet. As a result, the nutrient removal ability was considerably weakened by this bypass because of the short water retention time. In Boggy Pond, there may be an unknown water input which could adversely affect the water quality and natural water regime.

Boggy Pond is expected to have better water quality than Matthews Lagoon as the latter receives agricultural drainage from surrounding farms. The results from water quality monitoring also support this hypothesis. The nutrient balance in Matthews Lagoon showed very limited removal ability for phosphate but much higher removal rate for nitrate. The removal rate in summer for phosphate was less than 5% while in winter more phosphate was discharged from Matthews Lagoon than it received from Te Hopai drainage scheme. For nitrate pollutants, the removal rate was as high as 17% even in winter.

Some recommendations are given on the restoration of these two wetlands. First, set proper objectives according to their different functions. Second, enhance the nutrient removal ability of Matthews Lagoon by harvesting plants, removing old sediments, and creating a more evenly distributed flow across the wetland throughout the year. Third, restore the natural water level fluctuations and improve water quality in Boggy Pond by identifying any unknown water inputs first.

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1. Introduction

1.1. Context of study

Wetlands provide various ecological services such as water storage, flood control, nutrient retention, and carbon cycling (Russo, 2008). They are also a source of food and materials for human beings and wildlife (Schuyt & Brander, 2004). Known as "mother earth's kidney", the water purification or filtration function of the wetlands has been discovered and utilized by human beings for many years (Verhoeven & Meuleman, 1999). However, with human population growth and urban development, this practice is beginning to pose a negative impact on the health of wetlands. For one, the volume of wastewater is increasing as a result of economic development, but the size of wetlands that receive the wastewater usually remains the same or becomes even smaller. Consequently the natural water regime that occurs in wetlands will be dramatically altered because a significant amount of wastewater flows in (Cooke, 1991). Secondly, the chemicals in nutrient-rich or even toxic wastewater are changing the chemical environment in wetlands, which makes the habitat no longer able to support native floras or faunas (Cooke, 1991).

The damage that an ecosystem suffers can be measured and expressed by the degradation levels in its structure and function (Bradshaw, 1987). The structure is measured by species diversity and physical and biological complexity; the function is measured by productivity or biomass and nutrient cycling (Bradshaw, 1987). A healthy ecosystem usually has high levels of both, while a degraded ecosystem drives both attributes downwards (Bradshaw, 2002). There are many different approaches to bring back the original state of an ecosystem (see next chapter), among which, ecological restoration, according to the Society for Ecological Restoration (2004), is "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed."

Two wetlands on the eastern shore of Lake Wairarapa in the Greater Wellington Region, Boggy Pond and Matthews Lagoon, were the study objects of this research. Surrounded by dairy farms, these two wetlands suffer from different degrees of nutrient rich pollutants. However, to date, there is no quantified study on the water or nutrient regime of these wetlands. It is essential to discover and understand the problem first before applying any restoration actions on a degraded system (Bradshaw, 1987).

1.2. The importance of this research

The level of wetland degradation in New Zealand is high. There is an urgent need for wetland protection and restoration. This issue has been recognized by government organizations, non-government organizations and many wetland enthusiasts. For example, the New Zealand Wetland Management Policy published by the New Zealand Government in 1986 stated that “There is little legislation for protecting wetlands, and a lot of policy, equipment and expertise ready to facilitate destruction.” In addition, one of the aims of the National Wetland Trust is to “Ensure landowners and government agencies commit to wetland protection, enhancement and restoration.” Furthermore, one of the founders of National Wetland Trust, New Zealand wetland pioneer Gordon Stephenson, who helped develop the concept of the QEII Trust and was on the QEII board as deputy chairman until 1988, wrote a report “Wetlands: a Diminishing Resource” and a book “Wetlands: exploring New Zealand’s Shy Places”.

However, until today, the state of New Zealand wetlands is still not good. In a report produced by the Department of Conservation (DOC) (2012) summarising the conditions of the six Ramsar wetlands (wetlands of international importance, and more generally to improve the management of all wetland systems) in New Zealand, threats such as water quality decline and hydroloic regime alteration are identified as the main challenges in the future. These two major threats are the main concerns of this study.

For any restoration project, identifying the knowledge gaps and filling them is always the first step (Zedler, 2006, p. 349). To date, there are few detailed studies on the wetlands near Lake Wairarapa. Therefore, this study will provide basic but essential information about the hydrological and chemical environment of Boggy Pond and Matthews Lagoon.

As the main organisations responsible for management and restoration, Greater Wellington Regional Council (GWRC), DOC, and a local wetland committee are all interested in the study area. Water quality within Lake Wairarapa is a great concern to GWRC. Restoration and utilisation of the purification function of the wetlands around the lake is an effective way to reduce pollutant input. At the same time, GWRC is also seeking solutions to minimize the negative impact on the wetlands from agricultural activities around the study area. DOC focuses on the biodiversity of the wetland ecosystem around the lake. The works that DOC is involved in includes bird surveys, plant surveys, willow spraying, and predator control. The wetland committee represents the will of local residences, land owners, and farmers, who strongly concern about the value and future development of their land and surrounding areas. There are many potential restoration actions at this study site. Proposals including massive earth works such as diversion and damming are under discussion and consideration. Such actions will dramatically change the current hydrology regime in the wetlands. Implementing such actions without fully understanding the hydrological regime of the system is risky because it may alter the existing balance and change the habitat conditions so quickly that in some cases it may lead to local extinction of species (Sodhi et al., 2009). Therefore, a detailed study on the hydrologic regime is not only necessary but also crucial to the success of the restoration project.

1.3. Research objectives and goals

Therefore this research is aimed to: 1) identify and classify Boggy Pond and Matthews Lagoon; 2) investigate water balance and nutrient characteristics of these two wetlands that have been affected or potentially affected by nearby dairy farms; 3) provide information and suggestions on potential restoration actions on these two wetlands.

The specific objective of this study is to examine the water and nutrient balance within two wetlands near Lake Wairarapa in the Wellington region. Water quantity and quality within the two wetlands are the main interests because Boggy Pond is assumed to have better water quality and therefore higher ecological values for wildlife. On the other hand, the nutrient removal function and ability of Matthews Lagoon is valued by people because it acts as a filter for Lake Wairarapa. The questions that inspired this research are: Can human valued ecological services provided by wetlands, such as nutrient removal, coexist with other wetland services, such as wildlife habitat? How do people allocate restoration resources when both services are important for human beings? By comparing the results from the two wetlands, this study is hoped to provide wetland regulators the first hand information on the hydrological and chemical environment in these wetlands and assist future restoration actions for the wetlands within this region.

In addition to the rather broad goal, there are three specific objectives of this study, which break down the goal into three parts. First, record, analyse and compare the seasonal fluctuations of water levels in the two wetlands. Second, record, analyse and compare the nutrient levels within the two wetlands. Third, provide suggestions and recommendations on future restoration activities.

2. Background

2.1. What is a wetland?

2.1.1. Wetland definition

As Johnson and Gerbeaux (2004, p. 7) stated: “wetlands are precisely that: wet lands”. Similarly, Peters (2010) stated that “a wetland is literally a ‘wet’ land”. Therefore, the term “wetland” is a broad concept and covers various environmental variables. From a policy point of view, a clear and legally binding definition is the first step for wetland managers or regulators to protect or restore wetlands (Batzer & Sharitz, 2006). Government agencies and non-government organisations develop many different definitions for wetlands (table 2.1.1). However, legal definitions may not fulfil the needs of wetland ecologists. For example, none of the definitions in table 2.1.1 developed by these administrative bodies mentions the soil type of a wetland, which is one of the three wetland delineation criteria (vegetation, soils, and hydrology) according to US Army Corps of Engineers Wetlands Delineation Manual. These definitions mainly focus on water regime and landscape. Only one of them mentions plants and animals. As a result, ecologists developed more comprehensive definitions that facilitate classification, inventory, and research (Mitsch & Gosselink, 2011) (table 2.1.2). Because of the great diversity of wetland types (which will be discussed in detail in the next section), a seemingly straightforward task resulted in many definitions. In general, three major characteristics of a wetland are: 1) hydrologic condition that allows water to accumulate, 2) soils are dominated by anaerobic processes, and 3) plants and animals that are adapted to a wetland environment.

Table 2.1.1 Wetland definitions for the purpose of management by different organisations. Note that none of these definitions mention wetland soil, and only one of them mention plants and animals. These definitions developed by administrative organisations focus on water regime and landscape.

Organisation	Definition	Reference
Ramsar Convention on Wetlands (International)	Areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt including areas of marine water, the depth of which at low tide does not exceed 6 meters.	Convention on Wetlands of International Importance especially as Waterfowl Habitat, 1971
Resource Management Act (New Zealand)	Wetland includes permanently or intermittently wet areas, shallow water, and land water margins that support a natural ecosystem of plants and animals that are adapted to wet conditions.	Resource Management Act, 1991
U.S. Fish and Wildlife Service (United States)	Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water.	Cowardin et al., 1979

Table 2.1.2 Wetland definitions given by ecologists. Note that these definitions cover all three wetland parameters (hydrology, soils, and vegetation), which is different from the definitions given by administrative organisations (table 2.1.1).

Scholars	Definition	Reference
Paul Keddy	A wetland is 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.	Keddy, 2000 as cited in (Batzer & Sharitz, 2006, p. 3)
Stephen Zoltai	Land that has the water table at, near, or above land surface or which is saturated for a long enough period to promote wetlands or aquatic processes as indicated by hydric soils, hydrophytic vegetation and various kinds of biological activity which are adapted to a wet environment.	Zoltai, 1988 as cited in (Mitsch & Gosselink, 2011)
Julia A. Cherry	1. hydrology that results in wet or flooded soils 2. soils that are dominated by anaerobic processes, and 3. biota, particularly rooted vascular plants, that are adapted to life in flooded, anaerobic environments.	Cherry, 2012

2.1.2. Values of wetlands

Like forests and oceans, wetlands provide important ecological services, support a wide range of faunas and floras, and are traditional sources of goods, food, and materials. All these services, goods, and food are valued by humans. To distinguish and categorise wetland values and to better assist wetland management, the concept of total economic values (TEV) of wetlands has been adopted (Barbier, Acreman, & Knowler, 1997). Within the TEV, there are use values and non-use values. The former can further be subdivided into direct use values, indirect use values, and option use values (table 2.1.3).

Table 2.1.3 Total Economic Value for wetlands. Note that the values listed in this table are just some examples. Many other values may not be listed here. Source: Barbier, Acreman, & Knowler, 1997.

USE VALUES			NON-USE VALUES
Direct Use Value	Indirect Use Value	Option and Quasi-Option Values	Existence Value
• Agriculture • Fuelwood • Recreation • Transport • Wildlife harvesting • Peat/energy	• Nutrient retention • Flood control • Storm protection • Groundwater recharge • External ecosystem support • Micro-climatic stabilisation • Shoreline stabilisation	• Potential future uses (both direct and indirect uses) • Future Value of information	• Biodiversity • Culture, heritage • Bequest values

Direct use values

Food, water, materials, leisure, and shelters are some direct uses of wetlands (Schuyt & Brander, 2004). In New Zealand, eel hunting for food and flax gathering for weaving material are Maori traditional practice associated with wetlands (Hunt, 2007, p.71). Besides providing food and material, wetlands can also benefit local people by involved with wetland ecotourism or recreational hunting and fishing. In the U.S., wetland-related activities have become a multi-billion dollar industry (Ramsar Convention on Wetlands, 2011).

Indirect use values

Indirect use values of wetlands are not as obvious as direct use values, but they are equally important because the health of the entire ecosystems relies on the services delivered by wetlands. As transition areas between water bodies and land, water runs through wetlands before it runs into streams, rivers, lakes, or oceans. Studies have shown that wetlands are able to significantly trap and reduce sediments as water slows down when travelling through them (Ockenden et al., 2012; Olde Venterink et al., 2006; Zhu et al., 2012). Besides physical removal of the sediments, they also remove or reduce the level of pesticides, nutrients, heavy metals, and microorganisms through a series of chemical reactions (Woltemade, 2000). The purification function provided by wetlands plays a significant role in material and nutrient cycling. Wetlands also act as buffer zones which regulate and balance water between floods and droughts (Cernohous, 1979). In some wetlands, soil stores water from floods in the wet seasons and slowly releases water during dry periods. Other ecological services of wetlands include carbon sequestration, climate stabilization, and groundwater regulation (Schuyt & Brander, 2004).

Option values

It is believed that there are potential values (direct or indirect) of wetlands which have yet been discovered but which could have great use in the future. This category of values can also be called future values, potential values, or option values (Barbier, et al., 1997).

Non-use values

Many wetland ecosystems are so rich and fertile that they can support abundant fauna and flora (Moore & Garratt, 2008). Wetlands provide perfect breeding, feeding, and foraging habitat for many animals (Johnson, 2012), which makes wetlands great places for education and for preserving genetic, species, and biological diversity (Stuip, Baker, & Oosterberg, 2002). For those people whose life, culture, and history are closely related to wetlands, wetlands also have cultural and heritage values (Omari, 1993). These non-use values of wetlands are also called existence or intrinsic values.

2.1.3. Wetland classification

Classification of wetlands is complicated because wetlands are such diverse ecosystems. Wetlands can be classified by many factors, in which water quality, vegetation type, salinity, water depth, and hydrological conditions are the most common ones (Johnson & Gerbeaux, 2004). In North America, inland wetlands are usually classified as low-nutrient bog or marsh (Mitsch & Gosselink, 2011). In Europe, fresh water wetlands are classified into at least four different types based on the vegetation, nutrient level, pH, and substrate characteristics (Mitsch & Gosselink, 2011). Johnson and Gerbeaux (2004) summarised six classification levels for wetlands in New Zealand (appendix A), which cover the overall hydrological conditions and separate wetland classes according to pH, water quality, water regime, and dominant vegetation type. Three levels that are relevant to this study are listed in table 2.1.4.

Table 2.1.4 Three major wetland classification levels used to identify wetland type in this study. Source: Johnson & Gerbeaux, 2004, p. 15.

Hydrosystem	(Based on broad hydrological and landform setting, salinity, temperature) Marine, Estuarine, Riverine, Lacustrine, Palustrine, Inland saline, Plutonic, Geothermal, Nival
Wetland class	(Based on substrate, water regime, nutrients, pH) Bog, Fen, Swamp, Marsh, Seepage, Shallow water, Ephemeral wetland, Pakihi and gumland, Saltmarsh
Composition of vegetation	(One or more dominant plants)

The problem of classification not only arises from the diverse nature of wetlands, but is also caused by differences in terminology for different regions. There are many different terms that are used to describe wetlands around the world. Mitsch and Gosselink (2011) listed 35 common terms used for different wetland types in the world (see appendix B). Despite various terms being used, one term could represent different types of wetlands in different regions. For example, the word swamp means a wetland dominated by woody plants in the North America context (Mitsch & Gosselink, 2011), but in New Zealand the vegetation types in swamps are much more varied, including tall herb, flax, reed, rush, and sedge types (Clarkson & Peters, 2010 a). Therefore, caution should be used with an appreciation of international audiences when using these terms, even in the scientific literature (Mitsch & Gosselink, 2011).

In New Zealand, five major fresh water wetland classes are identified (Johnson & Gerbeaux, 2004; Clarkson & Peters, 2010 a):

Bogs

Bogs are peat-accumulating systems fed only by rainwater and thus have very low nutrient levels. They are usually strongly acid, and water flow is restricted. The water table is either at or just below the surface and remains relatively constant. Vegetation is highly variable in bogs: tree species to mosses can all be found in this type of wetland.

Fens

Fens have a shallower peat substrate with more decomposition than in bogs. They are fed by both rain and groundwater, resulting in low to moderate nutrient and acidity levels. The water table is typically just below the peat surface with small but noticeable fluctuations. Scrubs, tall herbs, tussock grasses, ferns, restiads and sedges are usually the dominant vegetation in fens.

Swamps

Swamps are relatively high in nutrients, supplied by nutrients and often sediment via surface runoff and groundwater from surrounding land. Substrates are typically a combination of mineral soils and well decomposed peat. The water table is usually above some of the ground surface, though due to large, seasonal fluctuations can periodically be much higher or lower. Vegetation cover is also wide-ranging, including sedge, rush, reed, flax, tall herb, or scrub types, often intermingled, and also forest. Heavily invaded by willow is often a typical signature of swamps.

Marshes

Marshes are characterised by large periodic fluctuations of water table or water level. They can experience water-level drawdowns that result in portions drying out and exposing the mineral substrate, but the soil usually remains moist. They have a lower overall water table, higher nutrient levels and a higher pH than swamps. Ephemeral wetlands are a subset of the marsh type in which ponding and drying out occur on a seasonal basis. In more extreme cases, the vegetation alternates between aquatic and terrestrial. Vegetation is mostly rushes, grasses, sedges and herbs.

Shallow water

Shallow water wetlands are characterised by the presence of open standing water, generally less than a few metres deep. This includes intermediate-size water bodies not large enough to be considered lakes or lake-like, though more significant than just smaller water bodies and leads (channels of open water). Also included are the margins of lakes, rivers, and estuary waters. Nutrient levels and water chemistry are basically those of the water as opposed to the substrate. Submerged, floating or emergent aquatic plants are the dominant plant species in shallow water.

The differences in water source, water flow and fluctuation, nutrient level, pH, and peat content among the five types of fresh water wetlands in New Zealand are shown in table 2.1.5. In terms of water quality and water regime, bogs have the lowest level of nutrients and fewer fluctuations. Marshes, on the other hand, are completely opposite. Shallow water has a wide range of water sources and water quality.

Table 2.1.5 Differences and gradation among the five major fresh water wetlands (wetland class as shown in table 2.1.3). The five parameters are shown as gradients across bog, fen, swamp, and marsh. Shallow water wetland could cover all ranges in the five parameters. Source: Clarkson & Peters, 2010a.

Wetland Class	Bog		Fen Shallow Water	Swamp	Marsh
Water Source	Rainfall	–›	Rainfall Groundwater	–›	Rainflall Groundwater Surface water
Water flow and fluctuation	Low	–›	Medium	–›	High
Nutrient availability	Low	–›	Medium	–›	High
pH	Low (acidic)	–›	Medium	–›	High (neutral)
Peat content	High (none)	–›	Medium	–›	Low

2.1.4. Brief history of New Zealand wetlands

McGlone (2009) made a research on the history of New Zealand's wetlands. Most New Zealand wetlands formed around 18,000 to 14,000 years before present (BP), at the end of the last glaciation. As climate warmed up, in the early Holocene (11,500 years BP), wooded wetland began to spread out. By the time Maori arrived approximately 800 years ago, 1% of the New Zealand landscape was covered with wetlands, most of which supported woody vegetation. Fire and logging removed the woody cover of wetlands resulting in altering hydrological conditions at both the local and catchment scale. Draining and developing wetlands for productive farmland or other purposes associated with European settlement dramatically reduced the total area of wetland. Since then, New Zealand has lost 90% of its origin wetlands, representing the highest rate of loss in the world (Greater Wellington Regional Council, 2005). In some parts of the country the remaining natural wetland is less than 3.5% of the original extent (Thompson, 2012).

2.2. Wetland hydrology

Wetland hydrology, in general, includes the water movement within a wetland and its interaction with plants, animals, and soils across a certain period of time (Campbell, 2010). More specifically, according to the United States Environmental Protection Agency (2008), water level, hydrological pattern, and residence time are the three major elements that wetland hydrology covers.

Water level is the general water depth above the soil surface. Different water levels favour different types of vegetation in wetlands (figure 2.2.1). Floating and submerged plants usually dominate deep water zones. Emergent macrophytes are present in shallower zones, while areas of exposed, saturated soil is generally covered with other macrophytic vegetation. Therefore, vegetation types can be used to estimate water levels when direct measurement is not available (Goslee, Brooks, & Cole, 1997). Water levels can also be used to predict vegetation types in different zones of a wetland (Barrett, Nielsen, & Croome, 2010; Weiher & Keddy, 1995). Water level in a wetland is also an important factor indicating the level of flow "short-circuiting" (McJannet, Wallace, Keen, Hawdon, & Kemei, 2012), as the higher the water level, the more likely water will be short-circuiting through the wetland, and therefore decreasing the purification effect of a wetland. Like many other hydrological variables such as water table, tides, rainfall, and evapotranspiration, water level fluctuates in a wetland. A study by Knight, et al., (1987) showed that appropriate water level fluctuation increases the removal of nutrients in the water.

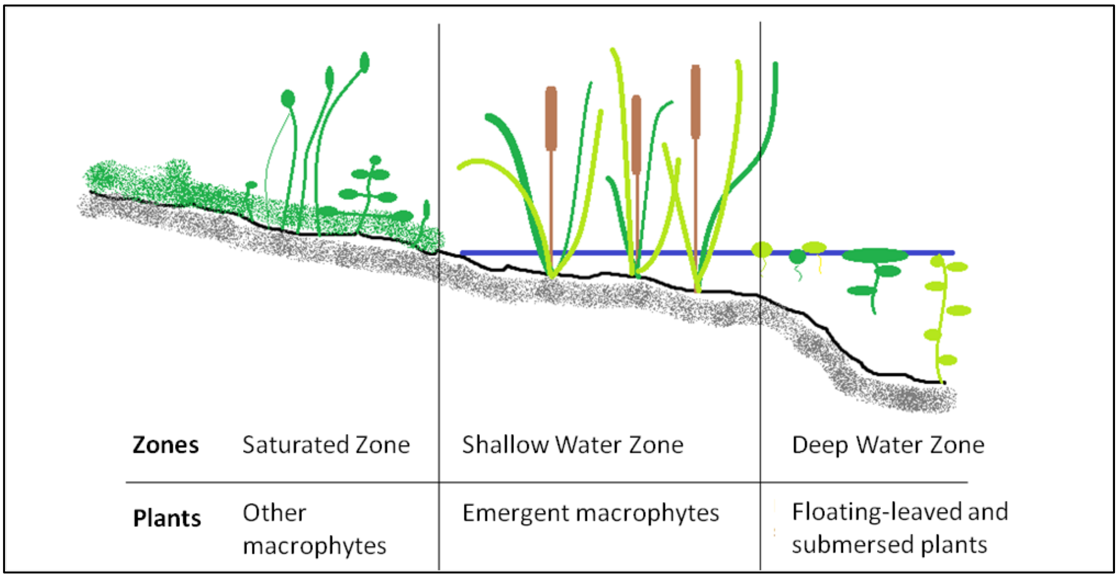


Figure 2.2.1 Cross-section of wetland indicating water level and vegetation types. Modified from Knight, et al., 1987

Hydrological pattern is the timing, duration, and distribution of water levels. Tidal wetlands exhibits water level changes within a day while seasonally-flooded wetlands have much slower fluctuations. Different length of hydropattern sometimes favours different plants (Davis, Bidwell, & Hickman, 2009).

Residence time is the travel time that the water takes to run through a wetland. Residence time is determined by two factors: wetland volume and flow rate. A large volume with a small flow rate results in longer residence time, while small volume with a large flow rate results in shorter residence time. Residence time plays a key role in the process of nutrient removal (Knight, et al., 1987), normally, the longer the residence time the better the nutrient removal (Dierberg & DeBusk, 2005). In most cases, in order to improve water quality, wetlands should retain water for at least four days to a few weeks (Huang, Reneau Jr, & Hagedorn, 2000; Tanner, Clayton, & Upsdell, 1995; Toet, Logtestijn, Kampf, Schreijer, & Verhoeven, 2005; and Woltemade, 2000).

Water movement is the result of energy flow; wetland hydrology therefore can be seen as the driving force of a wetland (Thompson, 2012). It is well recognised as the most important component of a wetland (Cherry 2012; Campbell, 2010; Mitsch and Gosselink as cited in Labadz et al, 2002; Rosenberry & Hayashi, 2013; and Thompson, 2012). Hydrology is also the primary determinant of wetland type and function (Jackson, 2006). Any alternation in hydrology can potentially result in wetland degradation or destruction (Campbell, 2010). Wetland managers and ecologists should also be aware that every wetland has its own hydrological regime which requires a unique management approach. There is no one-size-fits-all solution for wetland management (Thompson, 2012). Therefore, understanding the hydrology of a wetland is essential.

2.3. Wetland pollution and degradation

Human activities have dramatically changed the nature of wetlands in New Zealand (Hunt, 2007). Agricultural, industrial and domestic run off often contain high levels of nitrogen (N) and phosphorus (P) (Carpenter et al., 1998). Excessive inputs of N and P from human activities can result in eutrophication in the wetlands, which directly leads to wetland degradation (Carpenter, et al., 1998). Table 2.3 lists the trophic states and their N and P level for fresh water bodies. Algal blooms are one of the symptoms of eutrophication. The oxygen shortage and toxic release caused by algal blooms could significantly reduce the biodiversity in a wetland (Carpenter, et al., 1998). Although wetlands are able to tolerate and purify some levels of pollution, this ability is restricted by many factors such as the age of the wetland, vegetation type, how fast the water runs through the wetland, temperature, and even size and shape of the wetland (Woltemade, 2000).

Table 2.3 Approximate trophic states. Source: Thompson, 2012.

Trophic category	Total phosphorus (g/m^3)	Total nitrogen (g/m^3)
Oligotrophic	<0.02	<0.6
Mesotrophic	0.02-0.05	0.6-0.9
Eutrophic	0.05-0.2	0.9-2.0
Hypertrophic	>0.2	>2.0

The utilisation of natural wetlands as wastewater treatment sites has been practiced since the 1950’s (Verhoeven & Meuleman, 1999). Both chemical reactions and physical processes are involved in the purification process (McJannet, Wallace, Keen, Hawdon, & Kemei, 2012). Using wetlands to treat agricultural wastewater has been a common practice in New Zealand. There are three major reasons behind this: First, land application of agricultural wastewater is more economically feasible when compared to other options such as storing and transporting wastewater to treatment plants (Cooke, 1991). Second, with the introduction of the Resource Management Act (RMA) in 1991, the practice of wastewater discharge to streams was phased out by regional councils (Houlbrooke, et al., 2004). Third, in Maori culture, bodies of water are seen as a spiritual symbol (wairua). Direct discharge of wastewater to water bodies is considered offensive (Cameron & Trenouth, 1999).

However, using wetlands to treat agricultural wastewater also changed the water regime and enhanced the nutrient level of natural wetlands (Houlbrooke, 2004). Consequently, it may change the plant and animal communities and reduce habitat and intrinsic values in a wetland for a long period (Greater Wellington Regional Council, 2005). Figure 2.3 shows how agriculture activity, especially dairy farms, poses a threat to the water quality in wetlands.

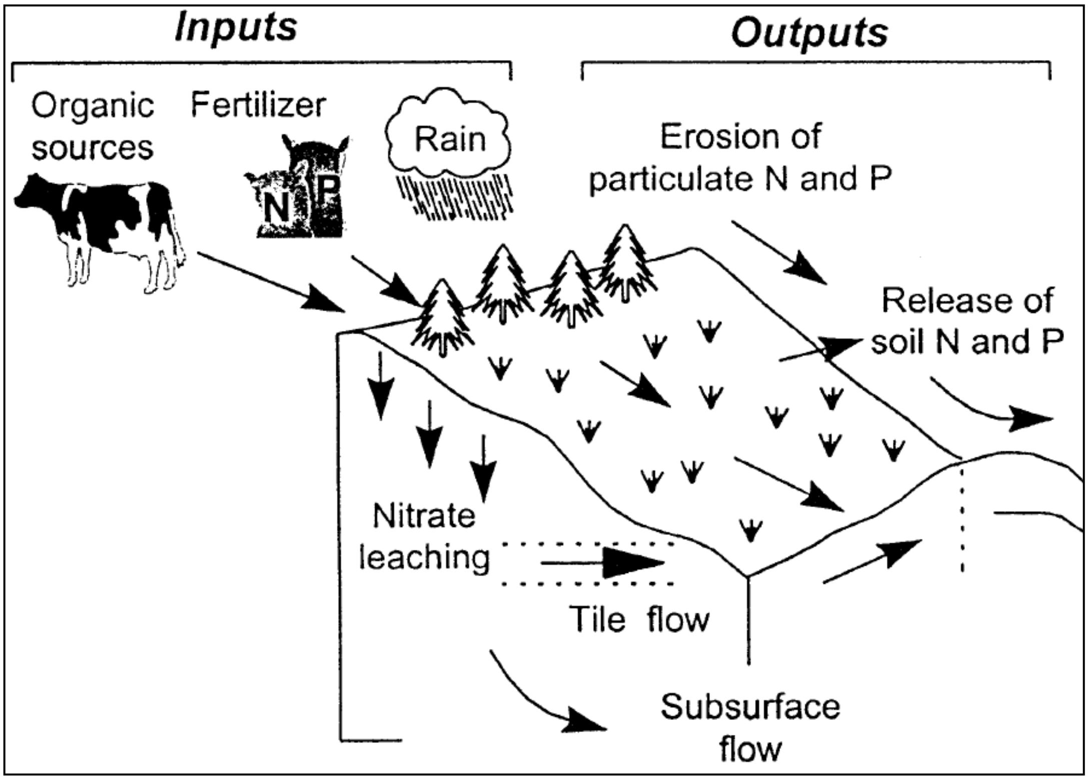


Figure 2.3 The process of nutrient-rich pollutants released from a dairy farm. Source: Carpenter et al., 1998.

2.4. Ecological restoration of wetlands

As stated in the introduction, ecological restoration is the process of bringing an ecosystem's structure and function back to its original state. In a narrow sense, restoration means bringing everything faithfully back to what it was before (Bradshaw, 2002). However, this understanding of restoration has led to many problems. First, the record on or the knowledge of the original state may be limited or absent (Egan & Howell, 2001). Second, even though the original state is known, the initial conditions for wetlands or other ecosystems may have changed which makes restoration to the original state impossible (Zedler, 2006). Lastly, because the ecosystem is constantly changing and the end point ecosystem is not a fixed entity, there is no way to measure whether the restoration is achieved (Bradshaw, 2002). A wide sense of restoration, on the other hand, can be applied to the individual components of an ecosystem (Bradshaw, 2002). This context allows ecologists, engineers, managers, and community groups to focus on restoring one or a few fundamental ecological processes. Successful restoration should then be built on good understanding of the system and therefore takes a relatively short period of time compared to natural succession (Bradshaw, 2002).

There is more than one approach to recover or improve a degraded ecosystem. Natural processes of primary succession will restore the ecosystem to its original state after the disturbance is removed (Miles & Walton, 1993 as cited in Bradshaw, 2002). If successful restoration is not completed, then what is achieved may be called rehabilitation (Bradshaw, 1987). Replacement or reclamation aims to only bring back or enhance the function of an ecosystem, but this is usually achieved by reducing the diversity or complexity in the structure (Bradshaw, 1987). These processes are all demonstrated in figure 2.4.

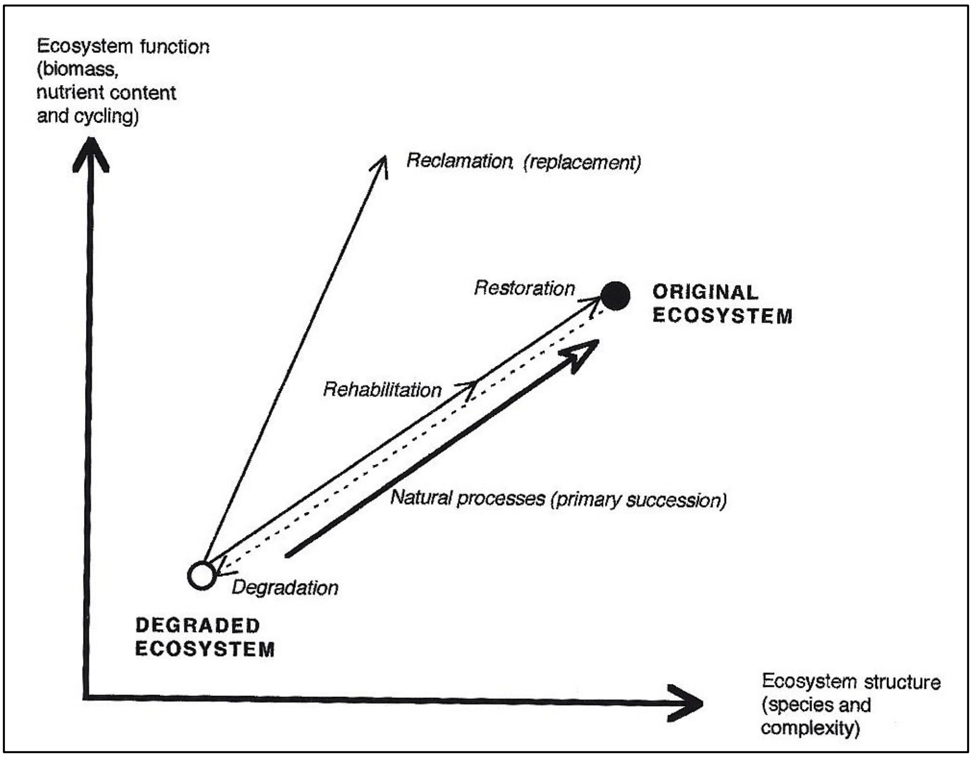


Figure 2.4 Different approaches for the improvement of a degraded system. Source: Perrow & Davy, 2002, p. 5.

Wheeler, et al. (2008) stated three major objectives of wetland restoration: restoration of wetland function, restoration of wildlife conservation, and restoration of traditional landscapes and land-use practices. Due to the complexity of wetland ecosystems and the diverse goals of stakeholders, a restoration project usually has more than one objective. Factors such as the size and scale of the project, the level of degradation, and the funding, labour, and time availability must be considered when setting restoration goals or objectives. The "SMART" (Specific, Measurable, Achievable, Realistic, and Time-bound) principle (Clarkson & Peters, 2010b) provides a good guideline for developing a set of goals and objectives for wetland restoration project.

3. Regional setting and site description

3.1. Lower Wairarapa Valley catchment

Lake Wairarapa is the largest lake in the Wellington region, about 50km east of Wellington city. The lake and its surrounding areas are part of the Lower Valley catchment of the Wairarapa Valley (figure 3.1.1). The Lower Valley has been modified and regulated for flood protection purposes since the 1960's (Airey, Puentener, & Rebergen., 2000) under the Lower Wairarapa Valley Development Scheme (LWVDS), which is "one of New Zealand's largest and most ambitious flood protection projects, benefiting a total land area of 31,500 hectares" (Greater Wellington Regional Council, 2013). 190 km of stopbanks were constructed under this scheme. One of the most remarkable projects was the diversion of the Ruamahanga River, which was diverted from its direct course into Lake Wairarapa, through a 4.5 km constructed channel into the Lower Ruamahanga (figure 3.1.2). Such earthworks effectively controlled the floods in the lower catchment, but also significantly changed the natural hydrological conditions of the wetlands in the same area. A lot of wetlands have lost their connectivity with the river (Watts and Perrie, 2007) and have been drained for agricultural development (Robertson and Heather, 1999).

Agriculture is an important industry in southern (lower) Wairarapa, which contains almost 50% of the dairy cattle in the Wellington region (Sorensen, 2012). Most of the farming near the lake takes place on poorly drained soils and would not have been possible without an engineered drainage system (Perrie & Milne, 2012). There are six pump drainage schemes servicing 3550 hectares near the lake (Figure 3.1.3). For example, the Te Hopai pump and drainage scheme benefits 1,003 ha of farmlands on the eastern shore of the lake. The water from the Te Hopai pump station goes into Matthews Lagoon directly, which is one of the two wetlands in the study area.

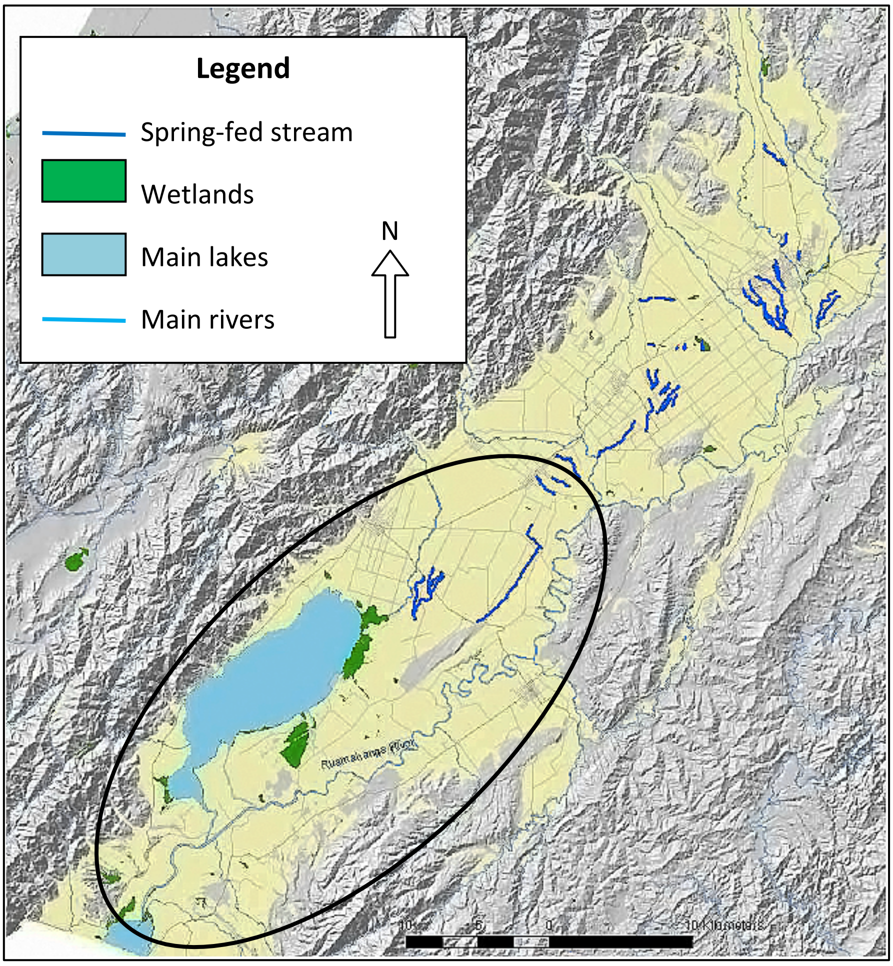


Figure 3.1.1 Wairarapa Valley with black oval indicating the Lower Valley catchment. Source: Greater Wellington Regional Council, 2011.

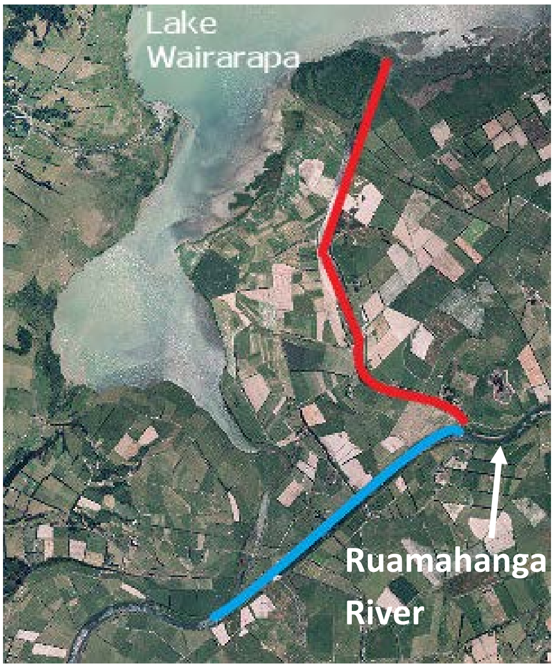


Figure 3.1.2 Ruamahanga Diversion. The blue line represents the man-made channel that diverts the Ruamahanga River away from the old Ruamahanga River channel (the red line) which went into Lake Wairarapa. The Ruamahanga River now bypasses Lake Wairarapa and flows to the lower Ruamahanga River through the man-made channel.

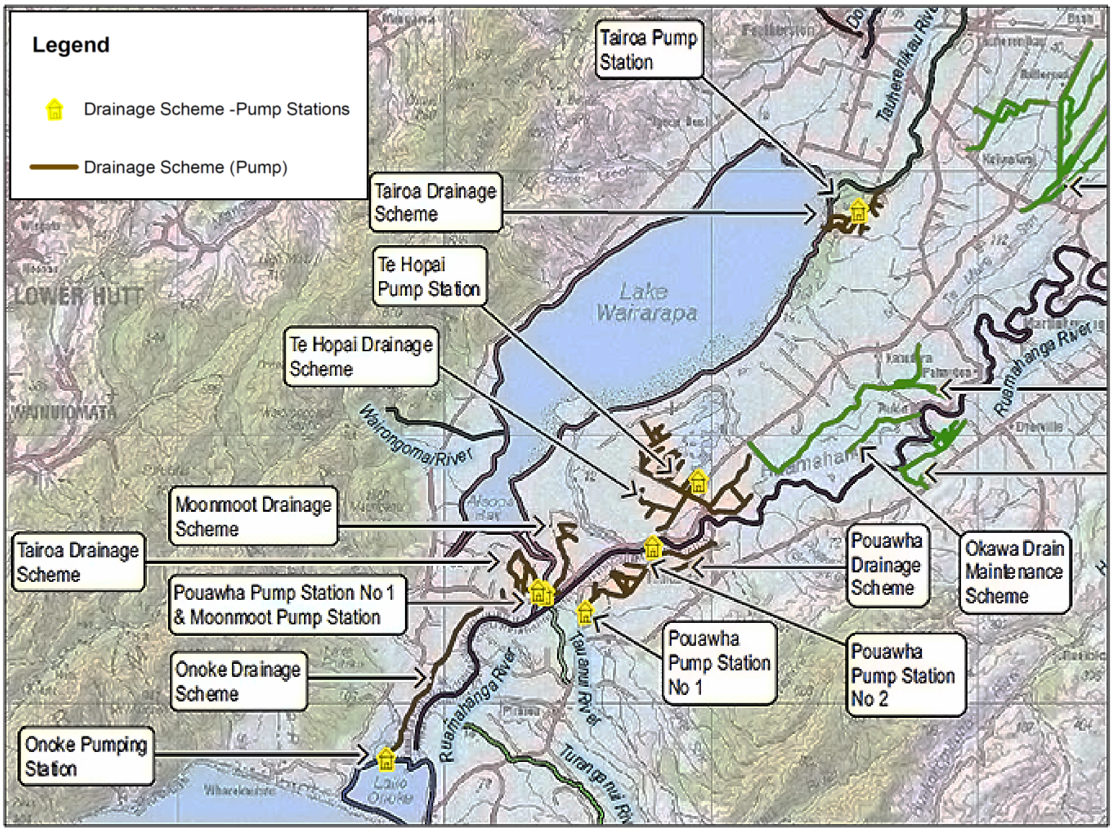


Figure 3.1.3 Locations of pump stations and drainage schemes in the Lower Valley Catchment. Source: GWRC, retrieved from: http://www.gw.govt.nz/assets/Our-Services/Flood-Protection/Other-River-and-Stream/Wairarapa-Watercourses-O-214-04.pdf

3.2. Matthews Lagoon and Boggy Pond

Matthews Lagoon and Boggy Pond are the two wetlands studied in this research. They are close to each other and located along the eastern shore of Lake Wairarapa (figure 3.2.1). They were formed as a result of depositions of sandstorms from the lake bed when the lake levels were seasonally very low, together with trapped water from changes in river courses (Airey, Puentener, & Rebergen., 2000). They were isolated by stop banking as part of the LWVDS, and were separated from each other by a common stopbank (Cooke, 1991).

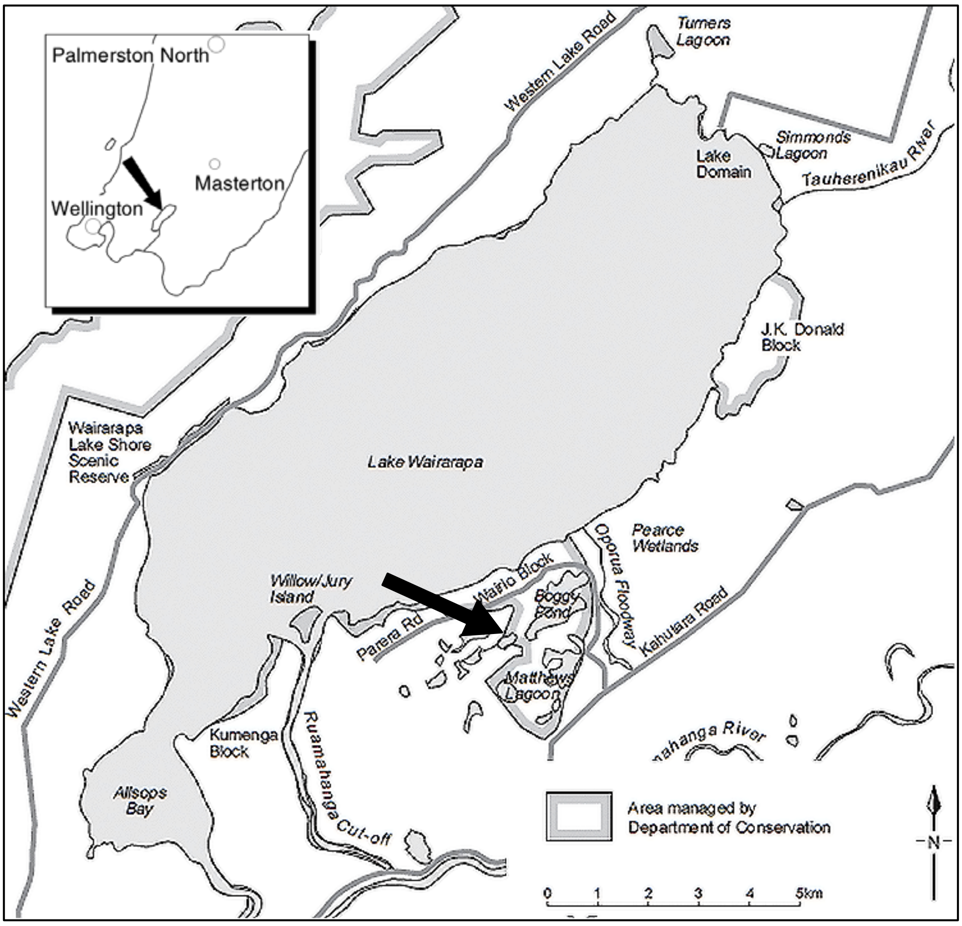


Figure 3.2.1 The location of the wetlands on the eastern shore of Lake Wairarapa. *Source*: DOC, 2000.

Matthews Lagoon occupies an area of 250 ha. Water from the Te Hopai pump station enters Matthews Lagoon from its southern end and joins the Oporua floodway at the outflow through twin culverts in the northern end near Parera Road (figure 3.2.2). Its surroundings are mainly dairy farms with some sheep and crop farms. There is a stopbank separating Matthews Lagoon and Boggy Pond. Water quality in Matthews Lagoon is assumed to be nutrient-rich. Raupos (*Typha orientalis*) and willows (*Salix cinerea*) are abundant in Matthews Lagoon. A weed plant, hornwort (*Ceratophyllum demersum*), has become a major problem in Matthews Lagoon.

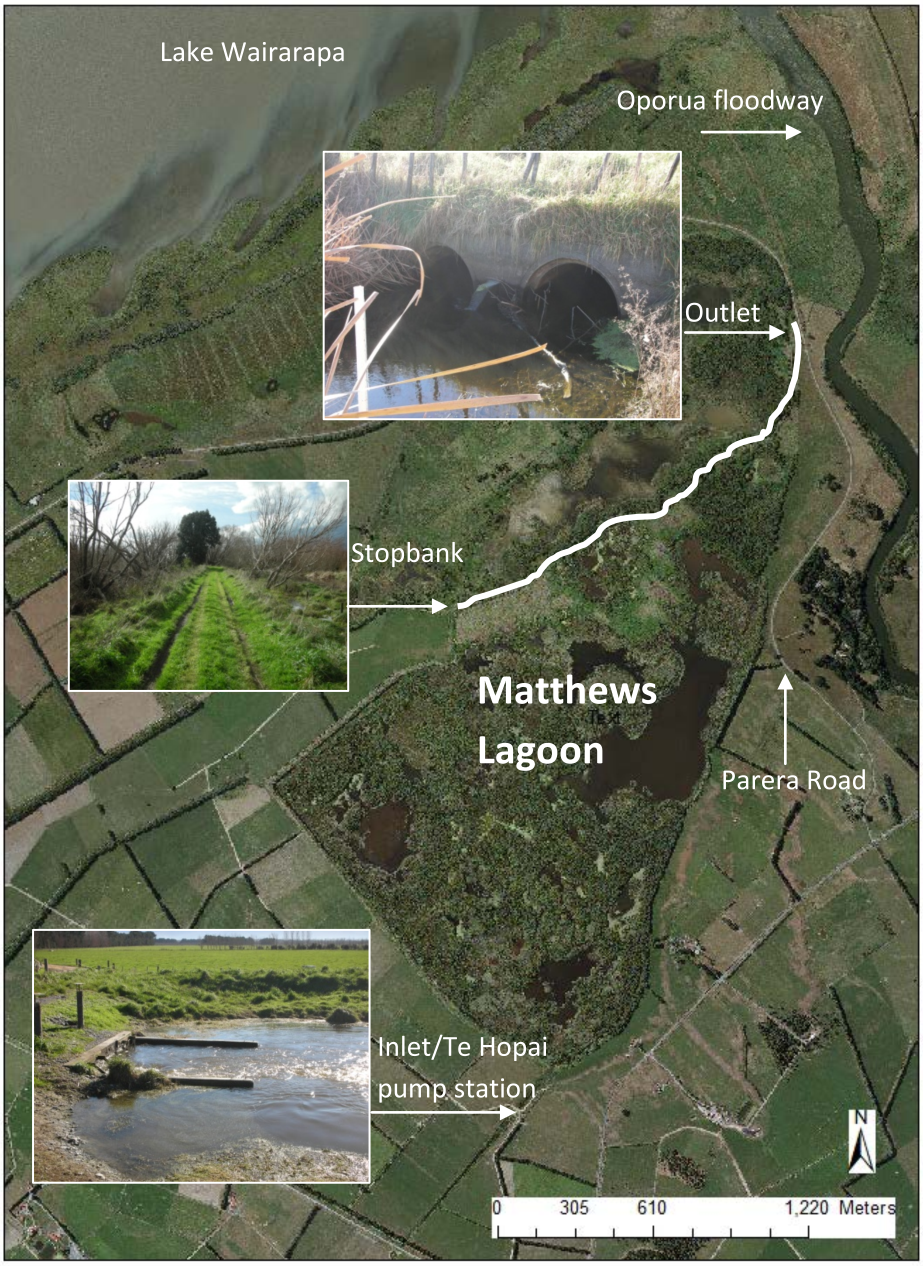


Figure 3.2.2 Matthews Lagoon and its surroundings with civil structures. The Te Hopai pump station (inlet) services 1,003 ha farm lands and pumps agricultural drainage to Matthews Lagoon. Water runs out through twin culverts at the northern end under Parera Road (outlet) and joins Oporua floodway. Raupo, willow, and hornwort are abundant due to the high level of nutrients from the Te Hopai drainage scheme. Source of aerial photo: GWRC.

Boggy Pond is to the north of Matthews Lagoon. It is about 145 ha and surrounded by Parera Road on its northern and eastern side. On its western side, there are agricultural lands (figure 3.2.3). In theory, rainfall and groundwater are its main inputs. This is because Boggy Pond is physically isolated from other sources of water input. However, in 1983, the stopbank separating the two wetlands was cut open at the eastern end allowing water to mix in the two wetlands. This cut was replaced by a control gate five years later (Cooke, 1991). There was also an outlet to Oporua floodway, but this was sealed in 2011. Surveys in the 1980's had found much more native and rare plant species in Boggy Pond than in Matthews Lagoon (Cooke, 1991). Raupo are now also abundant in Boggy Pond. The level of hornwart invasion is low (Airey et al., 2000).

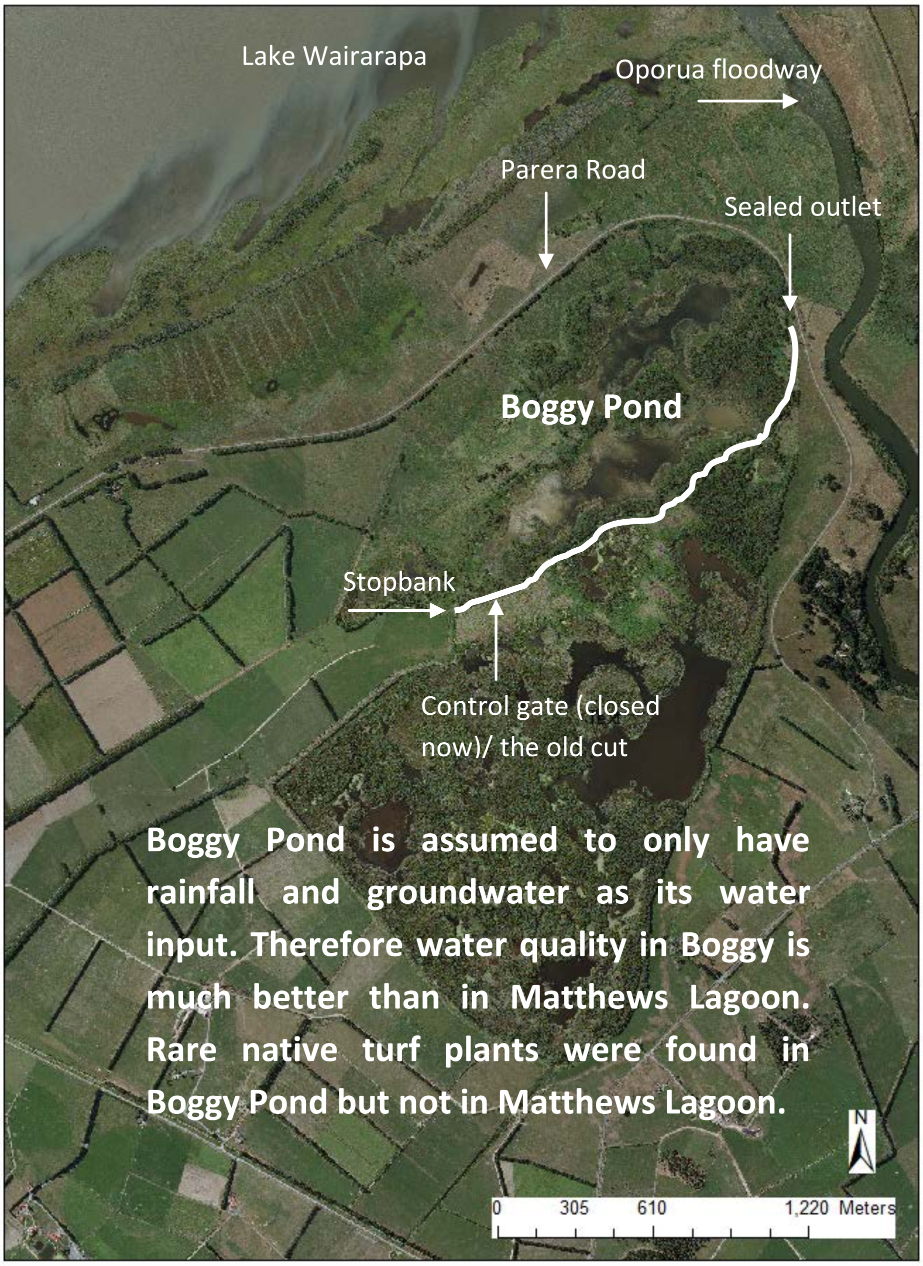


Figure 3.2.3 Boggy Pond and its surroundings. Source of aerial photo: GWRC.

4. Methodology

4.1. Water balance

In order to understand the hydrological processes of the study site, an insight into the water balance and quantitative water movement is useful. The concept of water balance or water budget is based on the physical principle of conservation of mass (Labadz et al., 2002; Jackson 2006), which can be simplified as:

$$changes\ in\ storage = inputs - outputs \qquad Equation\ 4.1.1$$

For wetland water balance, there are many different types of inputs and outputs. However, to measure all of them is expensive, difficult, and time consuming (Jackson, 2006). Some of these inputs or outputs are also insignificant or irrelevant to this study and therefore can be ignored (table 4.1.1).

Table 4.1.1 Potential water inputs and outputs for wetlands and their status in this study.

Potential inputs		Potential outputs	
Precipitation	(measured)	Evapotranspiration	(calculated)
Surface channel flow	(measured)	Surface channel flow	(measured)
Surface diffuse flow	(insignificant)	Surface diffuse flow	(ignored)
Tides	(insignificant)	Tides	(ignored)
Overbank flow during floods	(irrelevant)	River return flow following floods	(irrelevant)
Groundwater spring flow	(irrelevant)	Groundwater seepage flow	(estimated)
Groundwater diffuse flow	(estimated)	Human withdraws	(irrelevant)
Overland flow	(irrelevant)		
Human inputs	(irrelevant)		

A simplified water balance model is shown in figure 4.1.1 and a conceptual water balance equation that guided this study yields:

$$dS = Q_{in} + R + G_{in} - (Q_{out} + E + G_{out}) \qquad Equation\ 4.1.2$$

Where:

dS = changes in the wetland water volume (mm)

Q_{in}= surface flows into the wetland (mm)

R = precipitation (mm)

G_{in}= groundwater inflow (mm)

Q_{out}= surface flows out of the wetland (mm)

E = evapotranspiration losses (mm)

G_{out}= groundwater outflow (mm)

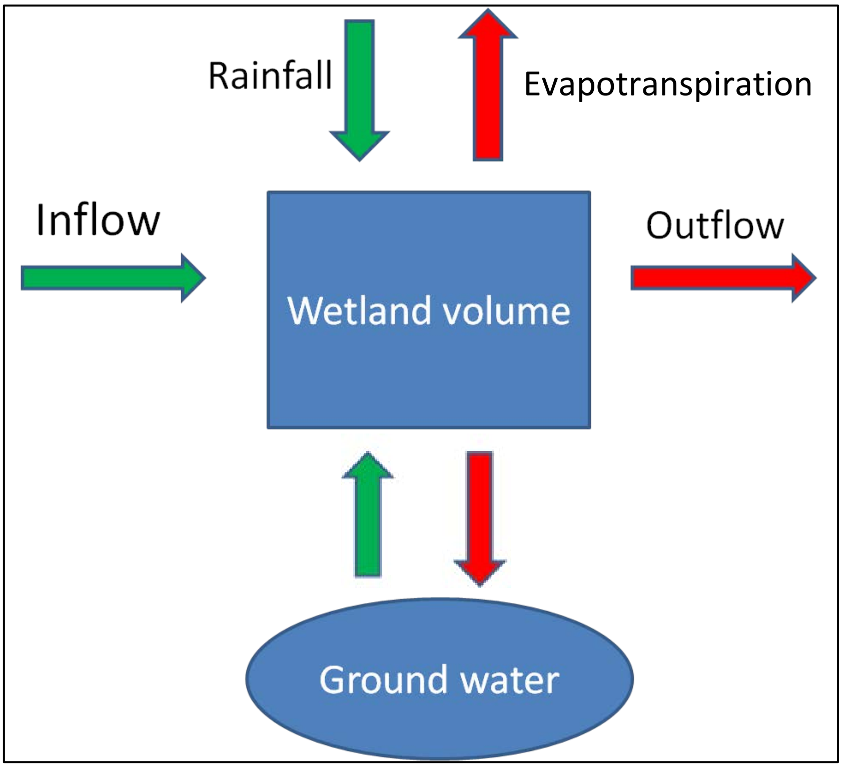


Figure 4.1.1 Conceptual water balance model. Green arrows indicate water inputs; red arrows indicate water losses.

When data are not available for one or more components in a water balance equation, certain assumptions can be made to eliminate those missing components. For example, groundwater level can be assumed to be the same throughout the year. Consequently, flows between groundwater and the wetland can be ignored. Similarly, wetland water volume can also be assumed to be unchanged throughout a year, which makes total water inputs equal to outputs.

4.1.1. Precipitation

Wetlands receive precipitation as water input in the form of rain, snow, hail, mist, dew, fog, and sleet (Holden, 2008; Labadz et al., 2002). Almost all wetlands will have some degree of direct precipitation, making measuring precipitation an important part in the water balance.

In practice, precipitation is expressed in the units of length (mm or cm). In this way, precipitation is assumed to be evenly distributed over a certain area so the total volume of water is divided by its surface area (Holden, 2008). If duration and time are considered in the process, then the intensity of the precipitation can be used (for example, a rainfall of 30 mm/h lasts for 30 minutes) (Labadz et al., 2002).

Rain gauges are traditional devices to record precipitation (Rasmussen, 2008). These instruments gather and record the amount of liquid precipitation over a period of time. There are many different types of rain gauges (e.g., standard rain gauge, tipping bucket rain gauge, weighing rain gauge, and optical rain gauge). Table 4.1.2 summarizes some advantages and disadvantages between weighing-type and tipping-bucket type gauges. Wind, forest canopy, steep terrain, extreme event, and instrument design are known to cause errors when measuring rainfall with gauges (Wagner, 2009). Nowadays, radar techniques are used to remotely estimate total rainfall over a catchment, which provide a more accurate and efficient way of gathering precipitation data (Holden, 2008).

Table 4.1.2 Comparison of two types of recording rain gauges.

Type of gauge	Advantages	Disadvantages
Weighing type	1. Can measure all kinds of precipitation (rain, snow and gale) 2. No underestimation in heavy rain	1. Expensive 2. Requires more maintenance
Tipping-bucket type	1. Easy to record the data (pulse) 2. Easy to observe rainfall intensity from raw data	1. Underestimates in heavy rain when bucket tipping 2. Underestimates in light rain when the amount of water is not heavy enough to tip 3. Cannot measure snow or hail unless install heating facility

In general, precipitation readings from one gauge cannot be applied to the whole catchment (Holden, 2008). First, according to Winters (1981, as cited in Dingman, 1993), point measurement of individual storms can lead to errors as high as 75%. Errors in short-term averages are commonly in the 15-30% range. Second, the windy nature of the study site may potentially increase the uncertainty of the measurements as well, because wind is known to cause the most significant and common errors for gauges (Dingman, 1993, p. 107). Lastly, due to topography and many localized factors, adding more tipping-bucket gauges measuring precipitation at the study site does not necessarily increase the accuracy of the results.

However, for this particular study, point measurement is used because the study site is relatively small and the purpose is to get a general trend in the overall water movement rather than precise components in water balance. Furthermore, errors from precipitation data may be insignificant when compared with other components in water balance computation (for example, groundwater and evapotranspiration). Lastly, since the limitations from tipping-bucket gauges are inevitable, increasing the sample size by using more tipping-bucket gauges may increase precision of the rainfall data but may not improve accuracy.

4.1.2. Evapotranspiration

Evapotranspiration (ET) consists of evaporation and transpiration. In the wetlands, evaporation represents the water movement from open water surfaces, plant canopy, and soil to the atmosphere. Transpiration accounts for the water movement from plants to the atmosphere through stomata in leaves (Allen, Pereira, Raes, & Smith, 1998). The level of evapotranspiration is affected by many factors (Holden, 2008): solar radiation (providing latent heat), air temperature (influencing the vapour capacity to hold moisture), wind speed (removing saturated air at the water surface), humidity, turbulence caused by topography or surface roughness, plant biology, and water availability. Therefore, quantifying evapotranspiration is a complex task.

The concept of potential evapotranspiration (PET) is adopted by hydrologists to indicate the meteorological conditions or the “drying power” of the climate (Dingman, 1994). It is the evapotranspiration from a uniform vegetated surface with unlimited water supply (Holden 2008). Therefore, it sets an upper boundary on the amount of water that can be lost through evapotranspiration (Law, 2008). Actual evapotranspiration (AET) is about 50% to 90% of potential evapotranspiration on an annual basis (Jackson, 2006).

Many methods have been developed to either directly measure or indirectly estimate evapotranspiration (appendix B). These methods have all been used in different hydrological models under different hydrological and meteorological conditions. Many studies and experiments have also compared the performances of these different methods (Dingman, 1994, pp. 256-302). In general, the Penman-Monteith equation (PM) (equation 4.1.3) provides the most corresponding results with that measured by lysimeters (Van Bavel, 1966 and Jensen, et al., 1990 as cited in Dingman, 1994) and it was used as a foundation to calculate potential evapotranspiration in this study:

$$PET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\lambda[\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)]} \qquad Equation\ 4.1.3$$

Where Δ=rate of change of saturation specific humidity with air temperature (kPa °C $^{-1}$), R_n=net irradiance (MJ m^{-2}), G=ground heat flux (MJ m^{-2}), ρ_a=air density (kg m^{-3}), c_p=Specific heat capacity of air (J kg^{-1} K^{-1}), $e_s - e_a$=vapour pressure deficit of the air (Pa), r_a=aerodynamic resistance (s m^{-1}), λ =latent heat of vaporization (MJ kg^{-1}), γ = psychrometric constant (kPa °C $^{-1}$), and r_s=surface resistance (s m^{-1}).

For open water, under the following assumptions: 1. Water is always available for evapotranspiration; 2. Ground heat flux is negligible (G =0); 3. Surface resistance is 0 for the study site (r_s=0), equation 4.1.3 can be written as:

$$PET = \frac{\Delta(R_n) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\lambda(\Delta + \gamma)} \qquad Equation\ 4.1.4$$

Where Δ=rate of change of saturation specific humidity with air temperature (kPa °C $^{-1}$), R_n=net irradiance (MJ m^{-2}), ρ_a=air density (kg m^{-3}), c_p=Specific heat capacity of air (J kg^{-1} K^{-1}), $e_s - e_a$=vapour pressure deficit of the air (Pa), r_a=aerodynamic resistance (s m^{-1}), λ =latent heat of vaporization (MJ kg^{-1}), and γ =psychrometric constant (kPa °C $^{-1}$).

For vegetated areas, the FAO Penman-Monteith (FAO PM) combination equation (equation 4.1.5) was used to calculate reference evapotranspiration (ET_o), which is the recommended standard by the Food and Agriculture organization (Allen et al., 1988). ET_o represents a theoretical value of evapotranspiration from a reference surface with an assumed crop height of 0.12 metre, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. The equation of ET_o is given as:

$$ET_o = \frac{0.408\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma \frac{900}{\mathrm{T} + 237} \mathrm{u_2}(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma(1 + 0.34\mathrm{u_2})} \qquad Equation\ 4.1.5$$

Where Δ=rate of change of saturation specific humidity with air temperature (kPa °C $^{-1}$), R_n=net irradiance (MJ m^{-2}), G=ground heat flux (MJ m^{-2}), γ =psychrometric constant (kPa °C $^{-1}$), T =air temperature (°C), u_2=wind speed at 2 meter height (ms^{-1}), and $e_s - e_a$=vapour pressure deficit of the air (Pa).

Since a wetland usually consists of both open water areas and vegetated areas, using open water PET or FAO PM ET_o alone would not reflect the diverse range of wetland landforms. Although total ET could have been calculated as a sum of PET and ET_o according to the proportion of open water areas and vegetated areas in the wetlands, this would have required several detailed landform surveys at different times of the year. Due to the limited time and resources available in this study, ET is simplified as the mean value of open water PET and FAO PM ET_o.

4.1.3. Surface flows

Normally, delimiting the catchment of the wetland of interest is the first step to identify and quantify surface inflows (Labadz, et al., 2002). A catchment is defined as an area that topographically contributes all the water that passes through a given cross section of a stream (Dingman, 1994, p. 14). On an annual basis, the volume of water that has been discharged by a river or stream can be seen as precipitation minus evapotranspiration (*Q*=*P*-*E*). The wetlands in this study, however, are not able to use this approach. First, the duration of this study is not long enough to neglect the groundwater interactions and soil water storage. Second, the hydrologic condition in the surrounding areas has been extensively modified by urban development including river diversion, road construction, and agricultural drainage. As a result, water movement in the catchment doesn’t necessarily contribute to the inflow of Matthews Lagoon. Instead, the inflow is controlled by a pump.

Measuring surface flows is relatively easy compared to other components in the water balance equation (Holden, 2008). Surface flows can be measured both directly and indirectly (table 4.1.3). Selecting a measurement method depends on the purpose and duration of the project, the nature of the channel, and equipment availability (Dingman, 1994, pp. 536-552).

Table 4.1.3 Classification of surface flow gauging methods.

Surface flow measurement methods	Direct measurement	Volumetric: Measuring the time taken to fill a container to a known volume.
		Velocity-area: Measuring the velocity of water passing a selected stream cross section in a certain time interval.
		Dilution: Adding a known concentration of chemical to the upstream and measuring the dilution at downstream location.
	Indirect measurement	Stage-discharge: Converting water levels into discharge values using a rating curve.
		Flumes or weirs: In-stream engineering structures that divert all the water through. Discharge is a function of the shape of the flume or weir and the water level in the structure.

In this study, the volume of inflow was obtained from GWRC. GWRC monitors the running time and electricity consumption of the pump that controls the Te Hopai Drainage Scheme. These data obtained from GWRC represent the "ideal" or "theoretical" volume of water that enters Matthews Lagoon. Overestimations may occur using this data because the efficiency of a pump reduces with pump age and without proper maintenance. This is due to wear on the impeller and general back leakage.

Three water level monitoring stations were established in the two wetlands in this study (figure 4.1.2). Each station consists of a staff gauge and a pressure sensor. A staff gauge is a vertical ruler marked at centimetre intervals used to measure water level relative to a reference elevation. It can be read by observers from a distance and has the advantage of low cost to install and maintain. The disadvantage is that the readings are not continuous, thus the intervals between the readings sometimes miss the natural fluctuations of levels (Labradz, et al., 2002). A pressure transducer measures the water or atmosphere pressure. Having one sensor at the bottom of the wetland and one above the water allows calculating actual water depth from the pressure difference between the two sensors.

Stations 1 and 3 were installed to record water levels in Matthews Lagoon and Boggy Pond, respectively. Station 2 was installed at the outlet of Matthews Lagoon. In this study, a 2-meter long PVC pipe was used as a staff gauge (figure 4.1.3). 40 holes were drilled every 5 centimetres on the pipe to mark the water level and allow water to enter the pipe freely. A pair of pressure transducers sits inside the pipe and are tied to the PVC pipe by ropes (figure 4.1.4) so the pressure transducers can be pulled out to retrieve data and put back to the same depth.

The elevations above sea level of these three stations (figure 4.1.2) were measured by a real-time kinematic (RTK) survey under NZGD 2000 datum. A RTK system consists of a base station and one or more rovers. The base station is at a known position while roving receivers occupy unknown positions. All devices communicate to the same satellites at the same time, and the communications between base station and roving receivers provide real-time corrective factors (Van Sickle, 2008). As a result, RTK can provide better accuracy than regular GPS. The devices used in this study (Trimble R4 GNSS system) give errors of about 15 mm for vertical measurement according to the manual.

Figure 4.1.2 Water level monitoring stations in Matthews Lagoon and Boggy Pond. Station 1 is in the middle of Matthews Lagoon, station 2 is at the outlet of Matthews Lagoon, station 3 is in the middle of Boggy Pond.

Figure 4.1.3 A 2-meter long PVC pipe with holes every 5 centimetres used as a staff gauge.

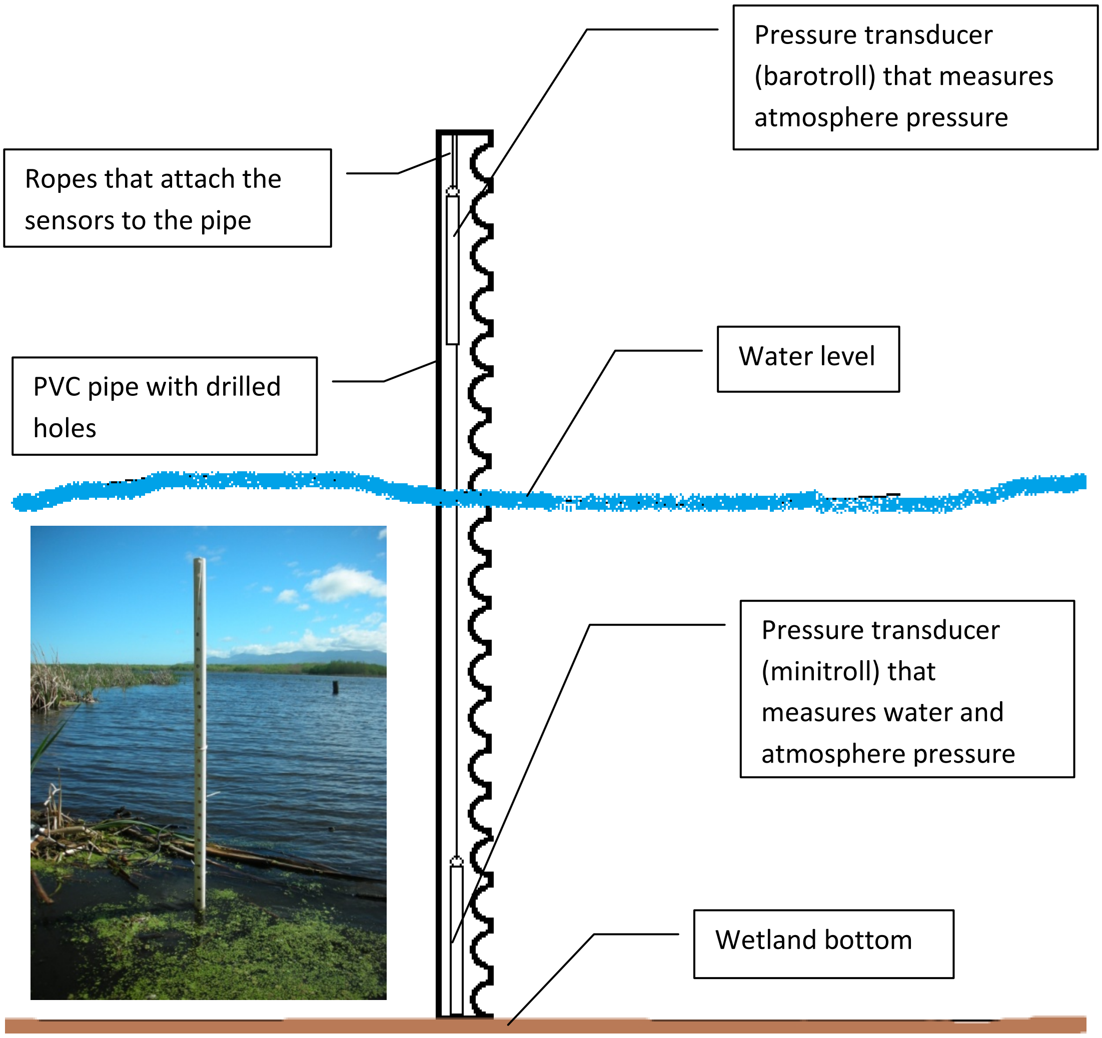


Figure 4.1.4 Cross-section of water level monitoring station.

The velocity-area method (Dingman, 1994, p. 537-539) was used to generate the rating curve for the outflow of Matthews Lagoon. The measurement has to be taken several times under different flow conditions at the outlet. The total discharge Q (m^3/s) is expressed as:

$$Q = \sum_{i=1}^{N} \frac{X_{i+1} - X_i}{2} (U_i Y_i + U_{i+1} Y_{i+1}) \qquad Equation\ 4.1.6$$

Where X_i are cross-stream distances to successive verticals measured from an arbitrary datum (m), U_i are the vertically averaged velocities of each vertical (m/s), and the Y_i are the depth of each vertical (m). Figure 4.1.5 shows how the components in equation 4.1.6 are obtained in the field.

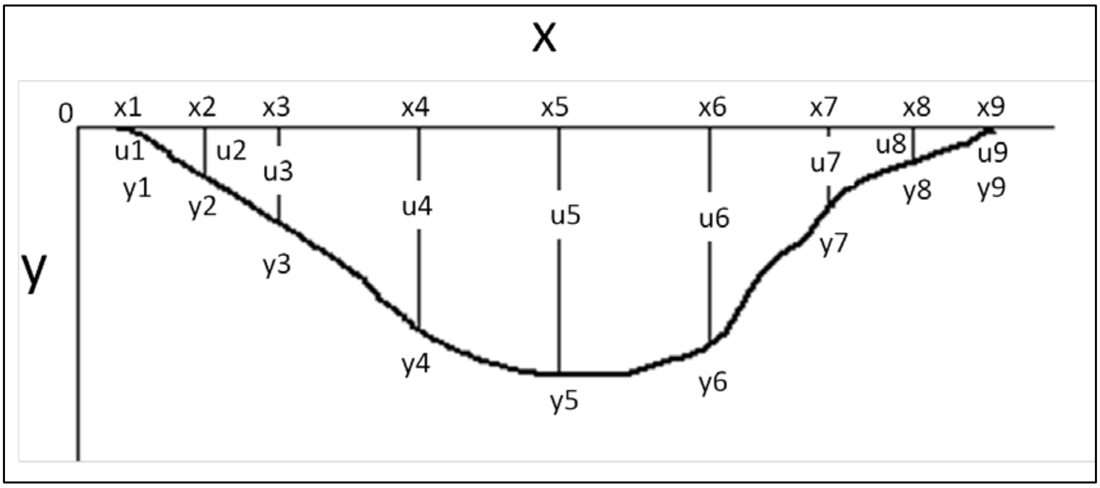


Figure 4.1.5 Cross-section of the channel at outlet of Matthews Lagoon and measurement points to calculate discharge using the velocity-area method. The starting point 0 for x axis can be any point on the shore. The starting point 0 for y axis is the water surface. Water velocity is measured at 0.6y to the water surface.

4.1.4. Groundwater

Groundwater by definition is the water held below the water table in saturated soils or other earth materials (Dingman, 1994; Holden, 2008). Its movement into and out of a wetland represents the interactions between groundwater and surface water. In geology, the medium unit in which the interactions between groundwater and surface water occur is an unconfined aquifer (Dingman, 1994). An aquifer is a geologic unit that can store enough water and transmit it at a rate fast enough to be hydrologically significant (Dingman, 1994).

Four types of interactions between wetlands and groundwater are identified (Greater Wellington Regional Council, 2005): A discharge wetland is fed by groundwater because it sits at a lower topographic point, where the wetland water table is below the surrounding water table (figure 4.1.6 A). A spring or seep wetland is at the base of a steep slope where the water table and the land surface are parallel (figure 4.1.6 B). A recharge wetland forms when the wetland water level is higher than the surrounding water table abd the wetland releases water (figure 4.1.6 C). If the amount of water released from wetland to the surrounding area is negligible, the wetland is then called perched wetland (figure 4.1.6 D). These interactions change with seasons, sometimes even reverse during the year (Dingman, 1994). Fluctuations in water table level are the result of recharge and discharge processes in groundwater (table 4.1.4).

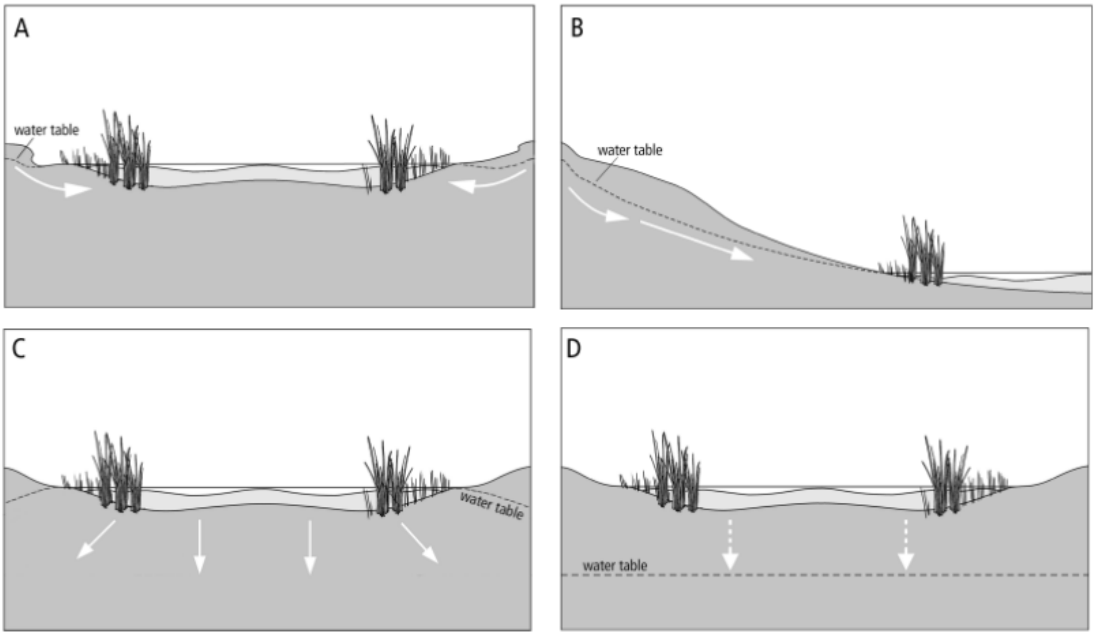


Figure 4.1.6 Four types of wetland-groundwater interaction. Dashed lines represent water tables, while arrows represent water movement directions. A. Discharge wetland. B. Spring or seep wetland. C. Recharge wetland. D. Perched wetland. Source: GWRC, 2005.

Table 4.1.4 Recharge and discharge processes of groundwater.

Recharge Processes	Discharge Processes
• Infiltration: movement of water from soil surface into the soil • Percolation: downward flow from unsaturated zone to saturated zone • Seepage from surface water or flows • Groundwater inflow	• Exfiltration: evaporation from the upper layers of the soil • Capillary rise: movement from saturated zone to unsaturated zone • Contribution to surface water or flows • Groundwater outflow • Plant uptake

Groundwater flow is the most difficult component to obtain in the water balance equation, as it cannot be measured directly and the water movement underground is complicated (Hunt, Krabbenhoft, & Anderson, 1996). Darcy's Law can be used to estimate groundwater flows in saturated soils (e.g., law, 2008):

$$V = \frac{Q}{A} = -K_s \frac{dH}{dx} \qquad Equation\ 4.1.7$$

Where:

V= discharge (cm/day)

Q= volume rate of flow (cm^3/day)

A= cross-sectional area of flow (cm^2)

K_s= saturated hydraulic conductivity of the soil (cm/day)

$\frac{dH}{dx}$= hydraulic gradient between observation points (the rate of change of head over distance, unitless ratio)

Certain assumptions must be made in order for Darcy's Law to be valid. First, the soils must be saturated at all times. For unsaturated soil, its hydraulic conductivity becomes a function of pressure head. It can change dramatically with different water content in the soil. Second, the hydraulic properties of the media must be homogeneous. Saturated hydraulic conductivity solely depends on the characteristics of soil and bedrock that is affected by porosity, texture, structure, and macropore networks (Jackson, 2006). Better permeable units like sand and gravel have high hydraulic conductivity values, while poorly permeable materials such as clay have low values (Schwartz and Zhang, 2002) (table 4.1.5).

Table 4.1.5 Saturated hydraulic conductivity values for a range of soils. Source: Schwartz and Zhang, (2002).

Materials	Hydraulic Conductivity (m/s)
Gravel	$3 \times 10^{-4} – 3 \times 10^{-2}$
Coarse Sand	$9 \times 10^{-7} – 3 \times 10^{-3}$
Fine Sand	$2 \times 10^{-7} – 2 \times 10^{-5}$
Clay	$1 \times 10^{-11} – 4.7 \times 10^{-9}$
Sandstone	$1 \times 10^{-10} – 6 \times 10^{-6}$
Permeable Basalt	$4 \times 10^{-7} – 2 \times 10^{-2}$
Fractured metamorphic rock	$9 \times 10^{-9} – 3 \times 10^{4}$
Unfractured metamorphic rock	$3 \times 10^{-14} – 2 \times 10^{-10}$

Although Darcy's law can provide a relatively good estimation of groundwater flow, there are certain drawbacks of this technique: First, the measurement is usually taken from a few points to represent an entire study site (Attanayake et al., 2006). Second, the hydraulic gradient changes through time (Kalbus, Reinstorf, & Schirmer, 2006). Third, the hydraulic properties of the media can be heterogeneous (Hunt, et al., 1996). It is better to measure groundwater flows with more than one method to reduce errors (Hunt, et al., 1996). Other approaches to estimate groundwater flows include stable isotope mass balance, temperature profile modeling, and numerical water balance modeling (Hunt, et al., 1996).

Water table data were obtained from GWRC. There are 4 boreholes monitored around the study area (figure 4.1.7). The water level was leveled against the NZGD2000 datum system. A borehole is simply a narrow hole bored in the ground vertically or horizontally. Its purposes include exacting liquid or gas, monitoring the properties of the water, soil, or gas within, or as an entrance hole to install underground facilities. The boreholes near the study site are vertical for water table monitoring.

At least three boreholes are needed in order to calculate direction of groundwater flow and hydraulic gradient. The procedure is shown in figure 4.1.8. Three boreholes (A, B, and C) with known water table elevations are connected by solid lines which indicate the distance between them. Water table contours can be drawn by connecting points on the solid lines with same water tables. Groundwater flow direction is the perpendicular line to the contours.

Figure 4.1.7 Boreholes (yellow dots) near Matthews Lagoon and Boggy Pond. Source: GRWC.

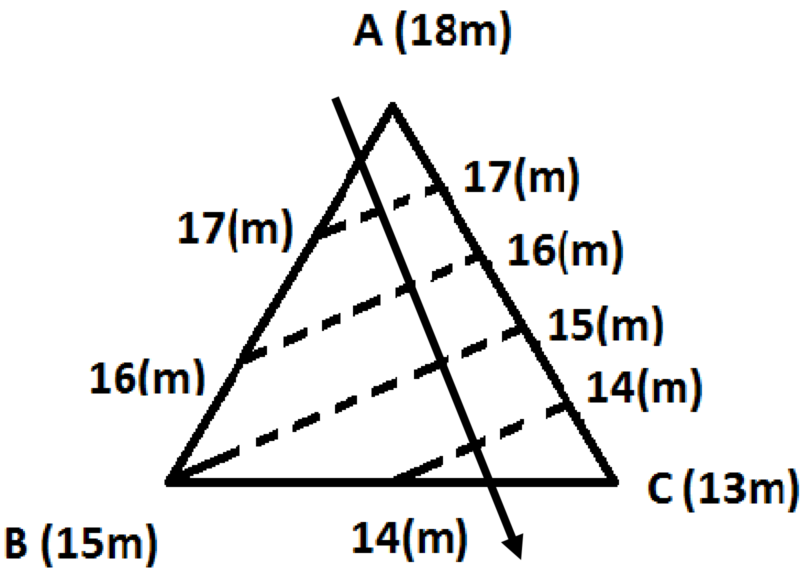


Figure 4.1.8 Determination of water table contours (dashed lines) and groundwater flow direction (perpendicular line with arrow to the contours) from three boreholes.

4.1.5. Wetland water volume and residence time

The fluctuations in open water level directly reflect changes in water storage in a wetland. Watershed (or catchment) is defined as an area of land in which water flowing across the surface drains into a particular stream or river (Holden, 2008). It is a fundamental unit in regional water balance. Watershed delineation information for this study was obtained from The New Zealand River Environment Classification (REC). The watershed surface area is used in water balance equation when converting between cubic meters and millimetres.

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 still water level favours one or a few plant species while a fluctuated water level can support more complex and diverse plant communities (Greater Wellington Regional Council, 2005). As mentioned in surface water monitoring methods, surface water levels can be monitored by staff gauge and pressure transducer.

In order to convert water level fluctuations to changes in water storage in a wetland, an understanding of the relationship between wetland volume and corresponding water level is essential (Labadz, et al., 2002; Rasmussen, 2008). This can be done by the production of a depth-volume curve, which estimates water volume for any given water depth similar to the rating curve in surface flow monitoring. Several topographic surveys under different water levels are required beforehand. Standard surveying techniques, which measure water depth at regular intervals across an entire wetland, can be used for topography monitoring. The wetland volume is calculated with the Create TIN function in ArcGIS 3D Analyst toolbox. A TIN is the acronym for triangulated irregular network, in which sample data points with x-, y-, and z-values are connected by lines to form Delaunay triangles. Summing up the volumes of these triangles yields the total wetland volume. Water depth was surveyed twice both in summer and winter at over 300 data points. The surface area of the water body is from an aerial photo taken in February 2013 by GWRC.

Storage of water in the soil is more complicated than in open water bodies (Labadz, et al., 2002). Some basic information is needed in order to calculate storage changes (Labadz, et al., 2002): the morphology of the water table, the volume of strata availability for water storage, and the relationship between change in volume of water stored and the change in water table. The changes of water storage in unsaturated zones and changes in the strata itself further complicate the monitoring of water storage in soil (Labadz, et al., 2002). Therefore, in this study, monitoring water storage solely focuses on open water bodies. The water content in the soil is assumed to be constant.

Water residence time can be calculated from wetland volume and the amount of water that flows through it (equation 4.1.8). This way of calculating residence time is based on the assumption that water is well mixed in the wetland, and therefore provides an upper boundary of the actual residence time.

$$RT = \frac{V}{Q} \qquad Equation\ 4.1.8$$

Where RT is the residence time (days), V is the volume of wetland (m^3), and Q is the amount of water that flows through the wetland in a day (m^3/day).

4.2. Nutrient removal

Monitoring of the chemical environment focused on nitrate, ammonium, and phosphate. Regular monitoring was carried out 5 occasions from July until November 2013 using a YSI handheld meter and a Phosphorus Test Kit (HACH PO-19) due to the availability of equipment. The locations of regular monitoring points in Matthews Lagoon were the inflow, outflow and in the middle of the wetland. There was only one monitoring point in Boggy Pond as it has no inflow or outflow (figure 4.2.1). In addition to this regular monitoring, a continuous monitoring of nitrate concentration using a YSI handheld meter at inlet and outlet was also done between December 2013 and January 2014. The YSI ProPlus handheld meter measures temperature (°C), dissolved oxygen (% and mg/l), pressure (mbar), conductivity (µs/cm), total dissolved solids (mg/l), pH, salinity (‰), nitrate-N (mg/l), and ammonium-N (mg/l). GWRC also collects water samples from stations A, B and C (figure 4.2.1) for detailed lab anaysis quarterly.

Multiplying the concentration of nutrients measured at stations A and C (figure 4.2.1) with the water volumes measured at stations 1 and 2 (figure 4.1.2) yields the mass of nutrients that Matthews Lagoon receives and discharges. A removal rate (RE) can then be calculated as:

$$RE = \frac{M_{in} - M_{0ut}}{M_{in}} \times 100\% \qquad Equation\ 4.2.1$$

Where M_{in} is the total nutrient mass (kg) from inflow and M_{0ut} is the total nutrient mass from outflow. Note that this removal rate treats the wetland as a black box, which means it only considers total inputs and outputs, does not account for the reactions that happens within the wetland. When using this removal rate to indicate the ability of the chemical and physical reactions, one should be aware that other factors such as nutrients released from soils by nitrogen fixers may influence the removal rate.

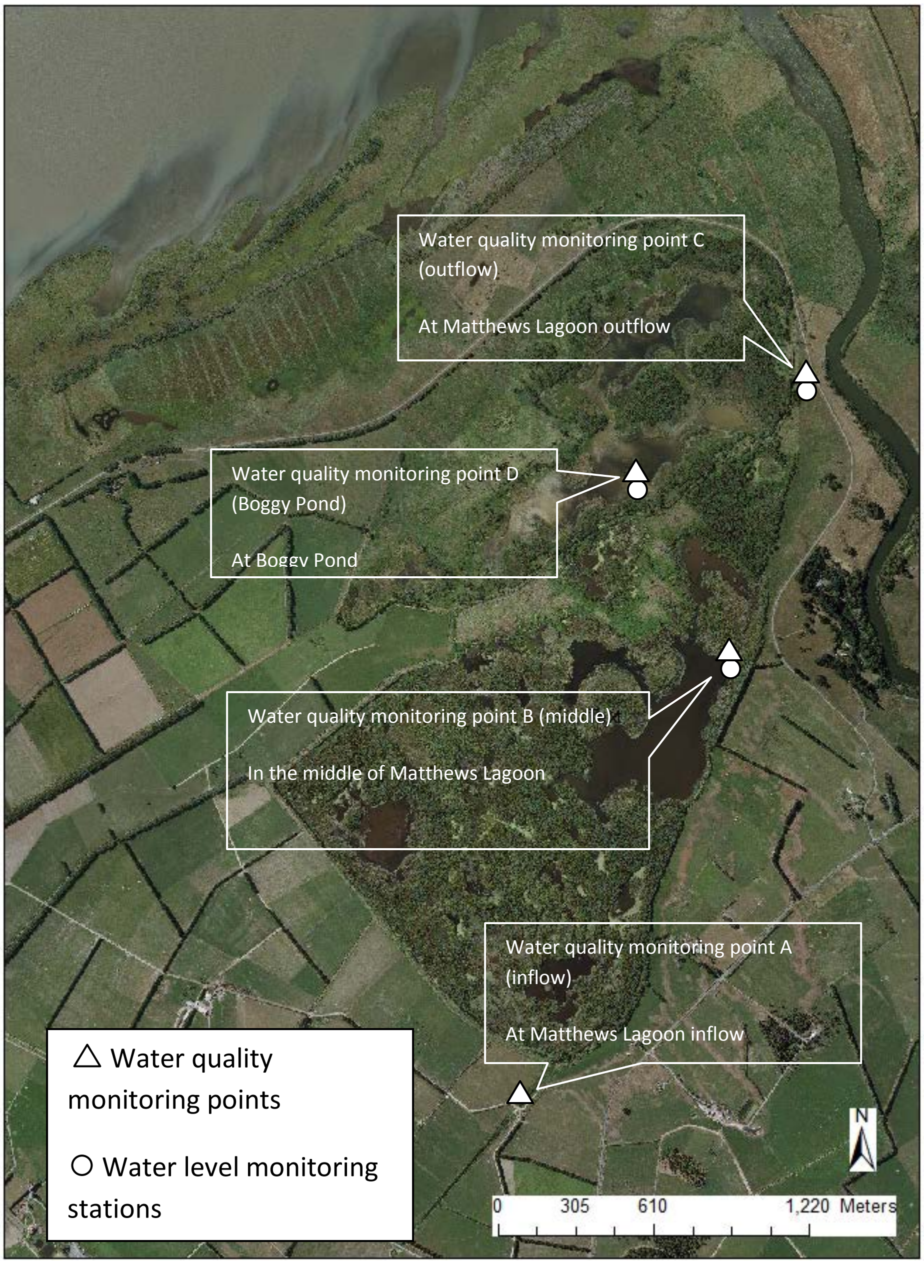


Figure 4.2.1 Monitoring stations for water quality and water level in Matthews Lagoon and Boggy Pond. Water level monitoring stations are the same as shown in figure 4.1.2. Water quality monitoring stations A, B, and C are at the inlet, middle point, and outlet in Matthews Lagoon; station D is in the middle of Boggy Pond. Water quality was measured with a YSI handheld meter and field test kits for nitrate, ammonium, and phosphate by C. Shi. GWRC also collected water sample from station A, B, and C for lab tests.

4.2.1. Nitrate

Nitrogen in the form of nitrate is a common pollutant from agricultural runoff (Houlbrooke, et al., 2004). Excessive usage of fertilizer and plant fixation are the sources of nitrate. Denitrification is the main process to remove nitrate from a wetland, during which nitrate is transformed to nitrogen gas (figure 4.2.2). There are some intermediates in different stages of denitrification (equation 4.2.2), among which nitrous oxide (N_2O) and dinitrogen (N_2) are in gaseus forms that can be released from the wetlands. Denitrification requires anaerobic conditions and carbon sources (Tanner, Clayton, & Upsdell, 1995; Woltemade, 2000). Plants can also uptake some nitrate, but the ability varies among different types of plant (Kirk & Kronzucker, 2005).

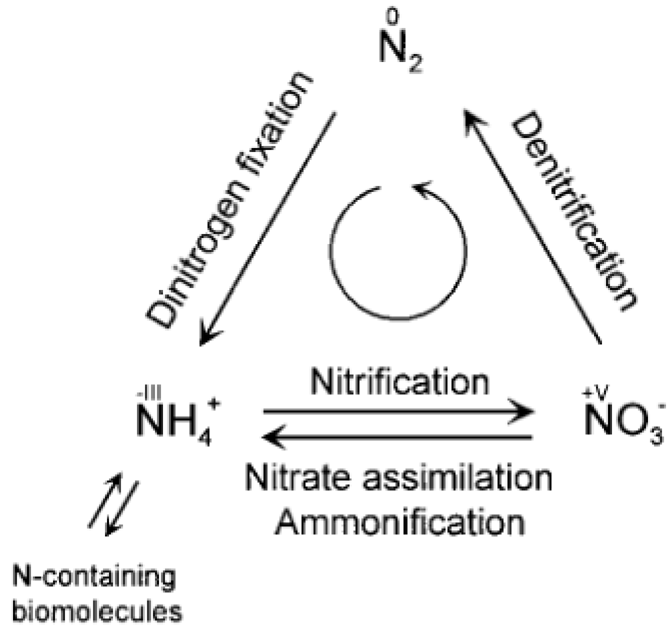


Figure 4.2.2 Nitrogen cycle. Source: (Zumft, 1997)

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \qquad \text{Equation 4.2.2}$$

The YSI handheld meter measures nitrate activity in the sampled water with a nitrate sensor (1006 Pro Series Nitrate Sensor) that consists of an ion-selective electrode in a custom filling solution. This internal solution is separated from the sample water by a polymer membrane, which selectively interacts with nitrate ions. The activity of nitrate ions affects the electric potential of the solution in the probe which can be measured by the meter and then converted to mg/l of nitrate.

One of the main problems of using ion-selective electrode is interference from other, undesired ions that have similar physical properties. High concentrations of chloride or bicarbonate ions in the sample water would potentially interfere with the nitrate selecting process. The YSI sensor manual stated that 500 mg/l chloride could increase the nitrate result by 3.6 mg/l. There are many sources of chloride in the water, both natural and anthropogenic sources (Kelly, Panno and Hackley, 2012). Livestock waste and potassium chloride (KCl) fertiliser are the most likely sources for chloride in the study area. Panno et al. (2006) found chloride concentrations in animal waste as high as 1980 mg/l. Potassium (K) is an important mineral for dairy cows and KCL is a common and cheap fertiliser in New Zealand.

In addition to the periodical monitoring, a real-time water quality monitoring at inflow and outflow of Matthews Lagoon was carried out using two YSI handheld meters for about two weeks in the 2013/14 summer. The meters were calibrated before monitoring with standard nitrate nitrogen solution (1mg/l). Both meters measure and record nitrate concentrations every 15 minutes at the inlet and outlet of Matthews Lagoon.

This real-time water quality monitoring could potentially reduce the errors from the equipment. Although it would be ideal if this real-time monitoring could have been done in both winter and summer for a longer period of time, due to the restrictions of resources, the summer was the only period when both handheld meters were available.

4.2.2. Ammonium

Ammonium nitrogen usually comes from the wastes from pasture animals (Hill, Owens, & Tchounwou, 2005; Lockyer, Pain, & Klarenbeek, 1989). It is toxic to some wetland organisms and can compress their growth (Britto & Kronzucker, 2002). Ammonia in the wetland is usually absorbed by plants (Miller, 1990). Nitrification can also occur, during which ammonium is oxidised to nitrate under aerobic condition

(Khanijo, 2002). Ammonium is also important in the formation of nitrogen in the nitrogen cycle (figure 4.2.2).

Similar to nitrate measurements, ammonium was measured by a YSI handheld meter using ab ion-selective electrode. The main interference ion for ammonium is potassium, which increases ammonium concentration by 3.4 mg/l for 50 mg/l of potassium in the water sample.

4.2.3. Phosphate

Phosphorus is another element besides nitrogen that contributes to eutrophication in water bodies (Carpenter, et al., 1998). Agricultural runoff carries phosphate from the point of application to the wetland (Hubbard, Newton, & Hill, 2004). Although plants can uptake some phosphate, the major removal process is through adsorption and sedimentation (Khanijo, 2002; Woltemade, 2000).

Adsorption and sedimentation happen mainly on the surface of wetland sediments under aerobic and neutral to acidic conditions, where phosphate reacts and attaches to iron, calcium and magnesium (Khanijo, 2002). Phosphate then is buried by new sediments as a result of sedimentation. However, two problems arise. First, adsorption and sedimentation are reversible processes. Therefore phosphorus is not really removed from a wetland system but stored within the sediments (Verhoeven & Meuleman, 1999). In other words, phosphorus can be washed out from wetlands when conditions are right and becomes a source of pollution (e.g. flood or earth work by human). Second, the amount of adsorption is controlled by various parameters and there is a point when a wetland is saturated (Verhoeven & Meuleman, 1999).

The phosphate test kit (HACH PO-19) uses ascorbic acid method to measure phosphate. Once the water samples are collected in the twin glass tubes from the field, reagents (either liquid or powder) containing ascorbic acid and ammonium molybdate are added to one of the samples allowing them to react with phosphate in the sample to form a blue compound, and the depth of the blue color indicates the amount of phosphate in the water. The other sample without added reagent is used as a control. Challenge arises for phosphate monitoring as the concentration is usually very low in the water samples. One of the drawbacks of this method is that readings can be highly subjective between different people, because the result is read based on the similarity of blue color between the water sample and the standard color comparator. Another drawback of this method is that it cannot pick up small differences in phosphate concentrations. As the phosphate level in water is usually very low, there are limitations when using the results from this method to generate a nutrient balances.

5. Result

5.1. Weather and climate data analysis

Rainfall, temperature, wind speed, and humidity data in 2013 was obtained from the climate station on the eastern shore of Lake Wairarapa, which is less than 2 kilometres to the north of Boggy Pond. This station, established by GWRC since 2012, measures all the parameters at 2.5 meters above ground. Historical rainfall and solar radiation data was downloaded from the NIWA National Climate Database. The nearest station that keeps long-term rainfall data is near Kahutara Road, about 10 kilometres to the northeast of Boggy Pond and Matthews Lagoon. This station has recorded rainfall information since 1982. Solar radiation was measured from Martinborough station which is 10 kilometres to the east of the wetlands. Figure 5.1.1 shows the locations of these stations.

Figure 5.1.1 Weather and climate stations near the study site. Station 1 on the eastern shore records rainfall, wind speed, temperature, and humidity for the study area in 2013. Station 2 at Kahutara Road keeps historical rainfall data since 1982. Station 3 in Martinborough measures solar radiation.

5.1.1. Precipitation

Total rainfall in 2013 at the eastern shore (station 1) was 1,093 millimetres . This is above the average annual rainfall recorded at Kahutara Road station (878.6 millimetres). In order to find out if there were any extreme events or abnormal weather conditions during the study period, rainfall data from the eastern shore station in 2013 was compared with historical monthly rainfall data recorded from Kahutara Road station. By comparing with the maximum, minimum and average rainfall records for each month between 1982 and 2013 (figure 5.1.2), it can be seen that rainfall in May, June, and October 2013 was relatively high. In May 2013, the rainfall was only 10 millimetres lower than the highest value in May 1996. In June 2013, a monthly rainfall of 192 millimetres became the new June rainfall record since 1982. The rainfall in October once again broke historical records since 1982. Rainfall in these three months were significantly greater than in other months. In fact, these three months together contributed 46% of the total rainfall in 2013, which indicates unevenly distributed rainfall in 2013. Because of this unevenly distributed rainfall in 2013, two of the months in the winter of 2013 were actually drier than previous years. In July and August, the rainfall was below the historical average and median values since 1982. Daily rainfall during the same period is shown in figure 5.1.3. Rainfall, inflow, and nitrate concentration at the inlet are closely related, which will be further discussed later.

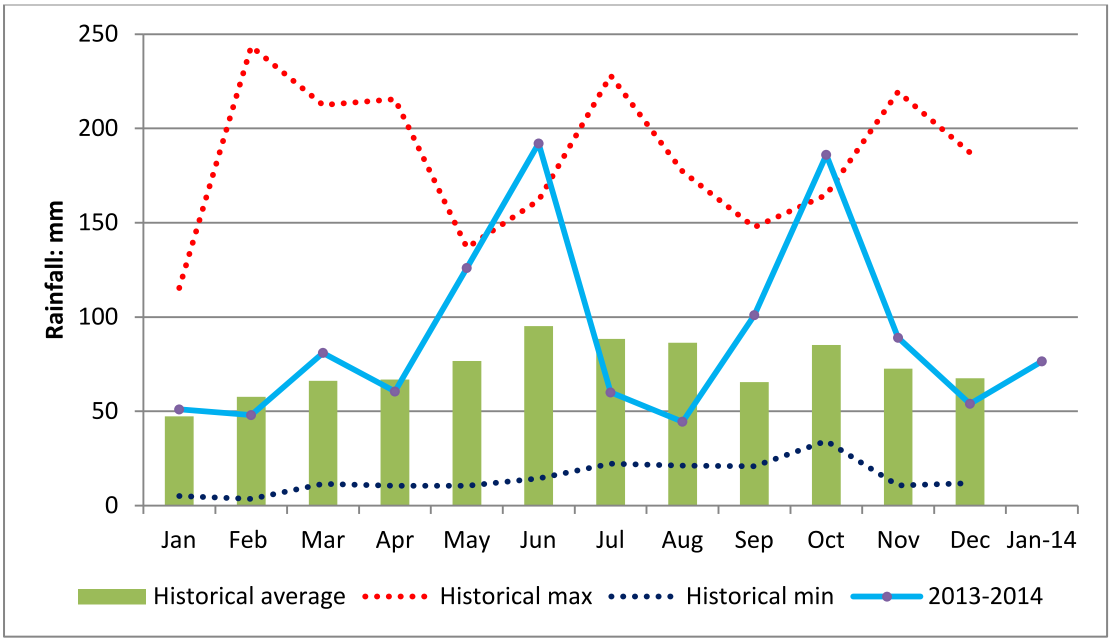


Figure 5.1.2 Eastern shore rainfall in 2013 and January 2014 (blue line) compared with maximum (red dotted line), minimum (black dotted line), and historical average (green bars) monthly rainfall in the period between 1982 and 2013 at Kahutara Road station.

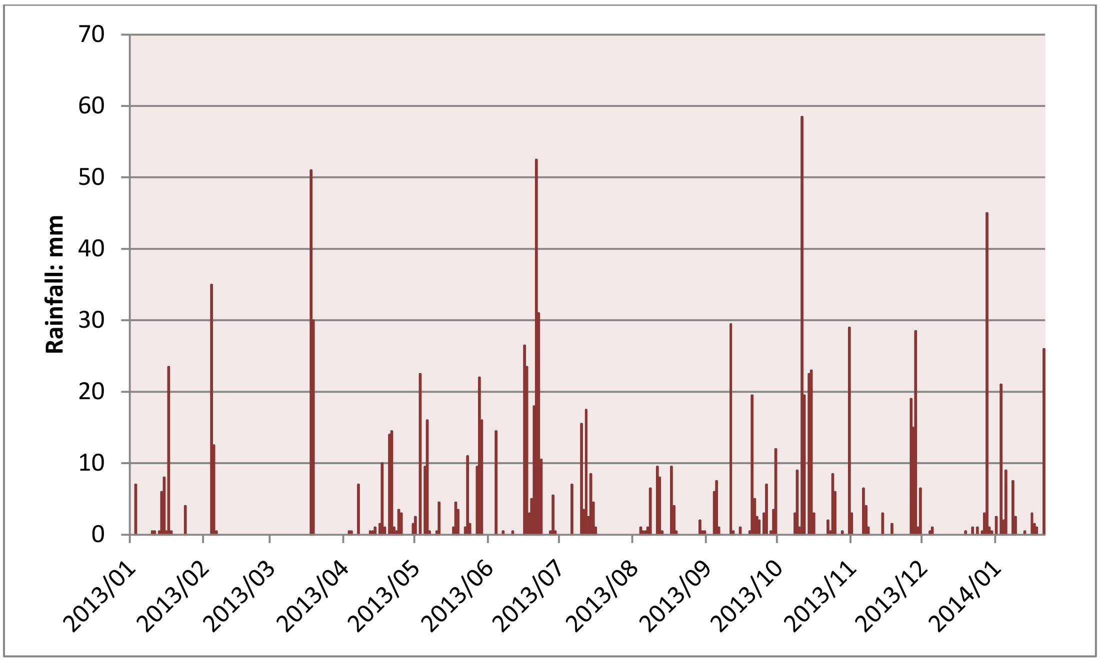


Figure 5.1.3 Eastern shore (station 1) daily rainfall between January 2013 and January 2014.

5.1.2. Evapotranspiration

As discussed in the previous chapter, evapotranspiration can be estimated from meteorological data. Meteorological parameters such as wind speed, relative humidity, and air temperature were measured from eastern shore station at 2.5 metres above the ground, while the calculation procedures can be found in appendix D. Substituting these quantities into equation 4.1.4 yields the daily open water PET of the study site. FAO PM ET_o was also calculated using the same parameters.

Figure 5.1.4 shows the results for open water PET and FAO PM ET_o. Seasonal fluctuations are obvious because solar radiation and temperature play important parts in both equations. Daily variations can be explained by the speed of wind and the level of cloud coverage.

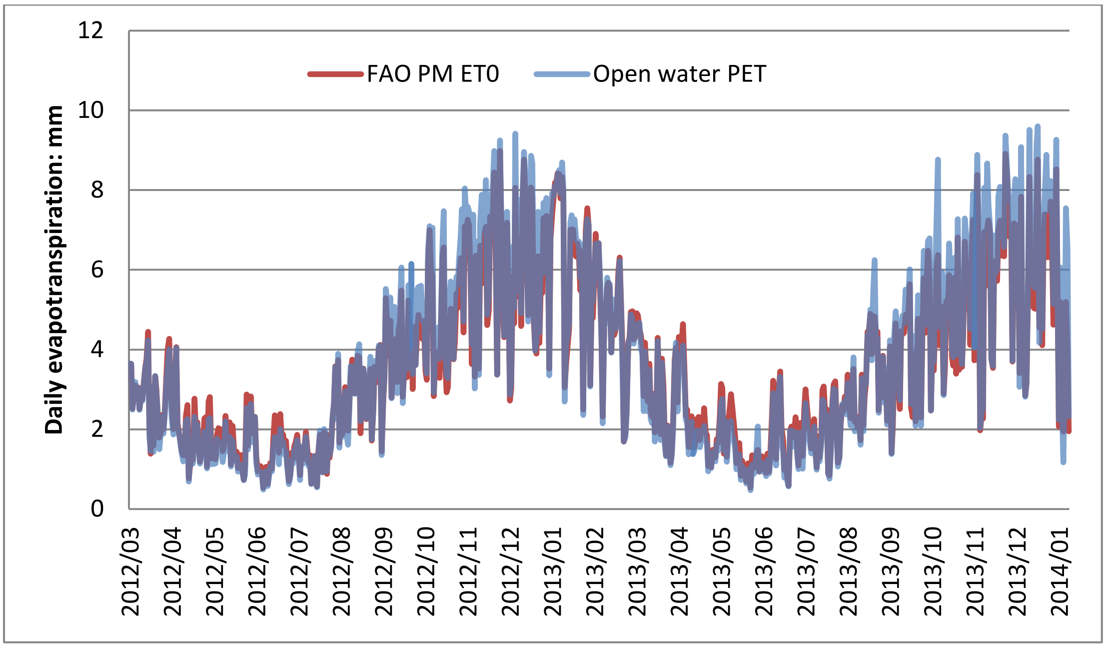


Figure 5.1.4 Daily reference evapotranspiration derived from FAO Penman-Monteith combination equation (red line) and daily open water potential evapotranspiration (blue line).

As discussed in chapter four, ET is simplified as the mean value of open water PET and FAO PM ET_oin this study. This is because of the diverse range of landforms in the wetlands in the study site. Only using open water PET or FAO PM ET_owould not be able to reflect this fact. Monthly evapotranspiration that was used in computing the wetland water balance is shown in figure 5.1.5.

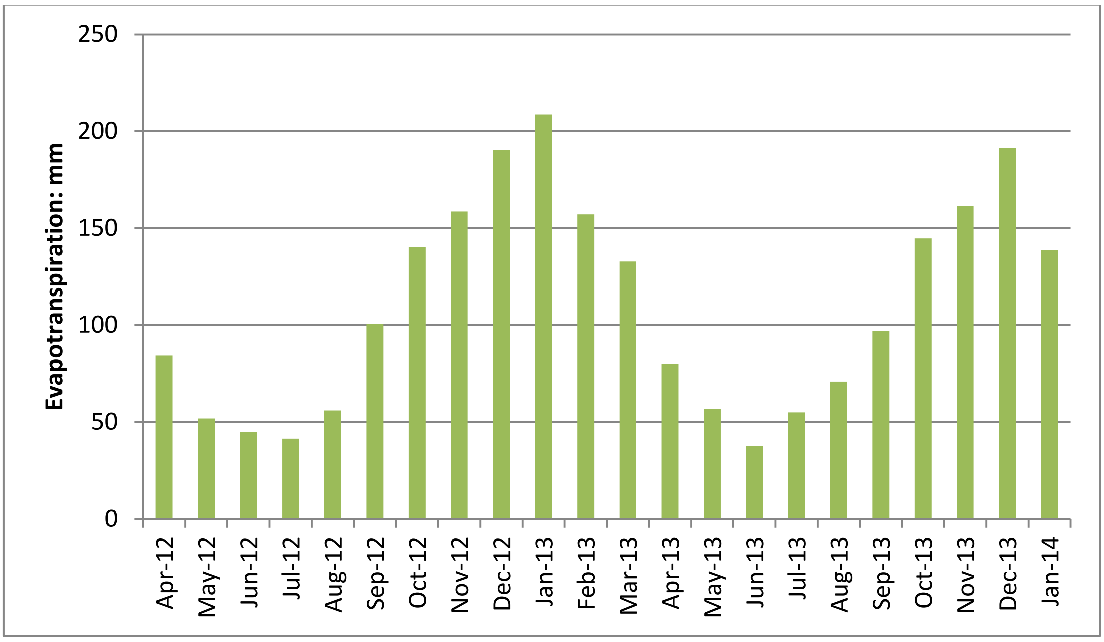


Figure 5.1.5 Monthly evapotranspiration derived from the mean value of free water PET and FAO PM ET_o.

5.2. Water level analysis

Surface water level data and groundwater table data are shown in figure 5.2.1. All the water levels are referenced to the NZGD2000 datum system above sea level.

Results show that Boggy Pond looks like a raised wetland as its water level was above the water table. There should be no groundwater input to Boggy Pond according to these results. Water level at the outlet of Matthews Lagoon (station 2) was higher than the middle point (station 1) which indicates that water may not flow through the entire wetland. Instead a bypass is likely to be present in Matthews Lagoon. Surface flow, wetland volume, groundwater flow, water balance and water retention time were all calculated from water level data.

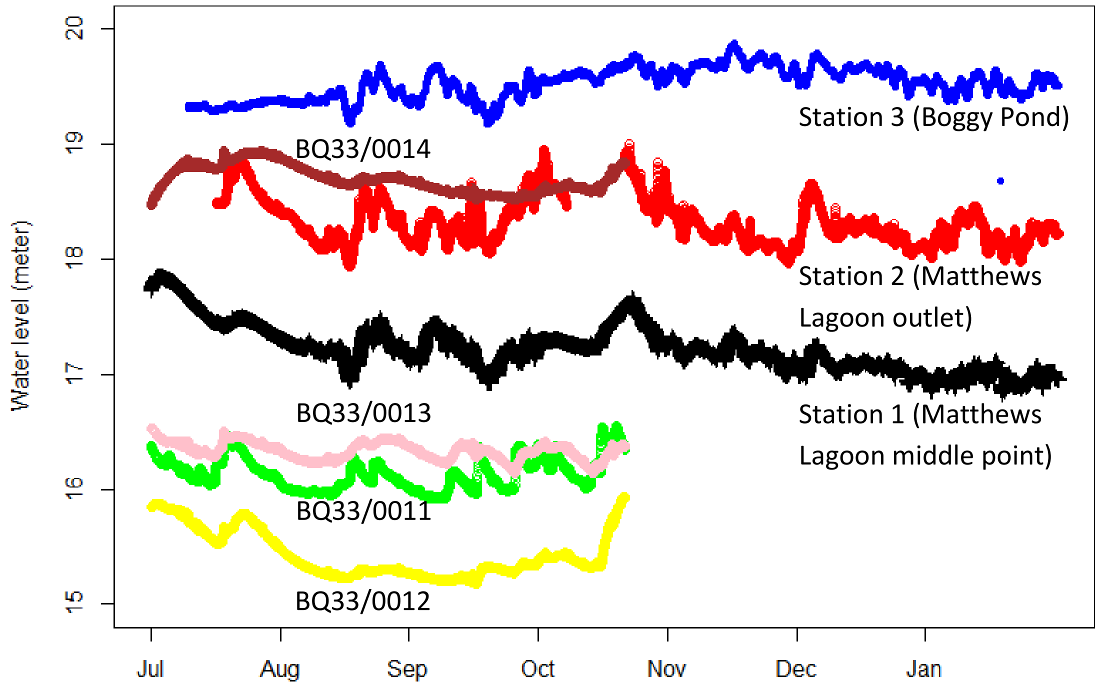


Figure 5.2.1 Surface water (station 1, 2, and 3) and groundwater (BQ33/0011, 12, 13, and 14) level recorded during the study period 2013-2014. Locations of these monitoring points are shown in figure 4.1.2 and 4.1.7. Water levels referenced against the NZGD 2000 datum.

5.2.1. Inflow and outflow

The inflow of Matthews Lagoon is controlled by the Te Hopai pump station. Greater Wellington Regional Council (GWRC) monitors the running time of the pumps (two identical pumps at Te Hopai pump station) since March 2013 at this station. The gauging of the pumps was also done by GWRC, once in May and once in June. The pumping rate was estimated to be 1.15 m^3/s for each pump.

When compared with rainfall data, a strong correlation can be observed where inflow happens after rainfall events in the autumn, winter and spring. However, there is no such correlation in the summer (figure 5.2.2). This effect will be further discussed in the next chapter.

Monthly inflow from the Te Hopai pump station can then be calculated from the gauging information and actual running time of the pumps (figure 5.2.3). In late June 2013, the rainfall was intensive (figure 5.2.2), which led to a huge amount of water that went into Matthews Lagoon in a short period of time. As a result, the inflow in June alone was greater than the combined inflow in May and July (figure 5.2.3).

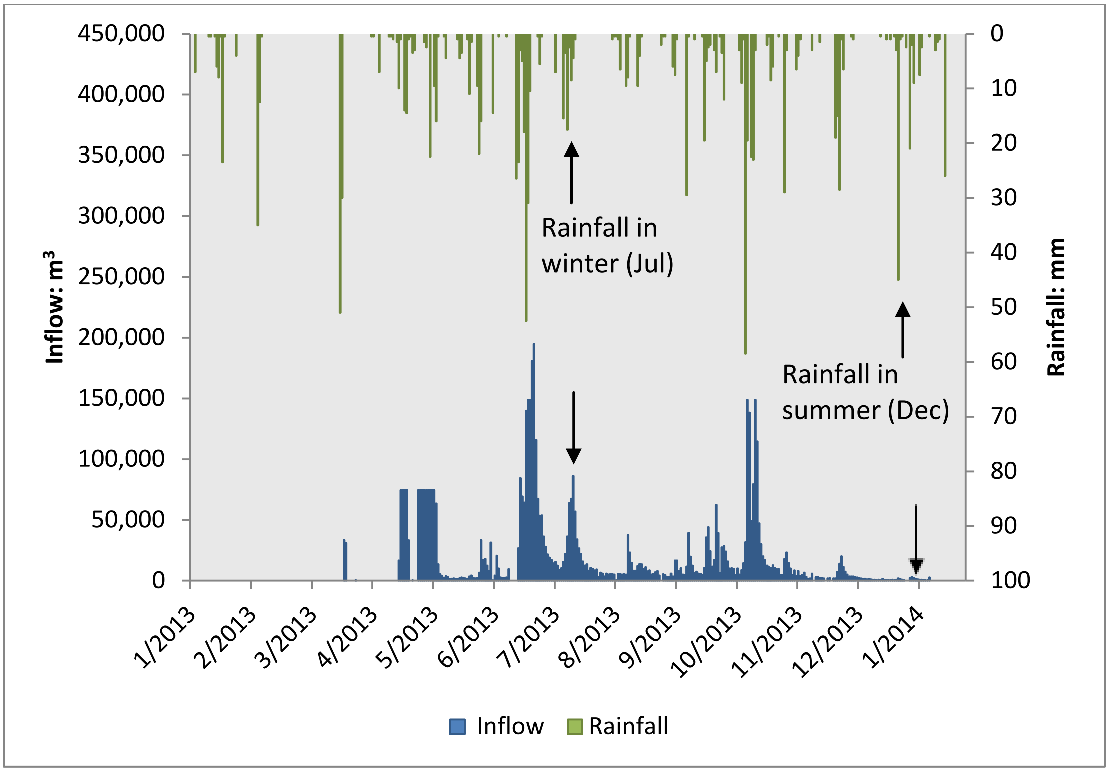


Figure 5.2.2 Daily inflow from Te Hopai pump station compared with daily rainfall. Note the inflow rate (downward arrows) responds differently to rainfall in winter and summer (upward arrows).

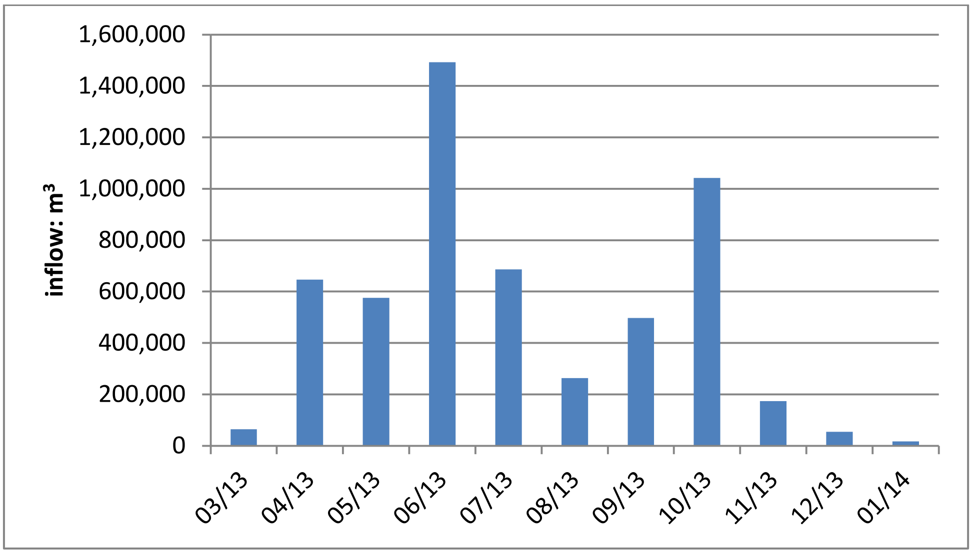


Figure 5.2.3 Monthly water inflow from Te Hopai pump station. Note that gauging started in late March 2013 and data are updated until late January 2014.

At the outflow of Matthews Lagoon, a pressure transducer and a staff gauge were installed to monitor water levels (see details in chapter 4) since July 2013. Velocity-area gauging in the channel near outflow was carried out several times to generate the rating curve at the outflow (figure 5.2.4). Using the curve and water level data recorded by the pressure transducer, the "total" discharge from Matthews Lagoon can be estimated.

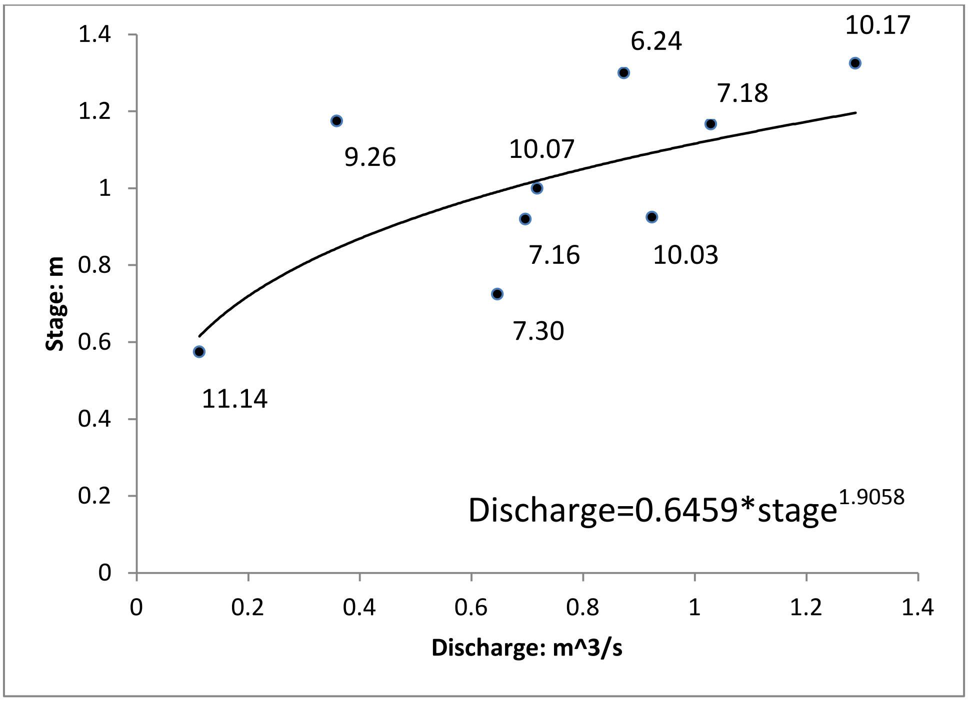


Figure 5.2.4 Rating curve at the outflow of Matthews Lagoon. Black dots represent the stage-discharge measurement taken at different times of the year. The date of measurement is labelled. The equation shows the stage- discharge relationship.

However, solely using this calculation to estimate outflow could potentially overestimate the water flow rate. Since the outlet is controlled by floodgates, whether there is water flow at outlet depends on the water pressure on both sides of the floodgates. When water pressure in the wetland is greater than in the Oporua floodway, water pushes the floodgates open and flows out. Otherwise, the floodgates stay closed and there will be no water flow.

To eliminate the affect from floodgates being open or closed, some assumptions were used to calculate the actual outflow. First, the floodgates did not open until late June and closed in early to late December. This assumption is made based on observations throughout the study. Second, water flow between January and June is negligible. Third, water flow happens when water level at outlet drops (the green periods in figure 5.2.5). Otherwise, it is assumed there is no water flow (the red periods in figure 5.2.5). Water level at the inside of outlet has to "recharge" first to reach a certain depth so the floodgates can be pushed open by pressure difference (usually happens when the water level peaks). When water flows out through the floodgates and "discharges", water level drops, pressure is not able to keep the floodgates open, and water flow slows down and gradually stops (when water level reaches the lowest point). After water level reaches its lowest point, the cycle of recharge and discharge begins again.

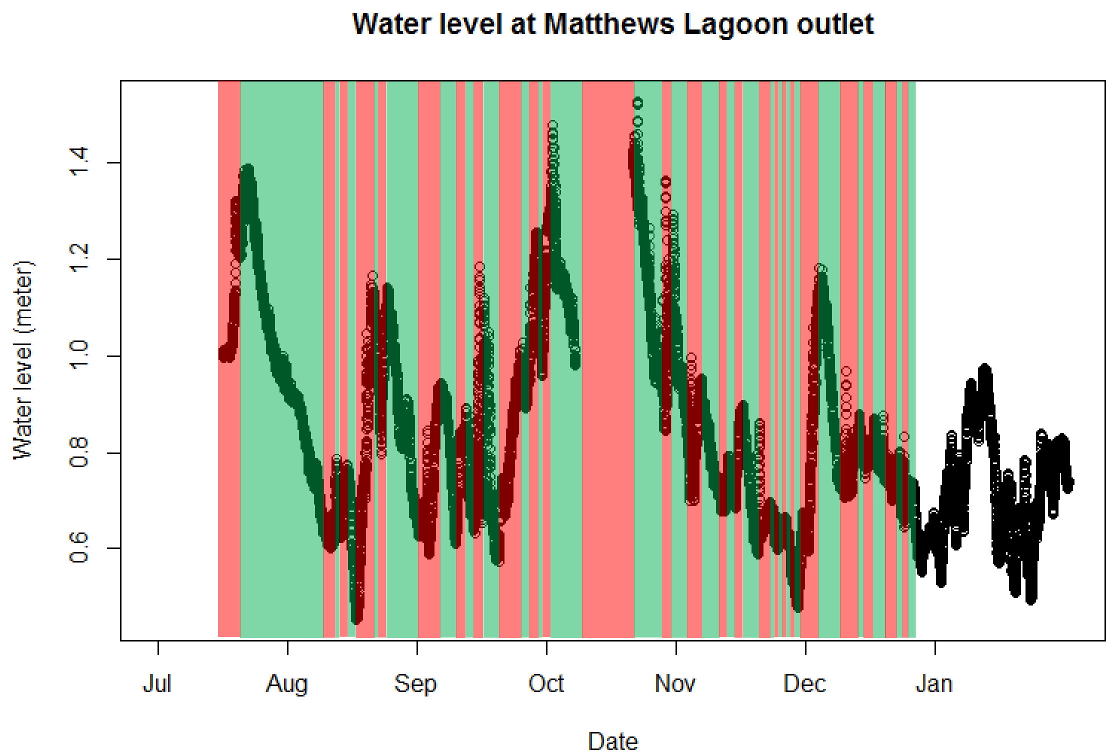


Figure 5.2.5 Water level at outlet in Matthews Lagoon with discharge (green) and recharge (red) processes labelled. Water only flows out through the floodgates during the discharge (green) process. The ratio of discharge to recharge is about 53:47.

Theoretically, actual outflow should be calculated only when discharge happens (during the green periods). However, since the ratio between discharge (outflow) and recharge (no outflow) processes is almost the same (53:47), outflow volume was simplified as half of the “total” discharge volume (figure 5.2.6) calculated from the rating curve and water level data.

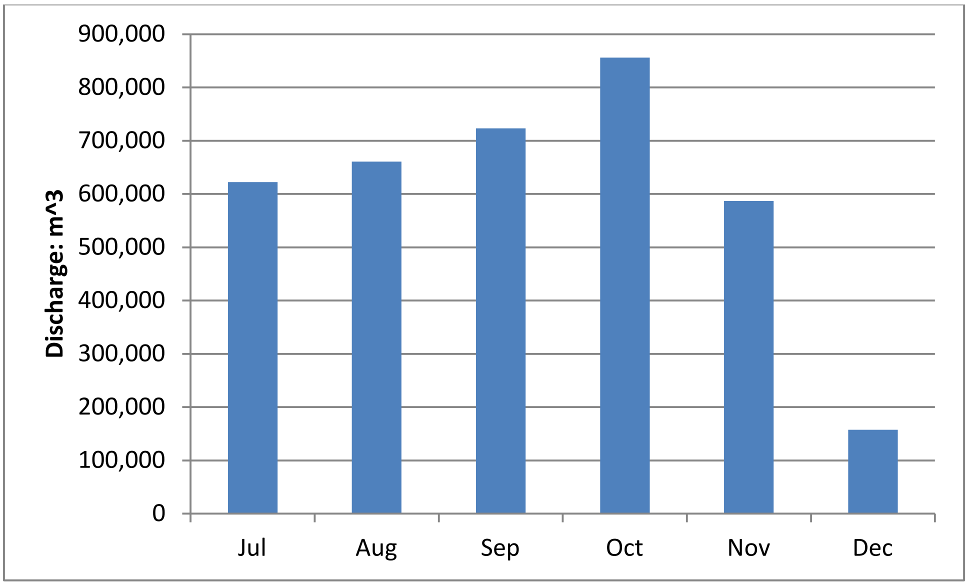


Figure 5.2.6 Monthly total discharge volume at the Matthews Lagoon outlet during the latter half of 2013.

5.2.2. Wetland size and volume

Figure 5.2.7 shows the watersheds and drainages of the study wetlands. Boggy Pond’s watershed area is 2.9 square kilometres, while Matthews Lagoon is 4.4 square kilometres.

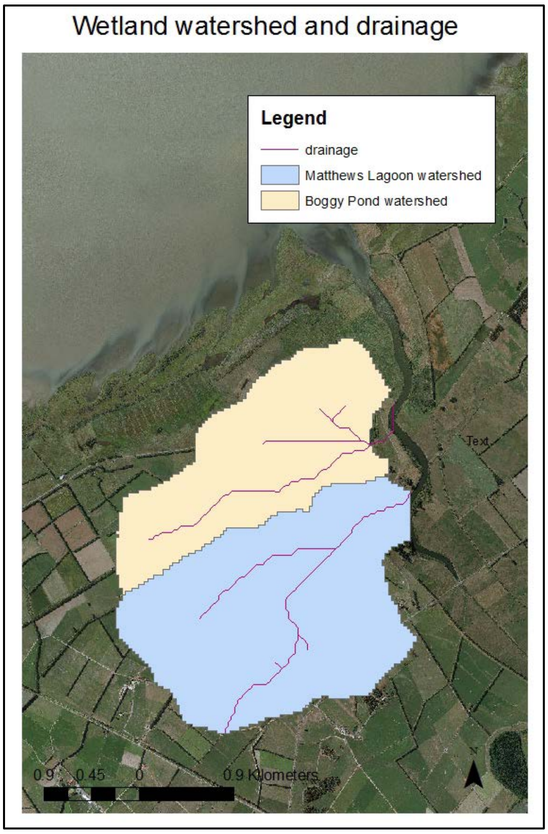


Figure 5.2.7 Watershed area of Matthews Lagoon and Boggy Pond (catchment surface area is used in water balance equation to convert between cubic meters and mllimeters).

Two water depth surveys were done once in summer (February 2012) and once in winter (June 2013). 124 survey points were accessed by kayak and water depth was measured by a staff gauge (figure 5.2.8). The edge, where water depth is always 0, defines the surface areas of both wetlands (figure 5.2.9). The GPS coordinates of the survey points were collected by a Garmin GPS 60 handheld navigation device. It gives a ±15 meters accuracy when used alone for positioning.

Note that the size and shape of the wetland surface area is different from the watershed (figure 5.2.7). This is because although the watershed contributes to the water gains or losses in a wetland, its size is constant, where the actual water surface area of a wetland changes with the fluctuations of water volume in the wetland. Therefore, the surface area is smaller in size than the watershed. Water depth of places that could not be accessed by kayak or on foot was estimated by using the water depth measurement from nearby accessible locations that had similar vegetation and landscape.

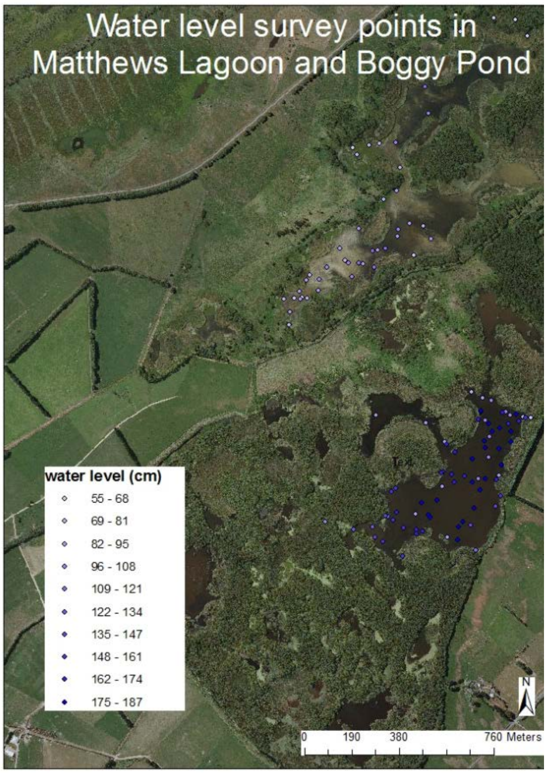


Figure 5.2.8 Water depth survey points in Boggy Pond and Matthews Lagoon (water depth survey carried out once in winter and once in summer. This picture shows the result from the winter survey).

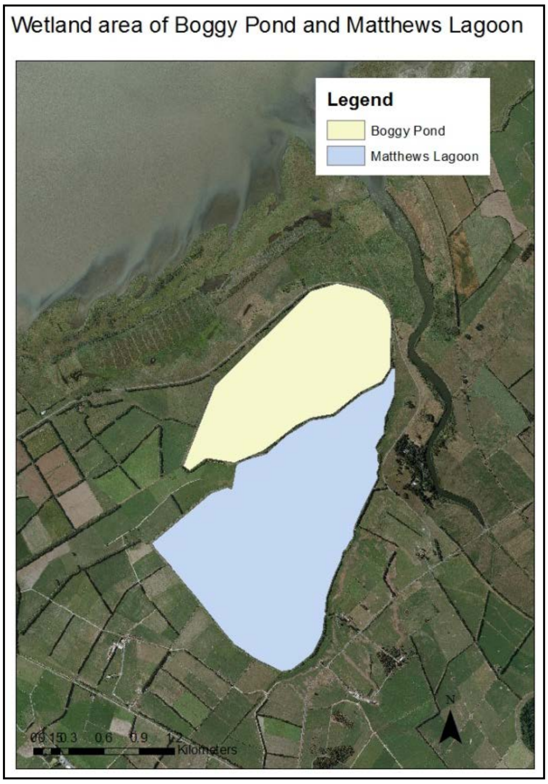


Figure 5.2.9 Wetland area of Boggy Pond and Matthews Lagoon (this is the actual surface area used in calculating wetland volume).

The Create TIN function in ArcGIS 3D Analyst toolbox was used to generate 3D models for Matthews Lagoon and Boggy Pond (see details in chapter 4). In total, about 300 water depth data points were used to create TINs for Matthews Lagoon and Boggy Pond. Using the results from the water depth surveys in winter and summer, a high (winter) and low (summer) water level model of the wetlands can be displayed (figure 5.2.10).

A linear relationship between the water depth measured at water level monitoring stations 1 and 3 (figure 4.1.2) and water volumes calculated from the TINs (figure 5.2.10) were used to estimate water storage changes in the two wetlands (figure 5.2.11). The water levels at stations 1 and 3 fluctuated differently (figure 5.2.12) indicating different hydropatterns in Boggy Pond and Matthews Lagoon.

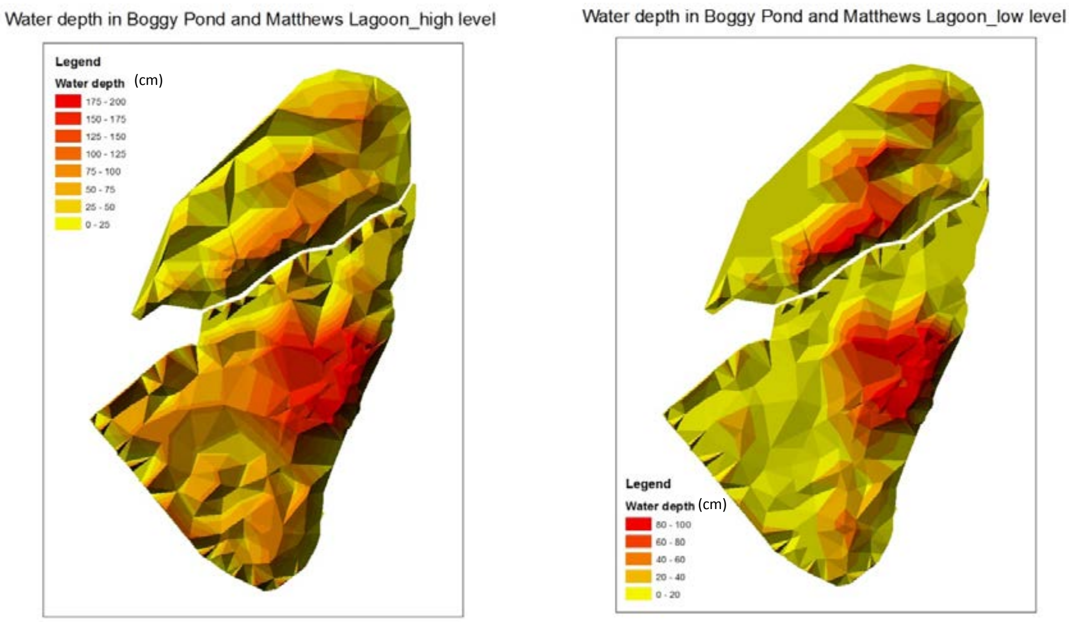


Figure 5.2.10 Water depth in Boggy Pond and Matthews Lagoon when water levels are high in the winter (left) and low in the summer(right).

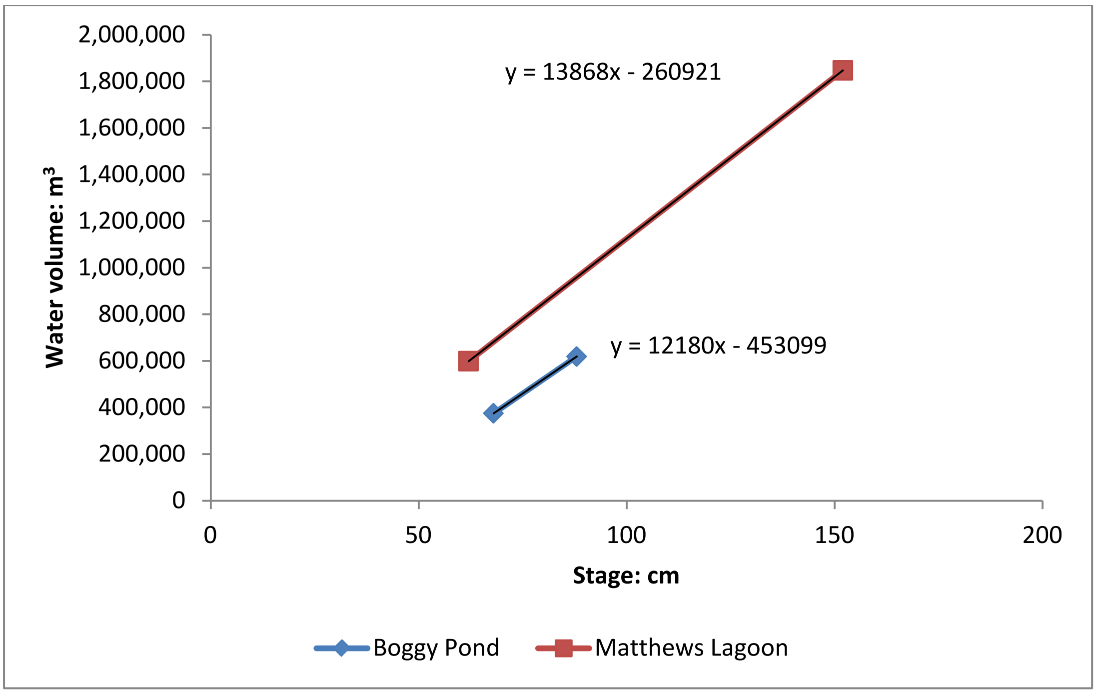


Figure 5.2.11 Stage-volume relationship of Boggy Pond and Matthews Lagoon. Stage data were measured from water level monitoring stations 1 and 3 (figure 4.1.2).

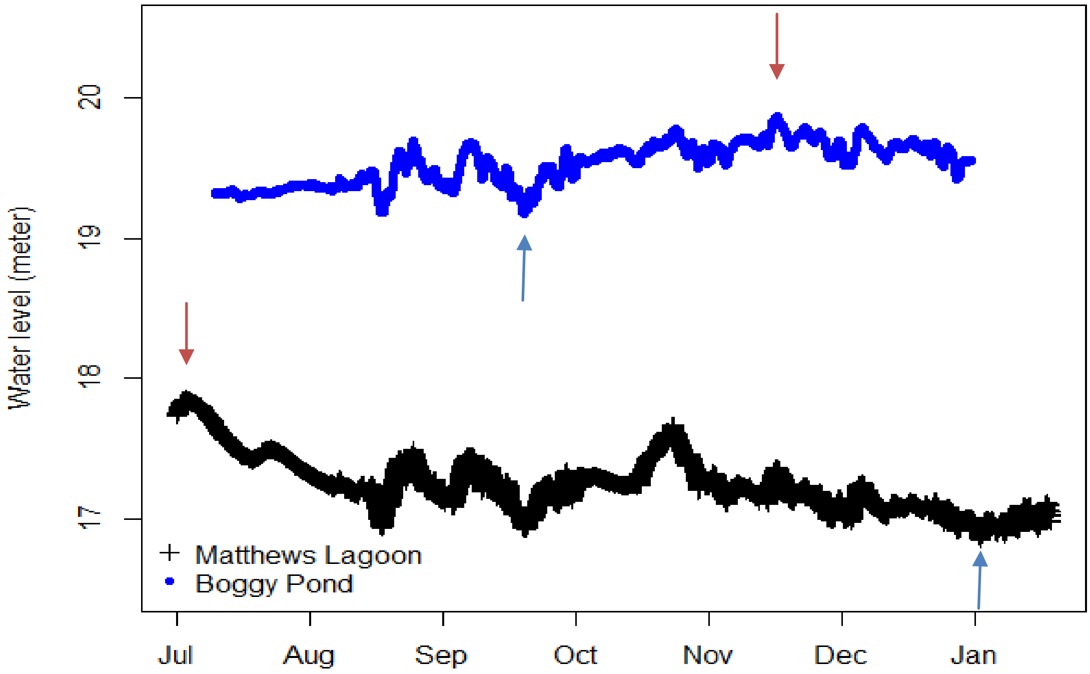


Figure 5.2.12 Water levels above sea level in Matthews Lagoon and Boggy Pond as shown in figure 5.2.1. Down arrows indicate the highest water levels and up arrows indicate the lowest in both wetlands. The high-low difference is 1m in Matthews Lagoon and 0.7m in Boggy Pond, corresponding to a change in wetland volume of 1,386,800 m^3 and 852,600 m^3, respectively.

From the literature review in Chapter 2, the water level in a wetland not only influences the type of vegetation in it but also significantly affects the nutrient removal function of a wetland. Between June 24th 2013 and January 16th 2014, water level in Matthews Lagoon dropped 0.76 meters from 17.73 meters above sea level to 16.97 meters above sea level. The water level peaked on June 26th 2013 at 17.85 meters and dropped down to the lowest levelon December 30th 2013 at 16.85 meters (figure 5.2.12). Boggy Pond, on the other hand, increased in water level from 19.32 meters in the beginning of the monitoring to 19.54 meters in the end. The highest water level happened on November 12th at 19.88 meters and the lowest happened on September 14th at 19.18 meters (table 5.2.1).

Table 5.2.1 Summary of water level changes in Matthews Lagoon and Boggy Pond. Water levels are in meters and are above the sea level.

	Highest (m)	Lowest (m)	Difference between highest and lowest (m)	Total water level changes (m)
Matthews Lagoon	17.85	16.85	1.00	-0.76
Boggy Pond	19.88	19.17	0.71	0.22

5.2.3. Groundwater

The water tables in the four boreholes in figure 4.1.7 are shown in figure 5.2.13. BQ33/0011 and BQ33/0013 (the boreholes that are close to the lake's eastern shoreline) have similar water tables throughout the study period. BQ33/0014 (to the east of Boggy Pond) and BQ33/0012 (to the west of Boggy Pond) have the highest and lowest water table, respectively. Water levels in Boggy Pond are above nearby water tables, indicating it is a recharge wetland or perched wetland as mentioned in chapter 4.

The groundwater flow directions can be drawn based on water level data from at least three boreholes (see details in chapter 4). An example of lateral groundwater flow directions is shown in figure 5.2.14. Groundwater enters Matthews Lagoon from its south-eastern side and exits from the north-western side, while Boggy Pond loses groundwater from the western end. These flow directions are estimated based on the information available. To fully understand the groundwater flow, a detailed groundwater table survey is required. Contours and flow directions slightly change from month to month due to the fluctuations of water tables, but the general direction is as shown in figure 5.2.14.

As mentioned in the previous chapter, saturated hydraulic conductivity is a property of soils. GWRC (Jones and Gyopari, 2006) has categorised six broad hydrostratigraphic units according to formation lithology, well yields, and measured aquifer properties in the Wairarapa Valley. In general, soils in Matthews Lagoon and Boggy Pond are low permeability lacustrine and estuarine deposits. The silts and clays accumulated within the central part of the lower valley and the sediments are over 200 meters thick. The saturated hydraulic conductivity is assumed to be less than 10 m/day.

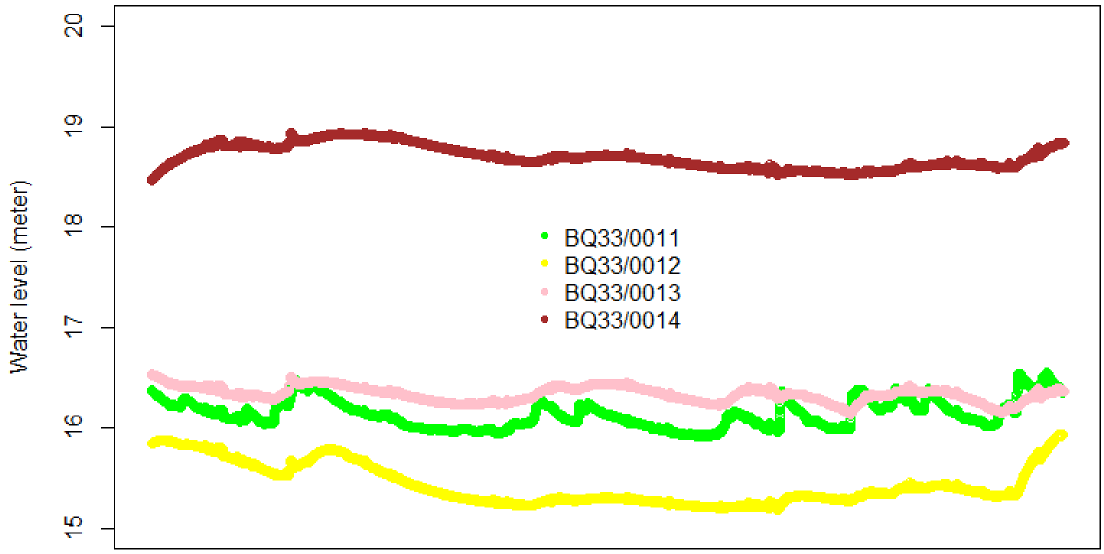


Figure 5.2.13 Water tables in four boreholes (BQ33/0011 and BQ33/0013: along the lake eastern shoreline, BQ33/0012: next to Boggy Pond on the west, BQ33/0014: to the east of Boggy Pond) as shown in figure 4.1.7.

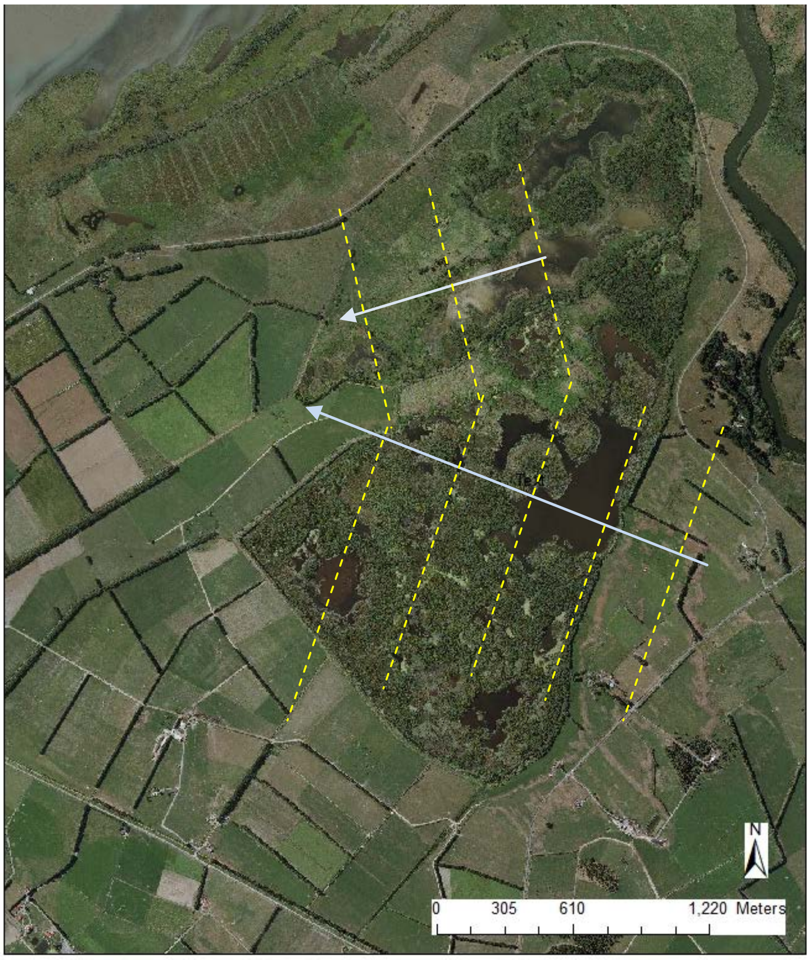


Figure 5.2.14 Groundwater flow directions (arrows) and water table contours (yellow dashed lines).

Monthly groundwater flow in both wetlands is shown in table 5.2.2. Some assumptions have been made in order to apply Darcy's Law (as explained in chapter 4). Only lateral flows are considered in this study as it is the dominant process of groundwater flows according to Bredehoeft et al. (as cited in Carrillo-Rivera, 2000). The hydraulic conductivity in equation 4.1.5 is 10 m/day after Jones and Gyopari (2006). The hydraulic gradient varies with the fluctuation of water tables. Overall, groundwater flows contribute insignificantly to the water balance compared with other water balance components.

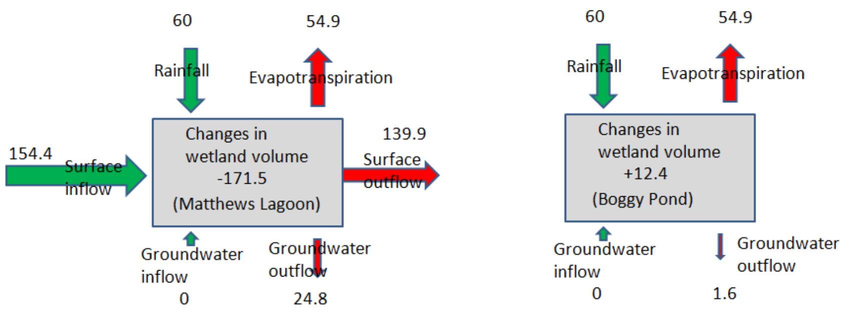
Table 5.2.2 Groundwater flows (positive value means groundwater flows into the wetland, negative value means the wetland releases water to groundwater) calculated using Darcy's Law. Only lateral flows are considered in this calculation, longitudinal flow is negligible, due to the impermeable nature of wetland bottom.

		June	July	August	September	October
Matthews Lagoon (cm)	In	19.80	0.00	33.56	30.25	30.08
	Out	19.90	24.79	20.41	19.33	19.40
Total (in-out) (cm)		-0.1	-24.79	13.15	10.92	10.68
Boggy Pond (cm)		--	-1.63	-5.30	-5.13	-5.27

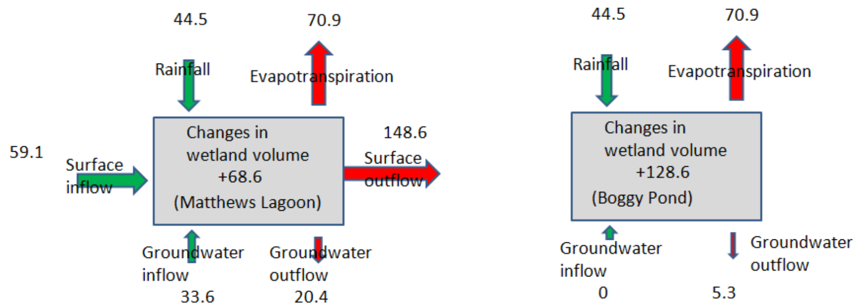
5.2.4. Water balance and residence time

Monthly water balances in Matthews Lagoon and Boggy Pond are shown in appendix E. Rainfall data is obtained from the climate station on the eastern shore (figure 5.1.1). Evapotranspiration is calculated based on Penman-Monteith equation (equation 4.1.4 and 4.1.5). Surface inflow is measured by GWRC since Mar 2013, inflow in Jan and Feb 2013 is estimated based on measurement in Jan 2014. Surface outflow is calculated using the rating curve (figure 5.2.4). Since the water level monitoring started in late June in Matthews Lagoon and early July in Boggy pond, groundwater flows and changes in wetland volume are not available until July in this water balance calculation. Groundwater data from GWRC was downloaded in October 2013, therefore groundwater flows after October are not available.

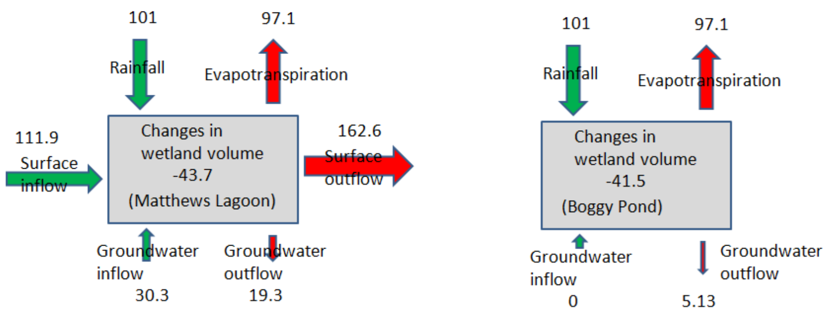
Figure 5.2.15 shows the water balances of Matthews Lagoon and Boggy Pond from July to October in 2013 when data were all available. It is clear that in these months surface flows dominated the water balance in Matthews Lagoon. Wetland volume decreased in Matthews Lagoon but increased in Boggy Pond. Groundwater flow was not significant in both wetlands. It would be ideal to compare the water balance between winter and summer in the wetlands, but little information was available for the summers in either 2013 or 2014.



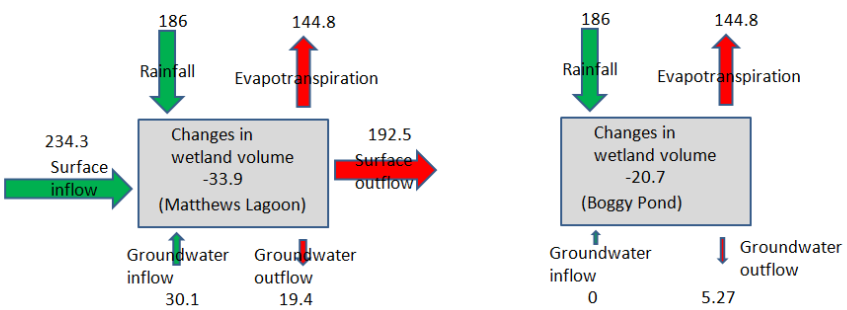
(a) Water balance in July 2013 in Matthews Lagoon (left) and Boggy Pond (right).



(b) Water balance in August 2013 in Matthews Lagoon (left) and Boggy Pond (right).



(c) Water balance in September 2013 in Matthews Lagoon (left) and Boggy Pond (right).



(d) Water balance in October 2013 in Matthews Lagoon (left) and Boggy Pond (right).

Figure 5.2.15 Water inputs (green arrows), outputs (red arrows), and volume change (grey boxes) in the wetlands in four months (Jul to Oct). Numbers are shown in mm.

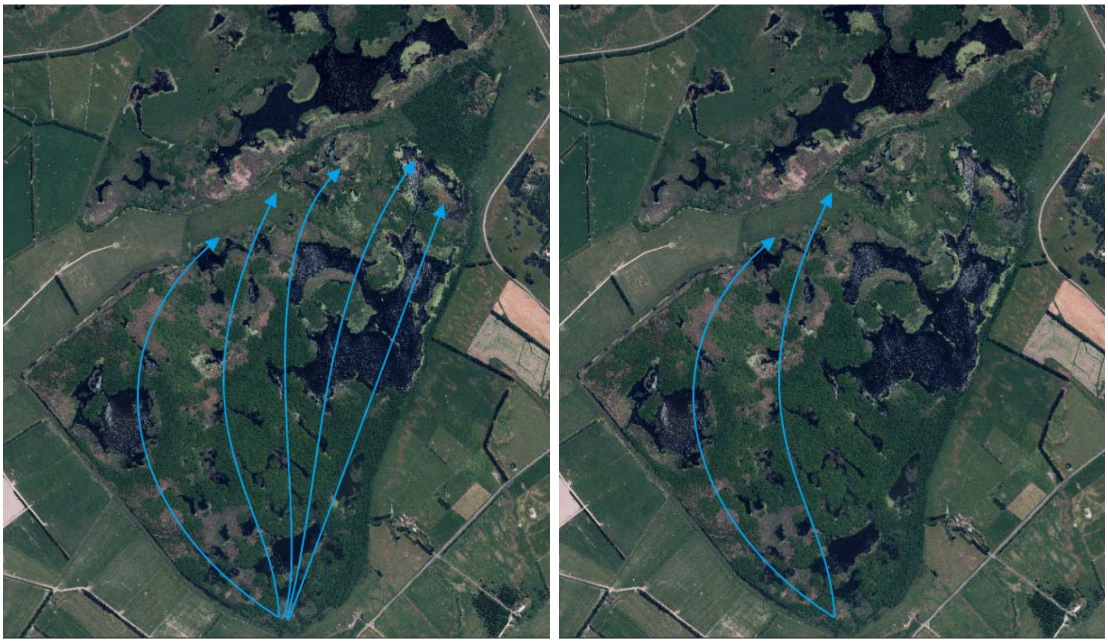
In addition to this water balance, a conceptual water balance can be calculated under certain assumptions using the data measured from this study under certain assumptions. First, wetland volume is assumed to be the same in January 2013 and 2014. Therefore, change in wetland volume (ds) is 0 throughout the year. This assumption may be unrealistic, but no other assumption is practicable due to the lack of data on the wetland size. Second, groundwater flows in Matthews Lagoon are neglected as they do not constitute a big portion in the water balance. The second assumption may also be unrealistic but there are no adequate data are available to support a more sophisticated assumption. Groundwater outflow from Boggy Pond assumes an average value from July to October in 2013. As for the surface flows in Matthews Lagoon, inflow and outflow are the same as shown in appendix E. This conceptual water balance is shown in table 5.2.3. According to the water balance equation (equation 4.1.1), if ds is 0, total inputs and outputs should be equal. Results from Matthews Lagoon follows this assumption better than Boggy Pond considering groundwater flow is neglected in this conceptual water balance. Evapotranspiration is acceptable in the water balance of Matthews Lagoon. For Boggy Pond, on the other hand, total inputs are about 360 mm less than total outputs. If the assumption on wetland volume being the same over the year is true, there might be other sources of water supply in Boggy Pond, which can be a major concern for the water quality in Boggy Pond.

Table 5.2.3 Conceptual annual water balance in Matthews Lagoon and Boggy Pond. Wetland volume is assumed to be the same throughout the year (ds=0). Rainfall, evapotranspiration, and surface flows are adopted from appendix D. Groundwater flows in Matthews Lagoon and Boggy Pond are negligible as they contributed little to the water balance. Total water inflow should be equal to total output according to water balance equation (equation 4.1.1).

		Matthews Lagoon	Boggy Pond
In	Rainfall (mm)	1169.5	1169.5
	Surface flow (mm)	1327.9	--
Out	Evapotranspiration (mm)	1532.6	1532.6
	Surface flow (mm)	811.1	--
In – Out (mm)		153.7	-363.1

Residence time is calculated for two scenarios here (figure 5.2.16). In the first scenario, it is assumed that water is well mixed in the entire wetland. In the second scenario, water bypasses the open water wetland. As mentioned in chapter 2, residence time is determined by wetland volume and water flow rate. The fluctuations of outflow can be used to divide the water residence time in Matthews Lagoon into long residence time mode and short residence time mode. Residence time is longer when floodgates are closed and becomes shorter when floodgates are open. Water residence times in Matthews Lagoon under the two scenarios are shown in table 5.2.4. Residence time is significantly shorter in scenario 2 than scenario 1. This is because the open water part takes up almost 90% of the total volume in Matthews Lagoon.

The water level results (figure 5.2.1) suggest that water flows in Matthews Lagoon follow the patterns shown in scenario 2. This is because the pressure head is higher at the outlet than it is at the middle point. Since water only flows from high pressure head to lower ones, it is assumed that there is no direct connectivity between the middle point and outlet in term of surface water flows. One possible explanation is that water bypasses the middle point and flows to the outlet directly.



(a) Scenario 1. Water is well mixed and flows through the entire Matthews Lagoon.

(b) Scenario 2. Water bypasses the main open water part of Matthews Lagoon.

Figure 5.2.16 Two scenarios of water paths through Matthews Lagoon that impact the length of water residence time. Blue lines with arrows indicates water flow directions and paths.

Table 5.2.4 Water residence time in Matthews Lagoon. Residence time (t) here is simplified as monthly average wetland volume (v) divided by monthly flow rate (v/t). Water is assumed to be well mixed in the wetland. Note the residence time difference in August (winter) and December (summer).

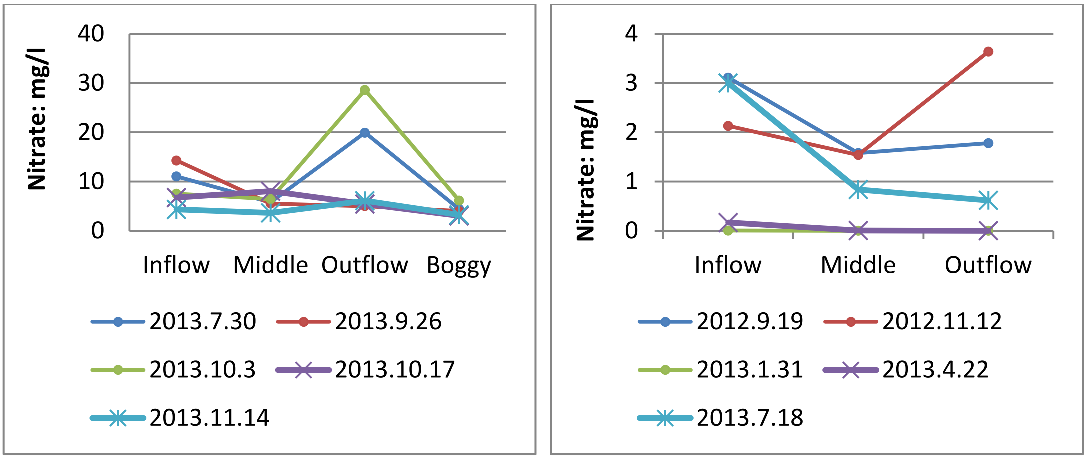
	Residence time (days)	
	Scenario 1 (flow through entire wetland)	Scenario 2 (bypass the main open water part)
July	23.0	3.5
August	14.6	2.2
September	12.3	1.8
October	14.3	2.1
November	13.7	2.1
December	38.2	5.7

5.3. Water quality analysis

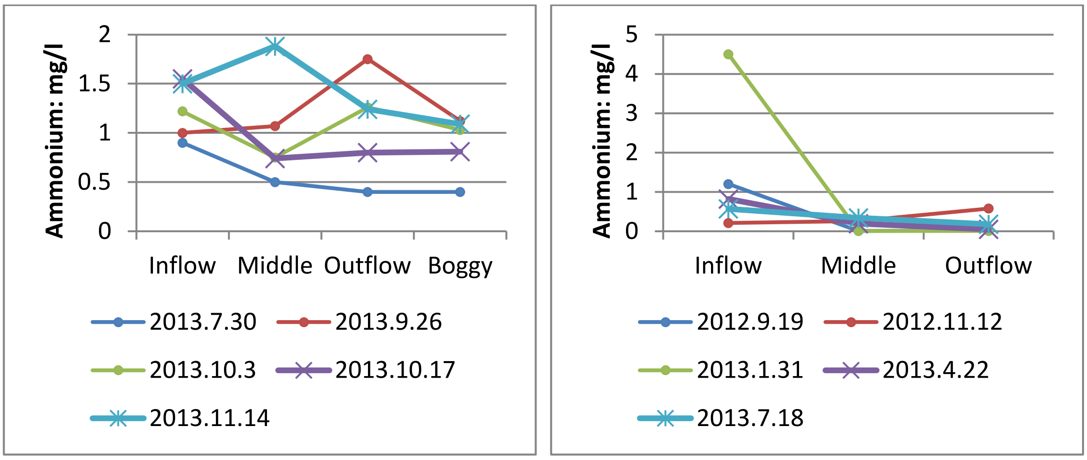
5.3.1. Overall characteristics

The results from water quality tests on different days at different locations are shown in figure (5.3.1). Detailed water quality test results can be found in appendix F. Boggy Pond in general had lower nutrient levels than other stations in Matthews Lagoon, which indicates its isolated hydrological nature. For nitrate nitrogen concentrations, the YSI handheld meter gives much higher results than lab tests. This phenomenon will be further discussed in the next chapter. Ammonium concentrations did not differ as much between the two methods (YSI handheld meter and lab analysis), which indicates low interference from other ions. For both methods, phosphate levels at the inlet and outlet did not differ too much, but was noticeably higher at the middle station of Matthews Lagoon.

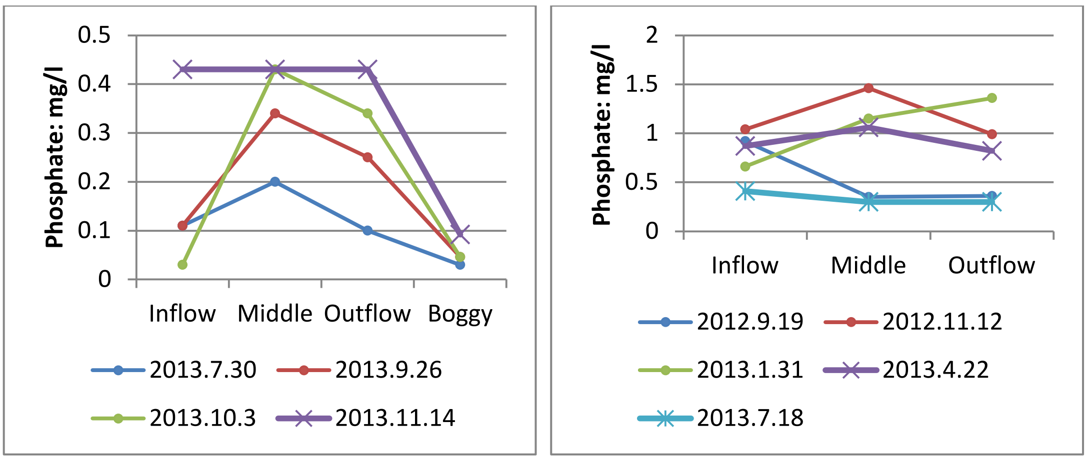
From figure 5.3.2, patterns of nutrient concentrations at the four monitoring locations show lower nitrogen levels at the outlet compared to the inlet for both measurement methods.



(a) Nitrate concentrations measured by YSI meter (left) and lab test (right).

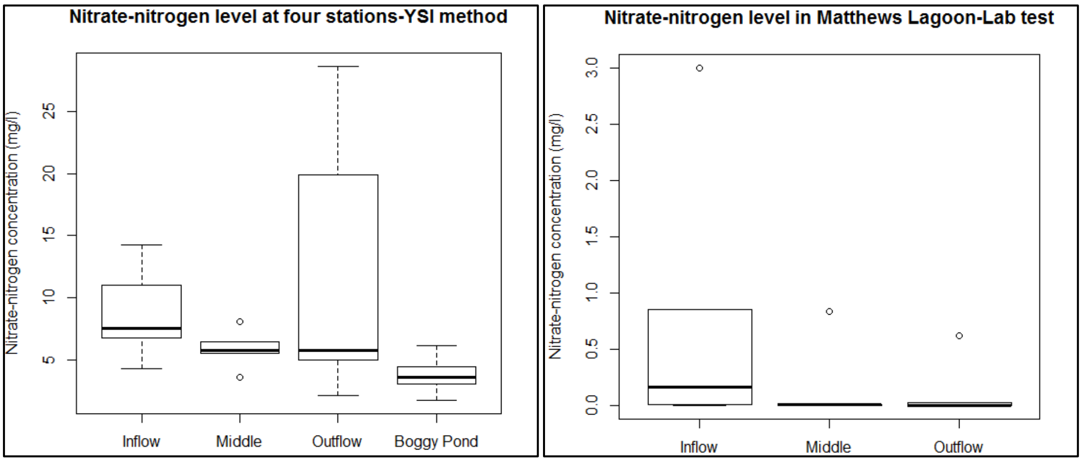


(b) Ammonium concentration measured by YSI meter (left) and lab test (right).

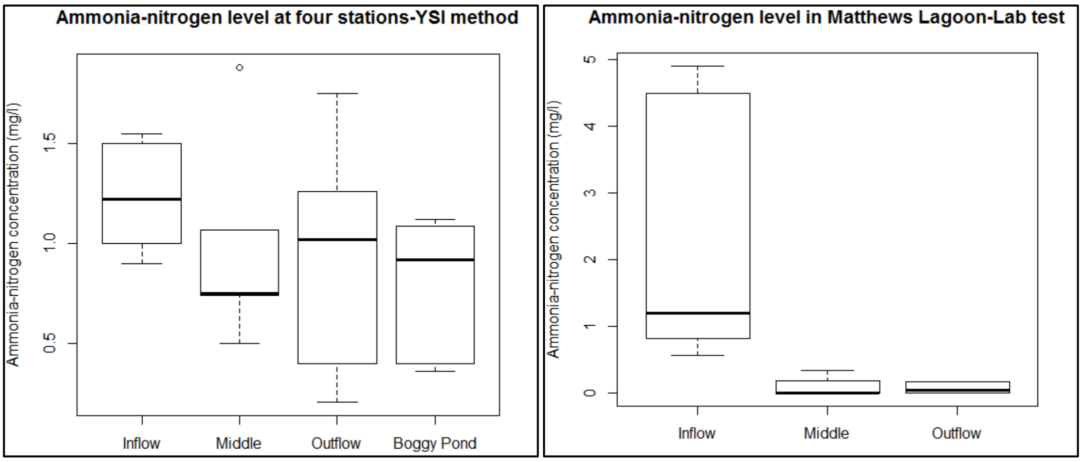


(c) Phosphate concentration measured by YSI meter (left) and lab test (right).

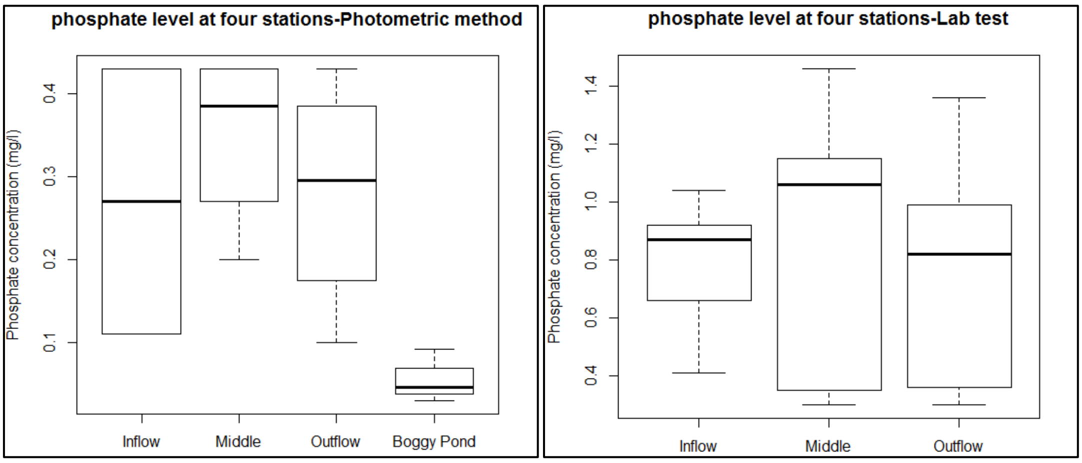
Figure 5.3.1 Concentrations of (a) nitrate, (B) ammonium, and (c) phosphate at different locations in Matthews Lagoon and Boggy Pond (refer to figure 4.2.1) on different days measured by YSI handheld meter (left) and lab test (right).



(a) Nitrate levels measured by YSI meter (left) and lab test (right).



(b) Ammonium levels measured by YSI meter (left) and lab test (right).



(b) Phosphate levels measured by YSI meter (left) and lab test (right).

Figure 5.3.2 Ranges of (a) nitrate, (B) ammonium, and (c) phosphate levels at different locations in Matthews Lagoon and Boggy Pond (refer to figure 4.2.1) measured by YSI handheld meter (left) and lab test (right). Box represents the interquartlie range, the thick line is the median. Data obtained from figure 5.3.1.

Results from the real-time measurement (figure 5.3.3) shows that before January 10th, Matthews Lagoon acted as a sink for nitrate nitrogen during the test. However, nitrate concentration at the outlet was higher than at the inlet from the 10th onward. In other words, Matthews Lagoon acted as a source of nitrate. This reverse can be explained by the "dilution" effect at the inlet and the "accumulation" effect at the outlet. These effects will be explained in the next chapter in detail.

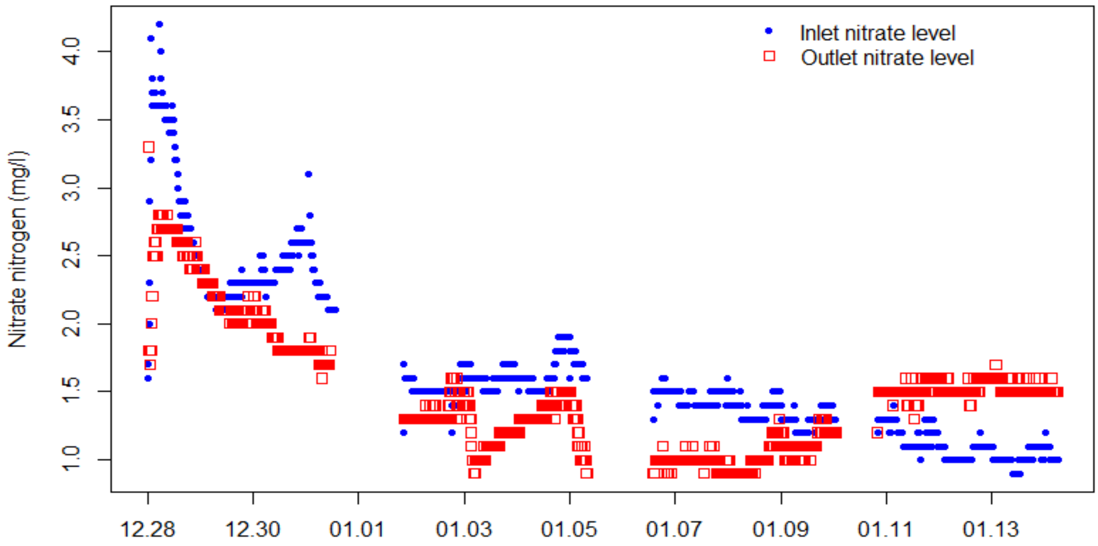


Figure 5.3.3 Nitrate concentration at inlet and outlet of Matthews Lagoon, measured by YSI handheld meters logging every 15 minutes.

The nitrate level at the inlet shows a realationship with pumping actions from Te Hopai pump station (figure 5.3.4). Nitrate concentration goes up when the pumps are working. This is understandable as water from farm lands is usually high in nutrients (figure 2.3). However, these nutrient pulses could possibly create some problematic issues for nutrient removal which will be discussed in the next chapter.

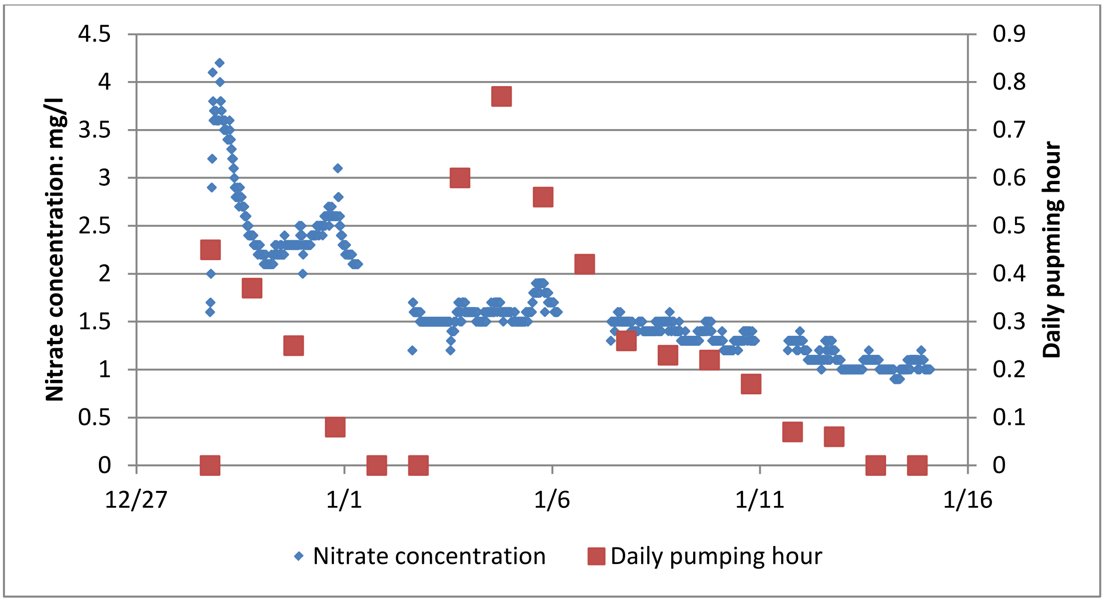


Figure 5.3.4 Nitrate concentration at the inlet (measured with YSI handheld meter logging every 15 minutes) and daily total pump working hours.

5.3.2. Removal rate

A nutrient removal rate (equation 4.2.1) will be able to show how well the wetland acts as a sink for nutrients. Similar to the water balance equation, a nutrient balance equation is built based on the mass balance equation. Water quantity and pollutant concentration are two important parts in the mass calculation. For a more accurate result, continuous monitoring in flow rate and pollutant concentration is essential. However, in this study, monthly average surface water input, output, and concentration from each test were used in nutrient balance calculation. Table 5.3.1 shows an example of the nutrient balance in Matthews Lagoon in July 2013. The concentration data is from GWRC water quality tests in July. Because the chemical reactions are complex among the pollutants and transformations from one form to another are common, total Kjeldahl nitrogen (TKN), total nitrogen (TN) and total phosphorus (TP) are used to represent the overall pollutant level.

Table 5.3.1 Nutrient balance in Matthews Lagoon in July 2013. Water quality data are from GWRC. Removal rate is expressed in equation 4.2.1. Total Kjeldahl nitrogen (TKN), total nitrogen (TN) and total phosphorus (TP) are used to represent the overall pollutant level, because the chemical reactions are complex among the pollutants and transformations from one form to another are common.

	Inlet			Outlet			Removal rate (%)
	Flow (m3)	Concentration (g/m3)	Mass (kg)	Flow (m3)	Concentration (g/m3)	Mass (kg)	
NO_3	686,504	3	2,059.5	1,244,490	0.62	771.6	62.6
NO_2		3	2,059.5		0.66	821.4	60.1
NH_4		0.57	391.3		0.18	224	42.8
TKN		1.76	1,208.3		1.51	1,879.2	-55.5
TN		4.8	3,295.2		2.2	2,737.9	16.9
PO_4		0.11	75.5		0.1	124.4	-64.8
TP		0.41	281.5		0.3	373.3	-32.6

In order to understand the nutrient balance in summer, a water quality test from December 2012 was used instead summer (there is no lab water quality test from GWRC in the 2013/2014 summer). Since water flow is unknown in the summer 2012, water inflow and outflow are assumed to be the same due to the low inflow and outflow in the summer months and the removal rate can be calculated from concentration data (table 5.3.2).

Table 5.3.2 Summer nutrient balance in December in Matthews Lagoon (2012). Water quality data are from GWRC. Water flows at inlet and outlet are assumed to be the same. Removal rate is expressed in equation 4.2.1. Total Kjeldahl nitrogen (TKN), total nitrogen (TN) and total phosphorus (TP) are used to represent the overall pollutant level, because the chemical reactions are complex among the pollutants and transformations from one form to another are common.

	Inlet (g/m^3)	Outlet (g/m^3)	Removal rate (%)
NO_3	0.002	0.002	0.0%
NO_2	0.002	0.004	-100.0%
NH_4	4.9	0.179	96.3%
TKN	5.8	1.6	72.4%
TN	5.8	1.61	72.2%
TP	1.04	0.99	4.81%

6. Discussion

6.1. Wetland classification

As stated in chapter 2, there are many factors that need to be considered when classifying a wetland. In this study, water quality and hydrological condition are the most important aspects. Therefore, wetland classification of Matthews Lagoon and Boggy Pond were done based on these two factors. The classification levels are adopted from Johnson and Gerbeaux (2004).

Matthews Lagoon and Boggy Pond were originally formed as sandstorm depositions on the eastern shore. They were formed on the immediate margin of the lake and most likely influenced by lake level fluctuations and wave actions, therefore, by definition, for the first level (hydrosystem) in the six classification levels, both wetlands were classified as lacustrine. However, the construction of Parera Road cut off these two wetlands from the lake (figure 3.1.5). As a result, both wetlands can be classified as palustrine base on their broad hydrological and landform systems, which are fed by rain, groundwater, or surface water, but not directly associated with estuaries, lakes, or rivers. A very small part of Matthews Lagoon has become riverine near the inlet and outlet, where water flows in and out of the wetland through open channels (figure 6.1.1).

Figure 6.1.1 Open channels at outlet (left) and inlet (right) of Matthews Lagoon. The channel at the outlet is about 3-5 meters wide and over 500 meters long while at the inlet is over 10 meters wide and about 215 meters long.

In the most important level of wetland classification, the wetland classes, according to Johnson and Gerbeaux (2004), there are 9 wetland classes that are recognised.

Both wetlands in this study have standing water in them most of the time which indicates that they are partially shallow water wetlands (details in chapter 2). For wetland areas not always covered by water, water regime, nutrient level, and pH are the factors that determine which class the wetland belongs to.

Table 6.1.1 summarises the hydrology and nutrient status of the wetlands in this study. Overall, Matthews Lagoon has a more variable water regime and higher nutrient level than Boggy Pond. Because Matthews Lagoon has a more complicated hydrological system, changes in water level in these two wetlands were not always similar, and the fluctuations were much greater in Matthews Lagoon than in Boggy Pond (figure 5.2.12). As for nutrient level, although results from YSI handheld meters were much higher than lab tests (this issue has been discussed in chapter 5), they can still be used as references when comparing the water quality between the wetlands. Based on the lab tests on nitrate and ammonia and field test on phosphate, water in Matthews Lagoon falls into mesotrophic to hypertrophic in the trophic category, while Boggy Pond falls into the oligotrophic to mesotrophic category (table 2.3). Once the water quality and water regimes are clear, it is easy to classify these wetlands. Matthews Lagoon, with high levels of water level fluctuation and high trophic status, is classified as a marsh (details in chapter 2). Boggy Pond, with relatively stable water level and better water quality, belongs to the wetland class of swamps (details in chapter 2).

Table 6.1.1 Comparison between Matthews Lagoon and Boggy Pond in water regime and nutrient level. Average nutrient concentration was calculated from 5 measurements between July 2013 and November 2013 by C. Shi using a YSI handheld meter and photometric field test kit. Lab test samples were collected 5 times by GWRC between September 2012 and July 2013. Trophic category is adopted from Thompson (2012), see details in table 2.3.

	Matthew Lagoon	Boggy Pond
Inflows	Rainfall, groundwater, and surface flow (pump station)	Rainfall
Outflows	Evapotranspiration, groundwater, and surface flow (outlet)	Evapotranspiration and groundwater
Average nitrate concentration	5.88 mg/l (C. Shi) 0.79 mg/l (GWRC)	4.17 mg/l (C. Shi)
Average ammonia concentration	0.99 mg/l (C. Shi) 0.16 mg/l (GWRC)	0.89 mg/l (C. Shi)
Phosphate concentration	0.35 mg/l (C. Shi)	0.05 mg/l (C. Shi)
Trophic state	Mesotrophic to hypertrophic	Oligotrophic to mesotrophic

Now that the classifications of both wetlands are known, it will be easier and more accurate to describe them in a way that different groups of audiences all understand. For example, Matthews Lagoon can be described as:

A combination of riverine and palustrine hydrosystem originally developed from lacustrine on the eastern shore of Lake Wairarapa. It is now a marsh and shallow water wetland complex with pump controlled inlet and floodgate controlled outlet. Emergent raupo (*Typha orientalis*), submerged aquatic weed hornwort (*Ceratophyllum demersum*), and willows (*Salix cinerea*) are commonly present in this wetland.

While Boggy Pond can be described as:

A combination of shallow water and swamp in a palustrine hydrosystem, which was separated from Lake Wairarapa by Parera Road. The water input is mainly rainfall. Rare turf plants and various bird species were found here in the 1980's (Ogle, 1989), but Raupo (*Typha orientalis*), hornwart (*Ceratophyllum demersum*), and willows (*Salix cinerea*) have become more abundant.

Knowing the classification of wetland types not only helps describe the wetlands more accurately, but also provides guidance with restoration actions (Clarkson and Peters, 2010). Clearly, Boggy Pond is cleaner and more isolated. Matthews Lagoon, on the other hand, is high in nutrients and invasive plants. Therefore, restoration goals for Boggy Pond should focus on prevention of further degradation and restoration of biodiversity, while Matthews Lagoon should focus on prevention of spreading of the weed plants and improving the nutrient removal ability.

This is the first attempt to officially classify and systematically describe these two wetlands. There are many other factors, such as soil type, substrate, vegetation, and landform (Johnson and Gerbeaux, 2004), that need to be taken into consideration when doing so. However, due to the scope of this study and restriction of resources, only nutrient levels and water regimes are considered. Although this attempt may not cover all aspects of these two wetlands, it should be able to start filling the knowledge gaps of this area.

6.2. Hydrological regime

6.2.1. Overall characteristics

One noticeable fact is that groundwater flows are not significant water inputs or outputs in these two wetlands when compared to other water balance components. In general, groundwater outflow is small due to the topographic setting of wetlands, usually in low-laying areas, and in the permeability of bottom layers (Campbell & Jackson, 2004). Groundwater inflow, however, varies depending on the type of wetland. As mentioned in chapter 3, water level in Lake Wairarapa is controlled by flood gates. This controlled hydrologic regime of Lake Wairarapa could have significant influences on the hydrological condition of the region. First, the lake is able to act like a buffer to offset the fluctuations in water table. The lake becomes source or sink of groundwater when the water table is low or high. Second, the controlled lake level can also influence surface flows that connect to the lake. Since the outlet of Matthews Lagoon joins the floodway which eventually goes to the lake, if the water level in the lake is higher than at the outlet, then the surface flow from Matthews Lagoon to the lake will stop. This is probably part of the reason that outflow from Matthews Lagoon only happens from July to January.

Another noticeable fact is that the difference between annual total inflow and outflow in Boggy Pond indicates an unidentified water input. Total water inputs minus outputs in Boggy Pond between January 2013 and January 2014 was -403mm. Wetland volume should be significantly smaller in 2014 than 2013 according to this calculation. However, the water level remained almost the same, which indicates little change in volume. Two water sources could explain this extra water input to Boggy Pond. First, there may be surface water flowing into Boggy Pond through the sealed outlet and control gate (figure 3.2.3). Matthews Lagoon and Oporua floodway are most likely the water sources. Second, groundwater may flow into the wetland. Lake level and the water table on the eastern shore of Lake Wairarapa could be temporarily raised by the strong wind that is common in this region (Perrie and Milne, 2012). Another possible explanation is that the evapotranspiration used in the water balance calculation might be overestimated. As mentioned in the previous chapter, AET usually accounts for 50-90% of PET, which means the AET could be about 100-700mm lower than what was used in the balance calculation. This is normal because potential evapotranspiration is calculated based on meteorological data with various assumptions and actual evapotranspiration could be influenced by cloud cover, so actual evapotranspiration is always less than potential evapotranspiration. To find out whether this unbalanced water input and output is caused by leakage or just due to errors in the calculation requires further investigation with more accurate data on net radiation of the study area.

In Matthews Lagoon, the discharge from the pump station showed quick and strong response to rainfall events from autumn to spring when soils were saturated or nearly saturated with water (figure 5.2.2). In winter, the initial response to rainfall events on the water inflow peaked about 2 days after the rainfall event and lasted for about 10 days. In other words, within two weeks, rainfall that falls on the farmlands that are within the Te Hopai drainage scheme will get to the pump station through various pathways. In summer, because the soil was dry, the pump station didn't respond to rainfall events as quickly as in winter, even when the rainfall event was large (figure 5.2.2). As introduced in chapter 3, the Te Hopai pump station services 1,003 ha farmlands near the site. Between March 20th 2013 and January 20th 2014, total rainfall was 9,663,905 cubic meters, meanwhile pump discharge to Matthews Lagoon was about 5,513,608 cubic meters, which means 57% of the rainfall was pumped to Matthews Lagoon from the catchment which is over twice the volume of water in Matthews Lagoon itself.

This water regime of the Te Hopai drainage scheme leads to two effects on the water and nutrient environment in Matthews Lagoon. First, inflow from the pump station shows seasonal patterns. As shown in figure 5.2.2, little water was pumped during the summer while in winter water was pumped after 2 to 14 days of each rainfall. Therefore, in summer, the Te Hopai drainage scheme decreases pumping water into Matthews Lagoon, while in winter the amount of water being pumped to the wetland is significant. The second impact from this kind of pulse-like water inflow is that the "first flush" after the first heavy rainfall after summer could contain high concentration of nutrients. Nutrients from fertiliser and manure from the farmlands within the Te Hopai drainage scheme could potentially be stored and concentrated in the soil over summer. Heavy rainfall in early Winter will flush out these nutrients all at once. Although the nitrate and total phosphorus tests by GWRC in January and April 2013 support this theory (appendix E), more detailed long-term water quality monitoring is required. In the 2013/2014 summer, continuous short-term water quality monitoring for about two weeks at the inlet helped to show the impact on water quality from the drainage. Nitrate was tested by a YSI handheld meter at the Te Hopai pump station from December 28th 2013 to January 15th 2014 (figure 5.3.5). During the same period, Te Hopai pump station ran for 5.14 hours. The nitrate concentration fluctuations were most likely the result from the pumping. Although in summer the pump station was not as active as in winter, there were still noticeable nitrate peaks flowed by pumping.

Since one of Matthews Lagoon's ecological services is to purify the water from Te Hopai drainage scheme before it gets to Lake Wairarapa, the ideal water regime should be steady and stable in Matthews Lagoon so it allows the nutrients to be removed through chemical reactions and physical processes. However, according to the monitoring results, the water inflow from Te Hopai pump station poses challenges for this water purification function of Matthews Lagoon. For one, the fluctuations in the amount of inflow separate the wetland into two functional states, long residence time state and short residence time state, which will be further discussed in the next section. Second, water with high nutrient loading rates goes into Matthews Lagoon in a relatively short amount of time, which is not an ideal situation for nutrient removal.

6.2.2. Water level and residence time

Changes in water level reflect the relationship of all water inputs and outputs over a certain period of time. In this study, water level in Matthews Lagoon decreased, while in Boggy Pond, water level increased. As mentioned earlier, there might be other water inputs to Boggy Pond according to the water balance. This could explain the more stable water level in Boggy Pond than in 1980's. According to Ogle (1989), Boggy Pond experienced dramatic water level fluctuations between summer and winter. Therefore, to restore the natural water fluctuation is important for native plants to regenerate.

Since inputs from rainfall and output from evapotranspiration were similar in the two wetlands, having surface inflow and outflow in Matthews Lagoon really made a difference in its hydrologic regime. The surface flow not only made a difference on the overall water level, but also influenced the residence time of water in Matthews Lagoon. As stated in chapter 5, discharge from Matthews Lagoon happens only from July to December. Consequently, the residence times of water in these months were relatively short (table 5.2.4). However, under scenario 1, even in winter when residence time is supposed be low, water still stayed in Matthews Lagoon for at least 12 days before it was discharged. Under scenario 2, water residence time was as low as 1.8 days in winter because water is potentially bypassing the main open water part in Matthews Lagoon (figure 5.2.15. b). This result from scenarios 2 could also explain the poor nutrient removal rate in the winter. As mentioned in chapter 2, in order to improve water quality, a residence time of 4 days is the minimum requirement.

Based on the fact that the water level at the outlet is higher than in the middle of the wetland in Matthews Lagoon (figure 5.2.1), the connectivity between the middle point and outlet in Matthews Lagoon is probably poor. Water bypasses the middle point and most likely move along the stopbank from the inlet to outlet. However, a tracer study on water movement within Matthews Lagoon would be necessary in the future.

6.3. Nutrient characteristics

6.3.1. Nutrient removal in Matthews Lagoon

As mentioned earlier, one of Matthews Lagoon’s ecological services is to purify water from Te Hopai drainage scheme before it goes into Lake Wairarapa. Looking at the nutrient levels at the inlet and outlet only, in July 2013, Matthews Lagoon showed significant removal of nitrate, nitrite, and ammonia, with removal rates of 62.5%, 60.1%, and 42.8%, respectively (table 5.3.1). This indicates the denitrification process and volatilisation process actively transforms nitrate, nitrite, and ammonia into nitrogen gas that is being released from the wetland (details in chapter 4). However, the total nitrogen removal rate was only 17% (table 5.3.1). This is because Matthews Lagoon has become a source of the organic nitrogen (organic nitrogen and ammonia nitrogen compose TKN) in the outflow. Organic nitrogen is rich in living organism, humus or in the intermediate products of organic matter decomposition (Yu, 2012). In Matthews Lagoon, dead leaf litter and dead water birds could possibly be the main source of organic nitrogen. The removal of organic nitrogen is through ammonification when microbes convert organic nitrogen into ammonium or through sedimentation when the organic nitrogen is buried by new sediments and exit nitrogen cycle (Lee, Fletcher, & Sun, 2009). The ammonification process could facilitate secondary pollution as its products, ammonia and buried organic nitrogen, can still be washed out if conditions are right. Note that this analysis is based on two water quality tests, once in winter and once in summer, and some assumptions. Although it shows some patterns in water quality in Matthews Lagoon, it should be treated as an isolated example other than general fact. In order to draw a more convincing conclusion to assist the future restoration project, long-term water quality monitoring is necessary.

The long term nitrate monitoring at inlet and outlet of Matthews Lagoon in the summer (figure 5.3.3) showed an average removal rate ($\frac{in-out}{in} * 100$) of 20% of nitrate nitrogen. However, this removal rate is calculated based on assuming water inflow and outflow are at the same rate, which is probably unrealistic. However, there are no data available on the water flow under summer conditions. Another problem with measuring water quality in the summer is that the result could be affected by the "dilution" effect at inlet and the "accumulation" effect at outlet depending on the availability of water. There was not significant rainfall since December 2013 in the study area. As a result, less pollutant was discharged from surrounding farms to the pump station and the pump station worked less frequently. This allowed the "dilution" effect to happen at inlet while water naturally flowed towards outlet. At the same time, there was hardly any measurable water flow at outlet since the long term monitoring started. Pollutants from inlet and entire wetland tended to accumulate at outlet.

Although the result from water quality tests suggested good overall nitrogen removal in Matthews Lagoon, the wetland does not seem to reduce phosphorus levels from the water. As mentioned in chapter 4, phosphorus removal is mainly through plant uptake, adsorption, and sedimentation, and all these removal mechanisms are reversible and have limited removal capacity. Since Matthews Lagoon has been used to purify water since the 80's, the capacity for phosphorus removal through adsorption may be saturated. Water flow in July was relatively high, hence phosphorus sedimentation is reduced. In the winter, when plant growth slows down and old leaves die off, phosphorus uptake by plants is outcompeted by phosphorus's release back to the water from decomposition. This is probably the reason for the increased phosphorus level in outlet in July in Matthews Lagoon.

When looking at the nitrate and ammonium levels at three monitoring stations in Matthews Lagoon, poor connectivity between the outlet and the middle point can be identified due to the nutrient level was much higher at inlet and outlet but much lower in the middle. This pattern can be observed in both measurement methods. Again, this difference in water quality indicates that the water may bypass the middle part of Matthews Lagoon.

6.3.2. Seasonal patterns

In the summer of 2012, TKN and TP were lower in outlet than inlet (table 5.3.2). This is because in summer, under low water flow condition, the up-taking effect by the plants is greater and there is less chance for leaching from sediments, resulting in lower TKN and phosphorus in outflow. However, TP removal rate was still very low, which indicates the saturation of phosphorus in Matthews Lagoon. Another interesting phenomenon is that inorganic nitrogen (nitrate and nitrite) level is high in the winter but low in the summer, where Kjeldahl nitrogen (organic nitrogen and ammonia) level is opposite (table 5.3.1 and 5.3.2). Correspondingly, removal efficiency for inorganic nitrogen is greater in winter while removal of Kjeldahl nitrogen peaks in summer. It seems that the chemical environment in summer and winter favours a different pollutant removal mechanism. This is probably because the temperature and dissolved oxygen in winter and summer favours different groups of microorganisms.

6.3.3. Limitations

As mentioned in the previous chapter, undesired ions could interfere with ion-selective electrode of the YSI handheld meter. Chloride is the most possible interference in this study site because animal waste and fertiliser from dairy farms could potentially contain high levels of chloride that influences the result of a nitrate test. However, there is no test to backup this theory in this study which could be a challenge in future projects.

Some other factors that could possibly influence the water quality test by YSI meter are that the ion-selective electrode probe is not properly maintained or readings are taken before equilibrium. Ion-selective electrode probe are fragile and requires high levels of maintenance according to the manual, which includes calibration before each test, probe rinse with clean water between samples, moist storage condition, and clean by moist lens paper when required. Due to the limitation of time and resource of this study and in the school, such high quality of maintenance was not always possible. The fact that the meter was shared among several projects makes the maintenance even more important to obtain a reliable result. During regular tests, it is found that the meter takes a long time (sometimes over 30 minutes) to stabilise so the reading can be taken, however most of the readings were taken within 10 minutes due to transportation arrangement and coordination with other projects.

6.4. Management suggestions

Ecological restoration project requires proper goals to set overall visions, guide restoration actions, and measure achievement as the project goes on (Ehrenfeld, 2000). The goal can be made based on species, ecosystem functions, or ecosystem services of a target area (Ehrenfeld, 2000). For wetland management, since the ecosystem services provided by wetlands are valued by human beings, restoration goals are usually set to recover or replace these service that are damaged by economic development and agricultural activities. For Matthews Lagoon, the main goal is to purify water from Te Hopai drainage scheme before it gets to Lake Wairarapa. Boggy Pond, on the other hand, its biodiversity and habitat value is important for plants, birds, and the fish community, therefore restoration goals for Boggy Pond should focus on maintaining or recovering biodiversity.

To achieve these goals, restoration actions should be made based on information and resources that are available. From what has been found in this study, several potential restoration actions may be applied to the wetlands in order to achieve these goals (table 6.4).

Table 6.4 Restoration goals, main issues and proposal actions in Boggy Pond and Matthews Lagoon.

Wetlands	Matthews Lagoon	Boggy Pond
Goals	Achieve better results in nutrient removal from the water	Recover the habitat and diversity of plants, birds, and fish communities
Identified issues in this study	1. Inflow is high in winter but low in summer 2. Nutrient concentration in inflow varies 3. Surface flow bypass may exist in the wetland 4. Secondary pollution from dead leaf litter or animals in the water 5. Saturated phosphorus removal ability	1. More stabled water level 2. Potential unknown water input
Actions	1. Make the inflow more steady in both quantity and quality 2. Identify the bypass and reduce the impact from bypass 3. Harvest plants at the end of growth season 4. Remove old sediments	1. Control the pond weed 2. Predator control around the wetland (already started since July 2013) 3. Restore the water level fluctuations

These actions are just principles that could theoretically help to achieve the goals, among which some are more feasible than others. In general, there are three levels of feasibility in these actions.

In the first level, the actions require little support from experts and limited resource. They are relatively easy to operate, for example, plants harvesting and sediments removal only require human or machine powers to cut the leaves off and dig dirt up. Potential problems could rise from the timing of harvesting and treatment of the leaves and sediments. If the leaves are harvested during the growth season (summer), the nutrient uptake effect by plants will be suppressed (Uusi-Kamppa, Braskerud, Jansson, Syverson, & Uusitalo, 2000). The leaves and sediment should be removed from the wetland completely or they could cause secondary pollution.

In the second level, technical support from experts will be required such as using trace study to identify the bypass in Matthews Lagoon and predator eradication in Boggy Pond. From the result of this study, a bypass might exist in Matthews Lagoon which leads to low nutrient removal rate. Tracer studies in winter and summer will help understanding the water pathways in Matthews Lagoon under different flow rate. Predator control in Boggy Pond will assist the recovery of the number of rare water birds. Traps have been put along the stopbank between Matthews Lagoon and Boggy Pond since July 2013 and they have been proved to be effective. Although these actions require intense monitoring or ongoing maintenance and they are more complicated than plants harvesting and sediment removal, they are worth to invest resources into because the long term benefits that they can provide are significant.

The third level actions involve with hydrology manipulations therefore are more difficult to operate. Once the bypass is identified, by creating structures that obstruct water through the bypass will help spread water across entire wetland and increase the water retention time in Matthews Lagoon, which in turn will improve the nutrient removal rate. In order to stabilise water flow and water quality from Te Hopai drainage scheme, water storage facilities at inlet, such as first flush retention ponds or buffer zones (Uusi-Kamppa, et al., 2000), will be able to regulate water between winter and summer. In winter when inflow is high, water can be stored temporarily in these facilities so it can be released later in summer when inflow is low. These storage facilities can also reduce the impact from “nutrient pulses” caused by highly concentrated nutrient run off from the first rainfall events (as known as first flush). Because these facilities act like huge mixing tanks where water can mix, so those “nutrient pulses” can be diluted. This kind of facility does not cost too much to build and requires low maintenance. However, since the total annual inflow of Matthews Lagoon is about 5.6 million cubic meters, the volume of the storage needs to be reasonably big (about 2.8 million cubic meters) to actively regulate water flow between high and low flow conditions.

7. Summary and Conclusion

Wetland degradation is severe in New Zealand. Because wetlands were once considered "waste lands", over 90% of the wetlands have been destroyed or modified for other purposes. Wetland restoration and protection is gaining more and more attention in New Zealand and around the world. Matthews Lagoon and Boggy Pond have high restoration priorities because their ecosystem services are valuable and critical. There are different groups of people who are interested in developing restoration projects around these two wetlands and the surrounding areas. Although these different groups of people have slightly different objectives, there is an opportunity to develop a plan that could address all these different perspectives. The first step in developing a restoration plan is to gather information, which was what this study has done. Some findings from this study are able to fill the knowledge gaps on the hydrological and chemical characteristic of the wetlands on the eastern shore of Lake Wairarapa and could potentially contribute to the management of the wetlands in the future.

Some key conclusions on the hydrology and nutrient environment of the wetlands can be drawn from the results of this study. First, Matthews Lagoon and Boggy Pond have completely different water regimes, therefore require different management approaches. Second, Boggy Pond had better water quality than Matthews Lagoon in general. Third, Matthews Lagoon was an efficient sink to nitrate and ammonia but was a source to organic nitrogen and phosphorus. Some major issues that might restrict the nutrient removal rate were also identified. Issues like variable nutrient load in the water from the pump station, short-circuiting bypass in the wetland, and secondary pollution caused by old and saturated sediments were most likely the reasons.

Because of these differences in hydrological and chemical characteristics, Matthews Lagoon and Boggy Pond should have completely different goals and corresponding actions in restoration. Matthews Lagoon requires treatment to improve the nutrient removal efficiency because this is its primary function and important for the health of Lake Wairarapa. As mentioned in previous chapters, there are many potential ways to improve the capability of nutrient retention in Matthews Lagoon. Boggy Pond, on the other hand, should be protected from further degradation. It has higher values for wild life and native plants. Restoring its natural water level fluctuation is important.

In conclusion, as many ecologists have pointed out, wetland restoration projects usually have to address many aspects of the wetlands: hydrological functions, landscape aesthetics, cultural and spiritual values, habitat for native floras and faunas, and nutrient cycles. The scale of this study may not be able to address all these aspects, but this may be a start to draw more attention and research on the wetlands near Lake Wairarapa. Piece by piece, the knowledge gaps will be filled by many different groups of people and will better assist the decision makers.

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Appendices

Appendix A. Classification system for New Zealand wetlands

Source: Johnson & Gerbeaux, 2004. pp. 15

Level 1	Hydrosystem (Based on board hydrological and landform setting, salinity, temperature) Marine, Estuarine, Riverine, Lacustrine, Palustrine, Inland saline, Plutonic, Geothermal, Nival
Level 1A	Subsystem (A description level relating to water regime)
Level 2	Wetland class (Based on substrate, water regime, nutrients, pH) Bog, Fen, Swamp, Marsh, Seepage, Shallow water, Ephemeral wetland, Pakihi and gumland, Saltmarsh
Level 2A	Wetland form • Landforms which wetlands occupy (e.g. slope, basin) • Forms which wetlands create (e.g. domed bog, string fen) • Forms or Features which wetlands contain (e.g. pool, rand)
Level 3	Structural class • Structure of the vegetation (e.g. forest, rushland, herbfield) • Predominant ground surface (e.g. rockfield, mudflat)
Level 4	Composition of vegetation (One or more dominant plants)

Appendix B. Different terms for wetlands used in the world

Source: Mitsch and Gosselink, 2011.

Billabong	Australian term for a riparian wetland that is periodically flooded by adjacent stream on river.
Bog	A peat-accumulating wetland that has no significant inflow or outflows and support acidophilic mosses, particularly *Sphagnum*.
Bottomland	Lowland along streams and rivers, usually on alluvial floodplains, that is periodically flooded. When forested, it is a bottomland hardwood forest in the south eastern and eastern United States.
Carr	Term used in Europe for forested wetlands characterized by alders (*Alnus*) and willows (*Salix*).
Dambo	A seasonally waterlogged and grass-covered linear depression in headwater zone of rivers with no marked stream channel or woodland vegetation.
Delta	A wetland-river-upland complex located where a river forms distributaries as it merges with the sea; there are also examples of inland deltas such as the Peace-Athabasca Delta in Canada and the Okavango Delta in Botswana.
Fen	A peat-accumulating wetland that receives some drainage from surrounding mineral soil and usually supports marsh like vegetation.
Lagoon	Term frequently used in Europe to denote a deepwater enclosed or partially opened aquatic system, especially in coastal delta regions.
Mangal	Same as mangrove.
Mangrove	Subtropical and tropical coastal ecosystem dominated by halophytic trees, shrubs, and other plants growing in brackish to saline tidal waters. The word “mangrove” also refers to the dozens of tree and shrub species that dominate mangrove wetlands.
Marsh	A frequently or continually inundated wetland characterized by emergent herbaceous vegetation adapted to saturated soil conditions. In Europe terminology, a marsh has a mineral sol substrate and does not accumulate peat.
Mire	Synonymous with any peat-accumulating wetland (European definition); from the Norse word “myrr”. The Danish and Swedish word for peatland is now “mose”.
Moor	Synonymous with peatland (European definition). A highmoor is a raised bog; a lowmoor is a peatland in a basin or depression that is not elevated above its perimeter. The primitive sense of the Old Norse root is “dead” or barren land.
Muskeg	Large expanse of peatlands or bogs; particularly used in Canada and Alaska.
Oxbow	A bandoned river channel, often developing into a swamp or marsh.
Pakihi	Peatland in southwestern New Zealand dominated by sedges, rushes, fens, and scattered shrubs. Most pakihi form on terraces or plains of glacial or fluvial outwash origin and are acid and exceedingly infertile.
Peatland	A generic term of any wetland that accumulates partially decayed plant matter (peat).
Playa	An arid- to semiarid wetland that has distinct wet and dry seasons. Term used in the southwest United States for shallow deoressional recharge wetlands occurring in the Great Plains region of North America.

Pocosin	Peat-accumulating, nonriparian freshwater wetland, generally dominated by evergreen shrubs and trees and found on the southeastern coastal plain of the United states.
Pothole	Shallow marshlike pond, particularly as found in the Dakotas and central Canadian provinces, the so-called prairie pothole region.
Raupo swamp	Carrail (*Typha*) mash in New Zealand.
Reedmace swamp	Carrail (*Typha*) mash in the UK.
Reedswamp	Marsh dominated by *Phragmites* (common reed); term used particularly in Europe.
Riparian ecosystem	Ecosystem with a high water table because of proximity to an aquatic ecosystem, usually a stream or river. Also called bottomland hardwood forest, floodplain dorest, bosque, riparian buffer, and streamside vegetation strip.
Salt marsh	A halophytic grassland on alluvial sediments bordering saline water bodies where water level fluctuates either tidally or nontidally.
Sedge meadow	Very shallow wetland dominated by several species of sedges.
Slough	An elongated swamp or shallow lake system, often adjacent to a river or stream. A slowly flowing shallow swamp or marsh in the southeastern United States.
Swamp	Wetland dominated by tree or shrubs (U.S. definition). In Europe, forested fens and wetlands dominated by reed grass (*Phragmites*) are also called swamps.
Tidal freshwater marsh	Marsh along rivers and estuaries close enough to the coastline to experience significant tides by nonsaline water. Vegetation is often similar to nontidal freshwater marshes.
Turlough	Areas seasonally flooded by karst groundwater with sufficient frequency and duration to produce wetland characteristics. They generally flood in winter and are dry in summer and fill and empty through underground passages. Term is specific for these types of wetlands found mostly in western Ireland.
Vernal pool	Shallow, intermittently flooded wet meadow, generally typical of Mediterranean climate with dry season for most if the summer and fall. Term is now used to indicate wetlands temporarily flooded in the spring throughout the United States.
Vleis	Seasonal wetland similar to a Dambo; term used in southern Africa.
Wad	Unvegetated tidal flat originally referring to the northern Netherlands and northwestern German coastline. Now used throughout the world for coastal areas.
Wet meadow	Grassland with waterlogged soil near the surface but without standing water for most of the year.
Wet prairie	Similar to a marsh, but with water levels usually intermediate between a marsh and a wet meadow.

Appendix C. Methods to calculate evaporation, evapotranspiration, and potential evapotranspiration

Methods	Theoretical explanation	Equation	Applicability	Advantage	Disadvantage
Mass transfer equation	Evaporation rate depends on the humidity in the air and the wind speed.	$E = (1.26 \times 10^{-4})v_a(e_s - e_a)$ where: *E*=evaporation rate (cm/day), v_a=wind speed at 2 meters above water surface(cm/s), e_s=saturated vapour pressure (mb), e_a=actual vapour pressure (mb).	Open water evaporation rate	The data is easy to be collected or calculated.	Average pressure and wind speed data could bring errors to the result.
Water balance equation	Solving the water balance equation for evaporation.	$E = Q_{in} + R + G_{in} - Q_{out} - G_{out} - dS$ where: *R* = precipitation (mm), Q_{in}/Q_{out} = surface flows into/out of the wetland (mm), G_{in}/G_{out} = groundwater inflow/outflow (mm), *dS* = changes in the wetland volume (mm)	Open water evaporation rate	NA	Difficult to measure all the terms on the right side of equation.
Energy balance equation	Solving the energy balance equation for evaporation.	$E = \frac{K + L - G - H + A_w - \Delta Q/\Delta t}{\rho_W \lambda_V}$ where: *K*=shortwave radiation input, *L*=long-wave radiation input, *G*=output by conduction to the ground, *H*=output of sensible heat exchange with atmosphere, A_w=input from inflows and outflows of water, ΔQ=changes in the amount of heat storage during Δt, ρ_W=water density, λ_V=latent heat of vaporization.	Open water evaporation rate	This method can provide reliable result if applied to period longer than 7 days	Difficult to measure all the terms on the right side of equation.
Temperature-based empirical methods	Only using air temperature and day length to calculate PET	$PET_H = 0.00138D[\rho_{vsat}(T_a)]$ where: PET_H= daily potential evapotranspiration rate, *D*=day length, $\rho_{vsat}(T_a)$=saturation humidity at mean daily temperature. Or, $PET_M = 0.409[e_{sat}(T_a)]$ where, PET_M=monthly potential	PET	Easy to use and measure	Result can be smaller than those calculated in other ways

		evapotranspiration rate, $e_{sat}(T_a)$=saturation pressure at the mean monthly air temperature.			
Radiation-based method	Using net radiation and air temperature to calculate PET	$PET_{PT} = \frac{1.26[s(T_a)](K+L)}{\rho_W \lambda_V [s(T_a)+\gamma]}$ where: $s(T_a)$=saturation vapour pressure at air temperature, *K*=shortwave radiation input, *L*=long-wave radiation input, ρ_W=water density, λ_V=latent heat of vaporization, γ=psychrometric constant.	PET		Underestimation when evaporation rate is greater than 0.4cm/day.
Penman-Monteith equation	Combining mass transfer and energy balance approaches together with canopy conductance	$PET = \frac{S(T_a)(K+L) + \gamma \rho_a c_a C_{at}[e_{sat}(T_a)](1-W_a)}{\rho_w \lambda_V \{s(T_a) + \gamma[1+\frac{C_{at}}{C_{can}}]\}}$ where: ρ_a=air density, c_a=heat capacity of air (usually 0.24), W_a=relative humidity, C_{at}=atmospheric conductance, C_{can}=canopy conductance, $S(T_a)$, K, L, γ, $e_{sat}(T_a)$, ρ_w, and λ_V are the same as in the radiation-based equation.		Addresses vegetation, provide the best estimation of PET	Complex
Pan-evaporation method	Solving the water balance equation in a pan which is filled with water and exposed to the atmosphere.	$E_{fw} = 0.7[E_{pan} \pm 0.00061\alpha_{pan}(0.37 + 0.00255v_{pan})\lvert T_{pan} - T_a\rvert^{0.88}]$ where: E_{fw} and E_{pan}=daily free-water and pan evaporation respectively, α_{pan}=proportion of energy exchanged through the side of the pan, v_{pan}=average wind speed 15 cm above the pan, T_{pan} and T_a=water surface temperature and air temperature respectively.	PET (For short vegetation, PET is very similar to free-water evaporation)	Direct approach to measure PET. Easy to use and cheap to maintain.	Heating effect from pan and cannot apply to larger area don’t address plant

Lysimeter	An enclosed block of soil with monitored inflow, outflow and storage.	NA	AET	Provides the best estimation of AET. Transpiration from vegetation can also be addressed.	Expensive to install and maintain.

Appendix D. Calculation procedures of Penman-Monteith equation

Basic parameters	T (°C)	$T = \frac{T_{max}+T_{min}}{2}$ Mean air temperature of each day is used in the calculation		
	u_2 (m/s)	$u_2 = u_{2.5}\frac{4.87}{\ln(67.8*2.5-5.42)}$ Converting wind speed at 2.5 metres to 2 metres		
	$e(T)$ (kPa)	$e(T) = 0.6108\exp\left(\frac{17.27T}{T+237}\right)$ Saturation vapour pressure at the air temperature T		
	R_s (MJ m^{-2} day^{-1})	Measured solar radiation	α	Albedo of water surface (0.1)
	R_{ns} (MJ m^{-2} day^{-1})	Net shortwave radiation, $R_{ns} = (1-\alpha)R_s$	R_{so} (MJ m^{-2} day^{-1})	Clear-sky solar radiation, $R_{so} = (0.75 + 2*10^{-5}z)R_a$ where z is station elevation above sea level
	R_a (MJ m^{-2} day^{-1})	Extraterrestrial radiation, $R_a = \frac{24*60}{\pi}0.082\left[1 + 0.033\cos\left(\frac{2\pi}{365}J\right)\right][\omega_s\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)]$ where J is the number of the day in the year, ω_s is sunset hour angle $= \arccos[-\tan(\varphi)\tan(\delta)]$, φ is latitude, δ is solar decimation $= 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right)$		
	R_{nl} (MJ m^{-2} day^{-1})	Net longwave radiation, $R_{nl} = 4.903*10^{-9}\left(\frac{T_{maxK}^4+T_{minK}^4}{2}\right)(0.34 - 0.14\sqrt{e_a})(1.35\frac{R_s}{R_{so}} - 0.35)$ where $T_{maxK} = T_{max} + 237$, $T_{minK} = T_{min} + 237$, e_a is actual vapour pressure		
Equation components	Δ (kPa °C^{-1})	$\Delta = \frac{4098[0.6108\exp\left(\frac{17.27T}{T+237}\right)]}{(T+237)^2}$	R_n (MJ m^{-2} day^{-1})	$R_n = R_{ns} - R_{nl}$
	e_s (kPa)	$e_s = \frac{e(T_{max})+e(T_{min})}{2}$	e_a (kPa)	$e_a = \frac{e(T_{min})RH_{max}+e(T_{max})RH_{min}}{200}$ where RH is relative humidity

	$\rho_a c_p$ (MJ m^{-3} °C^{-1})	$\rho_a c_p = \frac{\gamma \varepsilon \lambda}{1.01(T+237)R}$ where γ is the psychrometric constant, ε is ratio molecular weight of water vapour/dry air = 0.622, λ is latent heat of vaporization = 2.45, R is specific gas constant = 0.287
	r_a (s m^{-1})	$r_a = \frac{\ln\left(\frac{z_m - d}{z_{om}}\right)\ln\left(\frac{z_h - d}{z_{oh}}\right)}{k^2 u_z}$ where z_m is the height of wind measurements (2 m), z_h is the height of humidity measurements (2.5 m), d is zero plane displacement height (0 m), z_{om} is roughness length governing momentum transfer (0.00023 m), z_{oh} is roughness length governing transfer of heat and vapour (0.00023 m), k is von Karman's constant (0.41), u_z is the wind speed at height z
	γ (kPa °C^{-1})	$\gamma = 0.665 * 10^{-3} P$ where P is atmospheric pressure =101.3$(\frac{293-0.0065z}{293})^{5.26}$ where z is the elevation above sea level

Appendix E. Monthly water balance of Matthews Lagoon and Boggy Pond

The letters in the table represent the components in water balance: rainfall (*R*), surface inflow and outflow (Q_{in} and Q_{out}), groundwater inflow and outflow (G_{in} and G_{out}), evapotranspiration (*E*), and changes in wetland volume (*dS,* positive value means increasing in volume comparing to previous month, negative value means decreasing in volume). -- represents data not available. All water balance components are shown in mm.

			Jan ‘13	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan ‘14
Matthews Lagoon	In	*R*	51	48	81	60.5	126	192	60	44.5	101	186	89	54	76.5
		Q_{in}	6.5	6.5	14.58	145.3	129.5	335.6	154.4	59.12	111.9	234.3	39.21	12.20	3.72
		G_{in}	--	--	--	--	--	19.80	0	33.56	30.25	30.08	--	--	--
	Out	*E*	208.7	157.1	132.9	79.9	56.8	37.7	54.9	70.9	97.1	144.8	161.4	191.6	138.8
		Q_{out}	0	0	0	0	0	0	139.9	148.6	162.6	192.5	132	35.45	0
		G_{out}	--	--	--	--	--	19.90	24.79	20.41	19.33	19.40	--	--	--
	dS		--	--	--	--	--	--	-171.5	68.6	-43.7	-33.9	-9.36	-24.9	-9.36
	In - Out		-151.2	-102.6	-37.05	125.9	198.7	489.8	-5.22	-102.7	-35.90	93.69	-165.2	-160.9	-58.58
Boggy Pond	In	*R*	51	48	81	60.5	126	192	60	44.5	101	186	89	54	76.5
		G_{in}	--	--	--	--	--	--	0	0	0	0	--	--	--
	Out	*E*	208.7	157.1	132.9	79.9	56.8	37.7	54.9	70.9	97.1	144.8	161.4	191.6	138.8
		G_{out}	--	--	--	--	--	--	1.63	5.30	5.13	5.27	--	--	--
	dS		--	--	--	--	--	--	12.4	128.6	-41.5	-20.7	33.2	-8.3	-24.9
	In - Out		-157.7	-109.1	-51.9	-19.4	69.2	154.3	3.47	-31.7	-1.23	35.93	-72.4	-137.6	-62.3

Appendix F. Water quality in Matthews Lagoon and Boggy Pond

I,M and O represent the inflow, middle, and outflow of Matthews Lagoon, while B represents Boggy Pond. Data in grey boxes is from water samples analysed in labs by Greater Wellington Regional Council, other data is obtained from field test using YSI handheld meter (N) or photometric field test kits.

	Nitrate (mg/l)				Ammonia (mg/l)				Total Phosphorus / Phosphate (mg/l)			
Location	I	M	O	B	I	M	O	B	I	M	O	B
2012.8			2.13	1.78			0.21	0.36				
2012.9	0.85	0.012	0.023		1.2	0.01	0.012		0.92	0.35	0.36	
2012.12	0.002	0.002	0.002		4.9	0.01	0.179		1.04	1.46	0.99	
2013.1	0.004	0.002	0.002		4.5	0.01	0.01		0.66	1.15	1.36	
2013.4	0.167	0.005	0.002		0.82	0.192	0.051		0.87	1.06	0.82	
2013.7	3	0.84	0.62		0.57	0.34	0.18		0.41	0.3	0.3	
2013.7	11.05	5.75	19.92	4.44	0.9	0.5	0.4	0.4	0.11	0.2	0.1	0.03
2013.9	14.27	5.55	5.03	4	1	1.07	1.75	1.12	0.11	0.34	0.25	0.046
2013.10	7.54	6.44	28.61	6.14	1.22	0.75	1.26	1.03	0.43	0.43	0.34	0.046
2013.10	6.75	8.05	5.43	3.03	1.55	0.74	0.8	0.81				
2013.11	4.33	3.63	6.11	3.25	1.5	1.88	1.24	1.09	0.43	0.43	0.43	0.092