Hydrological characteristics of the Te Hapua wetland complex:

The potential influence of groundwater level, bore abstraction and climate change on wetland surface water levels

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Abstract

Te Hapua is a complex of small, privately owned wetlands approximately 60 km northwest of Wellington. The wetlands represent a large portion of the region's remaining palustrine swamps, which have been reduced to just 1% of the pre-1900 expanse. Whilst many land owners have opted to protect wetlands on their land with covenants, questions have been raised regarding potential threats stemming from the wider region. Firstly, some regional groundwater level records have shown significant decline in the 10 to 25 years they have been monitored. The reason for this is unclear. Wetlands are commonly associated with groundwater discharge, so a decline in groundwater level could adversely affect wetland water input. Secondly, estimated groundwater resources are currently just 8% allocated, so there is potential for a 92% increase in groundwater abstraction from aquifers that underlie the wetlands. Finally, predictions of future climate change indicate changes in rainfall quantity and intensity. This would likely alter the hydrological cycle, impacting on rainfall dependant ecosystems such as wetlands as well as groundwater recharge.

Whilst previous ecological surveys at Te Hapua provide valuable information on biodiversity and ecological threat, there has been no detailed study of the hydrology of the wetlands. An understanding of the relationship between the surface water of the wetlands and the aquifers that underlie the area is important when considering the future viability of the wetlands. This study aims to define the local hydrology and assess the potential threat of 'long term' groundwater level decline, increased groundwater abstraction and predicted climate change.

Eleven months of water level data was supplied by Wellington Regional Council for three newly constructed Te Hapua wetland surface water and adjacent shallow groundwater monitoring sites. The data were analysed in terms of their relative water levels and response to rainfall. A basic water balance was calculated using the data from the monitoring sites and a GIS analysis of elevation data mapped the wetlands and their watersheds. A survey of 21 individual wetlands was carried out to gather water quality and water regime data to enable an assessment of wetland class. Historical groundwater level trends and geological records were analysed in the context of potential threat to the wetlands posed by a decline in groundwater level. Climate change predictions for the

Kapiti Coast were reviewed and discussed in the context of possible changes to the hydrological cycle and to wetlands.

Results from the wetland survey indicated that there are two distinct bands of wetlands at Te Hapua. Fens are found mostly in the eastern band and are more likely to be discharge wetlands, some of which are ephemeral. Swamps are found mostly in the western band and are more likely to be recharge wetlands. Dominant water input to fens is via local rainfall and local through-flow of shallow groundwater, especially from surrounding dunes. The eastern band of wetlands is typified by higher dunes and hence has greater input from shallow groundwater than wetlands in the western band. Dominant water input to swamps is via local rainfall, runoff, and through-flow from the immediate watershed and adjacent wetlands.

Overall, the future viability of the Te Hapua wetland complex appears promising. Historical groundwater declines appear to be minimal and show signs of reversing. Abstraction from deep aquifers is not likely to impact on wetland water levels. Climate change is likely to have an impact on the hydrological cycle and may increase pressure on some areas, especially ephemeral wetlands. The effect of climate change on groundwater level is more difficult to forecast, but may lower water level in the long term.

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I Introduction

1.1 Context of study

The rate of wetland loss in New Zealand over the last century is amongst the highest in the world (Mitsch & Gosselink, 2007; Stevenson, et al., 1983). It is estimated that since 1900, farmers and developers have drained approximately 90% of wetland areas to create high yielding agricultural pasture. Other developed countries have more modest statistics for wetland loss over this period, though this is almost certainly the consequence of their comparatively long histories of settlement and farming. Threat of wetland loss continues today and it is probable that wetlands are still being lost at a fairly rapid rate, especially in developing countries (Mitsch & Gosselink, 2007). New Zealand wetland environments are no exception to the trend.

The Te Hapua wetland complex, 60 kilometres north of Wellington on the Kapiti Coast, is one such threatened wetland. Te Hapua represents a large portion of the region's[1] remaining palustrine swamps, which are estimated to have been reduced to just 1% of the pre-1900 expanse (Ausseil, et al., 2008). Palustrine wetlands are fed by rain, groundwater, or surface water and do not occur within the normal boundaries of estuaries, lakes or rivers (Campbell & Jackson, 2004). The wetlands are significant in that they are considered one of the best preserved examples of the 300 hectares of wetland that remain of '*The Great Swamp*' – a huge swamp network that once spanned over 2000ha along the Kapiti Coast (Fuller, 1993). The total wetland area of the Te Hapua complex is 59.6ha (Preece, 2005). Te Hapua wetlands are home to a number of rare species including the Australasian Bittern (nationally endangered) and several regionally threatened birds and plants (Beadel, 2003b).

Between 1986 and 2006, the population on the Kapiti Coast grew at a rate of 3.2% per annum from 29,398 to 46,197 - an increase of nearly one third in twenty years (Statistics NZ, 2006). Given limited regional surface water and groundwater resources, the past decade has seen a significant rise in issues related to shortage in public water supply. Te Hapua is situated in the 'Coastal Groundwater Zone', one of six zones established by Reynolds (1992) on the Kapiti Coast to describe areas with similar hydrogeological characteristics (figure 1.1). The Coastal Zone has a relatively sparse

[1] This is for the Manawatu / Wairarapa region, which includes Te Hapua (Ausseil et al. 2008).

population. Greater Wellington Regional Council (GWRC) records show that in January 2010, 8% of the Coastal Zone's total available groundwater resource have been allocated for domestic and irrigation purposes (according to current estimates of sustainable groundwater abstraction capacity (safe yield) by GWRC). In Wellington Regional Council's current Regional Freshwater Plan, 'safe yield' is derived using a dated and flawed concept – that 100% of rainfall recharge can be safely allocated, not taking into account the requirements of groundwater discharge to surface water ecosystems (Information obtained via personal communication with Mark Gyopari, Wellington Regional Council, May 3rd 2010) (Sophoscleous, 2000). In the neighbouring Waikanae Groundwater Zone groundwater resources are almost fully allocated, so councils and landowners are currently considering alternative sources to meet future water needs. As the population swells, coastal subdivisions spread northward and are steadily encroaching on the Te Hapua complex. Increasing groundwater abstraction is one possible solution for water supply to new subdivisions. Given the current assumed safe yield and allocation in the Coastal Zone, there is potential for a 92% increase in groundwater abstraction from bores close to Te Hapua wetlands.

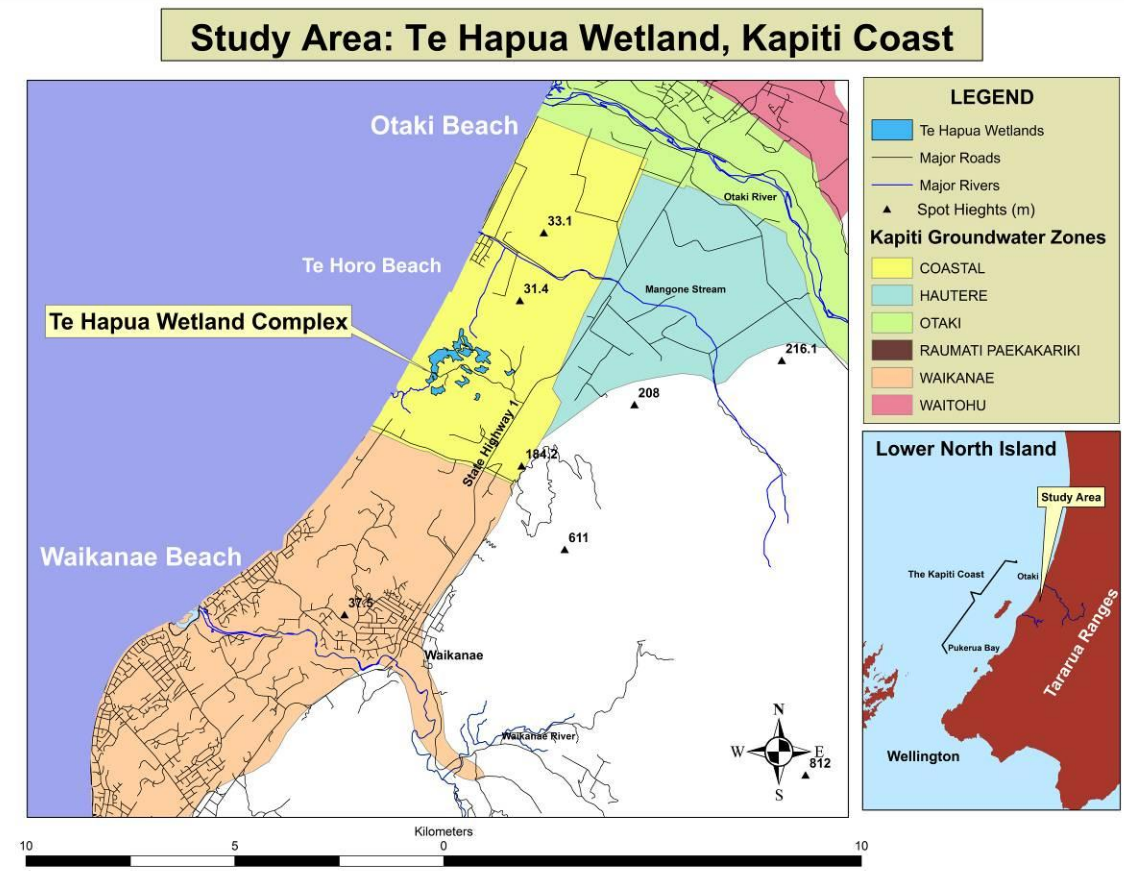


Figure 1.1: The study area, Northern Kapiti Coast, New Zealand. Six groundwater zones feature on the Kapiti Coast. The Te Hapua wetland complex lies within the Coastal Zone (yellow). Adapted from Hughes (1997)

Another potential wetland threat stems from fluctuations in groundwater level. This depends on the degree to which groundwater of various depths is connected to the surface waters of Te Hapua. An analysis (chapter 4) of the wider region's long term groundwater level data looked at the Coastal and Hautere Groundwaters Zones, which share a similar groundwater flow path westward from the Tararua Ranges (WRC, 1994). Four of the seventeen records show significant declines in groundwater level, whilst 4 more show significant increase in level over the past 10 to 25 years. The bores that show decline in water level are a concern because three of them are within 1500m of Te Hapua wetlands. The perception that a threat exists came originally from the record at the region's deepest bore (S25/5208 which is located 4.5km north of Te Hapua and is 192m deep), where groundwater has shown the greatest decline. Here, over the 17 year sampling period groundwater has been dropping at an average rate of 64mm per year. It is unclear if the groundwater level trends are due to climatic or anthropogenic influence and given that none of the region's records span longer than 25 years, medium and long term flow patterns may not be visible.

A third potential threat to the future viability of Te Hapua wetlands is modification of the hydrological cycle caused by climate change. Predictions for the Kapiti Coast include increases in temperature, evaporation, rainfall and flooding (Mullan, et al., 2007). Changes to the hydrological cycle could negatively impact on wetlands reliant on groundwater or specific rainfall regimes for recharge, as well as the distribution of plant and animal species. Predictions, however, are subject to considerable uncertainty and may impact significantly more or less than suggested in Mullan's report.

In recent years there have been efforts to protect and restore native species at Te Hapua. In 1992 DOC surveyed wetlands within the Foxton Ecological District to list as 'Protected Natural Areas'. Part of this involved a survey to establish what native and exotic plants and animals are present at Te Hapua, as well as the general nature and extent of anthropogenic modifications to the wetlands (Ravine, 1992). A 2002 survey by Wildlands Consultants was carried out for Kapiti Coast District Council to assess the wetlands' suitability for inclusion on a list of 'Ecological Sites'. Splitting the Te Hapua complex into 4 separate survey areas, the survey identified site boundaries and collected detailed information on native flora / fauna; dominant hydrologic class; dominant soil characteristics; dominant vegetation classes; landforms and pests (Beadel, 2003b). Preece undertook a similar ecological assessment in 2005, producing a report on some

of the wetlands for private landowners (Preece, 2005). These reports also gave recommendations for future management.
Whilst these surveys provide valuable information on biodiversity and ecological threat, the hydrology of Te Hapua wetland has not yet been studied in any detail and is consequently poorly understood (Preece, 2005). Given that some wetlands are considered to be the surface expression of local shallow groundwater, an understanding of the local hydrology is crucial for directing effective efforts toward the protection and restoration of the wetlands. Mitsch and Gosselink point out that "….*hydrology is probably the single most important determinant in the establishment and maintenance of specific types of wetlands and wetland processes.*" (Mitsch & Gosselink, 2000)

Te Hapua wetlands may be threatened by increasing pressures on local groundwater resources, a possible long term decline in groundwater level, and changes in hydrology brought about by predicted future climate change. Coupled with a gap in knowledge regarding the local hydrology, the level of vulnerability to wetland loss is unknown given future changes in hydraulic input, groundwater abstraction, and landuse. Ecological efforts alone may not be enough to save this remnant wetland area. This study aims to define the geomorphology and hydrology of the Te Hapua complex, and assess the potential level of threat that comes from changes in regional groundwater level; local abstraction; and climate change. Preece (2005) notes the issues of drainage, groundwater take, landuse, and water quality have important implications for future management of the wetlands and surrounding landuse.

1.2 Justification for this study

Defining the hydrology of Te Hapua wetlands will compliment the conservation efforts of local residents and regional authorities. Gathering and interpreting hydrological information will help gain an understanding of the system as a whole and add to broader literature on wetland hydrology. There has been concern among local residents over the impact of groundwater abstraction on wetland water levels, so an assessment of potential threat will be well received. The use of 'Safe Yield' to allocate groundwater resources is in review by GWRC. Defining the relationship between groundwater and wetland water will help feed in to this review and may be of value when determining future regional allocations.

1.3 Key Questions and Research Objectives

Key questions facing the Te Hapua area are:

What defines the hydrology of the wetland?

- Where does the wetland water come from?
- Is this uniform across all the individual wetlands within the complex?
- Where does the water leave the system?

What is the relationship between groundwater and wetland surface water?

- Is there leakage between underlying aquifers?
- Is wetland surface water likely to be affected by the fluctuations in the deep confined aquifers?

Is the apparent historical decline in deep groundwater level a result of abstraction from bores, climate change (i.e. natural variation), or both?

What are the local predictions for climate change and what effect could it have on existing wetland areas?

Given the current safe yield and allocation, what effect could future abstraction have on existing wetland areas?

- If a large scale groundwater abstraction was permitted near the wetland, would it impact on wetland surface water levels?

Once the above questions have been answered, what is the future prognosis for the wetlands?

- Are the water allocation limits used today appropriate for the future given projected population increase, historical trend in groundwater level, and estimates of future climate change?

To answer these questions, this study has the following objectives:

I. To investigate historical groundwater trends and determine spatial and temporal patterns.

II. To define the hydrology and nature of the wetland complex by classifying individual wetlands according to a standard New Zealand classification system and by mapping surface flow patterns.
III. To define the hydraulic relationship between the wetland and shallow groundwater as well as determining the source of wetland surface water.
IV. To investigate the effect of local groundwater abstraction on wetland surface water.
V. To use information gathered from objectives I to IV to discuss the future prognosis of the wetland complex.

1.4 Summary of work carried out to achieve these objectives

Regional groundwater level records obtained from Wellington Regional Council were analysed to satisfy Objective I. To explore long term trend in groundwater level, bores with records that spanned 6 years or more were selected for further analysis. The 17 records were plotted with trendlines and 95% confidence intervals. Bores showing significant decline / increase in water level were further analysed to determine the average annual drop / increase in water level. This analysis is presented in chapter 4, section 4.2. Bores showing significant water level decline were then considered in the context of threat to Te Hapua wetland surface waters. To help determine the nature of the aquifers that underlay Te Hapua wetland, the same 17 records were analysed to look for changes in groundwater level according to season; proximity to mountains, coast and major rivers; level / fluctuation with respect to bores in the same aquifer; and level / fluctuation with respect to bores in adjacent aquifers. This was done by comparing the hydrographs of various bores and using ArcGIS to map spatial patterns. Geological cross sections were drawn using bore strata profiles that were recorded at the time of drilling and kept on record by Wellington Regional Council. The cross sections, displayed in section 4.2, show the depths of the various confining layers and give a reasonably accurate picture of the depth and thickness of underlying aquifers. Water level data from wells close to the complex were plotted on a second geological cross section and compared to look for the difference in pressure head in adjacent aquifers. This gave an indication of the pressure gradient and potential for leakage in adjacent aquifers.

To achieve Objective II the wetlands were surveyed to assess the nutrient status and dominant water regime. To define the nutrient status of the 21 largest individual wetlands, pH and conductivity was measured at each location. These were compared to the approximate values for New Zealand fens, swamps, marshes and bogs, as defined by Johnson and Gerbeaux (2004). Each wetland was circumnavigated to look for surface water inflows, surface water outflows, water movement within the wetland and, where possible, the range of water level fluctuation. GIS was used to overlay the results of this classification (see Chapter 5, section 5.3) with variables such as elevation and soil type to see if there were any patterns. GIS was also used to model the watershed of the wetlands and the flow accumulation pathways that delineate the probable surface drainage. The watershed analysis is presented in section 5.2.2.

To further define the hydrology of the wetland complex it was necessary to determine the hydraulic relationship between the wetland and shallow groundwater. Meeting objective III required high definition monitoring of wetland water level verses adjacent shallow groundwater level. Wetland surface water staff gauges and shallow groundwater piezometers were installed by Wellington Regional Council at three sites around the wetland in April 2009. A rain gauge was also installed at one of the sites. Water level was recorded at each site every 15 minutes for 11 months. These data were analysed in terms of relative water level; response to significant rainfall; and seasonal variation; and is presented in Chapter 5, section 5.2. By considering the relative inputs from surface water, groundwater and rainfall, the dominant source of wetland pond water was assessed. Surface water input was analysed by looking at the GIS flow accumulation and watershed layers from section 5.2.2. Calculating the volumetric pond level response to individual rainfall events helped assess the relative inflow from rainfall and runoff.

A literature review in Chapter 4 section 4.3 looks at the IPCC Fourth Assessment Report and a downscaled prediction for climate change on the Kapiti Coast to assess the impact of climate change on the wetlands.

Objective IV was largely addressed through interpretation of the geological cross section in section 4.2. A small pump test was also carried out on two bores that lie close to the wetland. The bores used are in separate aquifers; one in the first confined aquifer (65m deep), and the other in the second confined aquifer (92m deep). During pumping, water levels were monitored in all wetland monitoring sites (pond and shallow bore), as well as nearby bores in confined aquifers. The results to this test are shown in Chapter 5, section 5.2.5.

Objective V looks at the prognosis for Te Hapua in the context of potential threat from groundwater level decline, increased abstraction, and climate change. This is discussed in Chapter 6 as part of the conclusion.

II Conceptual Background

2.1 Wetland definition and classification

A wetland can be defined as a place where surface water, ground water and ‘dry’ land meet (Campbell & Jackson, 2004). The Ramsar Convention on Wetlands defines them as “areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salty, including areas of marine water the depth of which at low tide does not exceed 6 metres” (Peck, 1996; Ramsar, 2010b). Johnson and Gerbeaux describe wetlands simply as “….precisely that: wet land” (Johnson & Gerbeaux, 2004a). In a New Zealand context, the Resource Management Act (1991) defines wetlands as “permanently or intermittently wet areas, shallow water or land/water margins that support a natural ecosystem of plants and animals that are adapted to living in wet conditions (Clarkson, et al., 2003).

Given the diversity of the physical environments encompassed by the above definitions, a classification system is necessary in order to describe individual wetlands. The Ramsar Convention is an intergovernmental treaty that provides a framework for national action and international cooperation for the conservation and wise use of wetlands and their resources (Ramsar, 2010a). Ramsar provides the best established international classification system, categorising wetlands initially into three broad groups: marine, inland or human made (Ramsar, 2010b). Ramsar’s wetland definition covers a broad range of environments and recognises 42 different types. Examples include inter-tidal marshes, coral reefs, peatlands, oases, irrigation channels and rice fields.

Johnson and Gerbeaux (2004) developed a New Zealand wetland classification system that defines individual wetlands in accordance with a number of hierarchical variables that together describe any wetland found in the country. Table 2.1 summarises this classification system. In the Johnson and Gerbeaux system, wetlands are initially classified into nine groups according to their hydro-system (Campbell & Jackson, 2004; Johnson & Gerbeaux, 2004a). One of these, palustrine, is the class that the inter-dunal wetlands along the Kapiti Coast fall within. Palustrine wetlands are fed by rain, groundwater, or surface water and do not occur within the normal boundaries of estuaries, lakes or rivers (Campbell & Jackson, 2004). Most New Zealand wetlands have this type of hydrosystem (Johnson & Gerbeaux, 2004b).

The subsystem, section IA of Johnson and Gerbeaux's system in table 2.1, looks at components of the water regime such as water source, movement, drainage, fluctuation and hydroperiod; categorising wetlands as either ephemeral or permanent (Johnson & Gerbeaux, 2004b). Ephemeral wetlands typically occupy closed depressions with no surface outlet and may dry up during times of low rainfall. They receive their water mostly from shallow groundwater and seasonal rainfall so have highly variable water levels (Mitsch & Gosselink, 2007). Nutrient levels are low to moderate depending on the degree of input from surface water and runoff. Permanent wetlands are just that – a high water table and / or consistent climatic influence means surface water levels fluctuate very little seasonally so wetland species are present year round (Clarkson, et al., 2003). Wetland subsystems found in the Te Hapua complex may be ephemeral or permanent (Preece, 2005).

Table 2.1: Semi-hierarchal classification system for New Zealand Wetlands (Campbell & Jackson, 2004; Johnson & Gerbeaux, 2004b).

Semi-hierarchal classification system for New Zealand Wetlands

I. Hydrosystem (Based on broad hydrological and landform setting, salinity, temperature)
- Marine – coastal saline
- Estuarine – tidal estuaries, brackish water
- Riverine – rivers and streams
- Lacustrine – areas of open water / lakes
- Palustrine – waters fed by groundwater or surface water that do not occur within the normal boundaries of estuaries, rivers or lakes.
- Inland saline
- Plutonic – underground, such as caves
- Geothermal
- Nival. – alpine snow

IA. Subsystem (A descriptive level relating to water regime)
- Permanent – is present year round where surface water levels fluctuate very little
- Ephemeral – may dry up during times of low rainfall

II. Wetland Class (Based on substrate, water regime, nutrients, and pH) also see Appendix 1.
- Bog – see table 2.2
- Fen – see table 2.2
- Swamp – see table 2.2
- Marsh – see table 2.2
- Seepage – an area on a slope where groundwater diffuses to the surface
- Shallow water – aquatic habitats (less than a few metres deep) that have standing water most of the time
- Pakihi / gumland – mature soil well leached with very low pH; rain-fed, frequently saturated but seasonally dry
- Saltmarsh – estuarine habitats including intertidal, subtidal and supratidal zones as well as inland saline areas

IIA. 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

III. Structural Class
- Structure of the vegetation (e.g. forest, rushland, herbfield), or:
- Predominant ground surface (e.g. rockfield, mudflat)

IV. Composition of Vegetation
- One or more dominant plants (e.g. bog pine, wire rush)

The second major hierarchical aspect of New Zealand wetland classification (section II, table 2.1) is ‘wetland class.’ Wetlands are most commonly referred to by their name as defined by this wetland class. Wetland class is determined by the combination of water regime, soil properties / substrate, and the consequent nutrient status and pH (Johnson & Gerbeaux, 2004b). There is often overlap between wetland classes and most classes can be found in more than one hydrosystem (Johnson & Gerbeaux, 2004b). A total of eight classes are found in New Zealand. The four classes most relevant to the Kapiti Coast are described in detail in table 2.2, as defined by Johnson and Gerbeaux (2004). Appendix 1 provides a detailed description of each wetland class.

Table 2.2: Properties of Palustrine Wetland Classes relevant to the Kapiti Coast (Clarkson, et al., 2003; Johnson & Gerbeaux, 2004b; WRC, 2005). (See Appendix 1 for a full description of wetland class properties.)

Wetland Class	Water Regime						Substrate	Nutrient Status	pH
	Water Origin	Water flow	Drainage	Water table position	Water fluctuation	Period			
Bog	Rain only	Almost nil	Poor	Near surface	Slight	Wetness permanent	Peat	Low or very low (Oligotrophic)	Acid 3 to 4.8
Fen	Rain, runoff via nutrient rich mineral soils, groundwater seepage	Slow to moderate	Poor	Near surface	Slight to moderate	Wetness near permanent	Mainly peat	Low to moderate (Oligotrophic to mesotrophic)	Low to moderate 4 to 6
Swamp	Surface water and/ or groundwater seepage	Moderate	Poor	Usually above surface in places Gentle surface inflow /outflow (maybe seasonal)	Moderate to high	Wetness permanent	Peat and / or mineral	Moderate to high If high, usually from surface water runoff (Mesotrophic to eutrophic)	Varies 4.8 to 6.3
Marsh	Groundwater + surface water	Slow to moderate	Moderate to good	Moderate to high Usually below surface	Moderate to high	May have temporary wetness or dryness	Mainly mineral, sometimes with peat	Moderate to high (Mesotrophic to eutrophic)	Slightly acid to neutral 6 to 7
Ephemeral	Groundwater + rain	Nil to slow	Moderate to good	Well above to well below ground	Marked wet / dry alternation	Seasonal	Mineral	Moderate (Mesotrophic)	Slightly acid to neutral 5.5 to 7

2.2 Wetland loss

All of the wetlands of interest in the Te Hapua complex are palustrine wetlands, so from this section forth discussion of wetlands is relevant to palustrine wetlands only and to classes defined in table 2.2 (unless stated otherwise).
Palustrine wetlands accumulate nutrients and form rich, fertile soils as plant material breaks down anaerobically given the high water table. Highly valued in agriculture, many wetland soils have long been converted from what has been seen as 'wasteland' into highly productive and fertile pasture for grazing stock or cropland. Given the differing definitions and associated uncertainty of wetland extent, it is difficult to quantify just how much wetland area remains. The estimate for global wetland loss since before human modification is 50% of the original wetland area, though some of these were drained centuries ago (Mitsch & Gosselink, 2007).
Developed countries such as the US and European nations have converted much more than developing countries as agriculture has historically played a major role in their economic progress. A study conducted in 1985 estimated that in total, 56% to 65% of North American and European wetlands have been drained for agriculture; 27% in Asia; 6% in South America; and 2% in Africa (Mitsch & Gosselink, 2007; Peck, 1998). Wetlands are still thought to be disappearing at a fairly rapid rate, especially in developing countries (Mitsch & Gosselink, 2007). Currently in Asia approximately 5000km^2 of wetland is cleared every year to make way for agriculture or dam construction (Zedler & Kercher, 2005).

In New Zealand the early settlers of last century were faced with vast swampy plains and bog bearing lowland areas. A nation founded on primary production, it didn't take long before many of these areas were drained, logged, and seeded with grass. The high yielding present day farmlands of Waikato, Bay of Plenty, Manawatu, Otago and Southland, as well as many other areas of New Zealand were developed from wetland (Stevenson, et al., 1983). Historical statutes that have influenced the drainage of wetland areas in New Zealand include The Swamp Drainage Act (1915), The Land Act (1948), The Mining Act (1971), The Coal Mining Act (1979), and The Public Works Act (1981) (Keller, 1988). It wasn't until the 1980s that government subsidies toward land drainage for agriculture were removed (Cromarty & Scott, 1995) and various statues have since been passed that protect remaining wetland areas. The rate of wetland loss in New Zealand is the highest in the world – approximately 90% has been drained since 1900

(Dugan, 1993; Mitsch & Gosselink, 2007; Stevenson, et al., 1983). National estimates for loss of 'swamp' are in the vicinity of 94% (Ausseil, et al., 2008).

The regional[2] estimate of wetland loss (since 1900) is 97.4%, with just 1% of swamp areas still intact (Ausseil, et al., 2008). Previous studies have classified the Te Hapua complex as swamp and it is considered one of the best preserved remnants of a formerly extensive regional wetland (Fuller, 1993). Fuller (1993) mapped estimated wetland extent in 1840 compared to the wetland extent in 1993 (figure 2.2.1). Estimates of 2000 hectares and 300 hectares were produced respectively. Based on GIS data supplied by GWRC (May 2009), the current estimated wetland extent is 263 hectares.

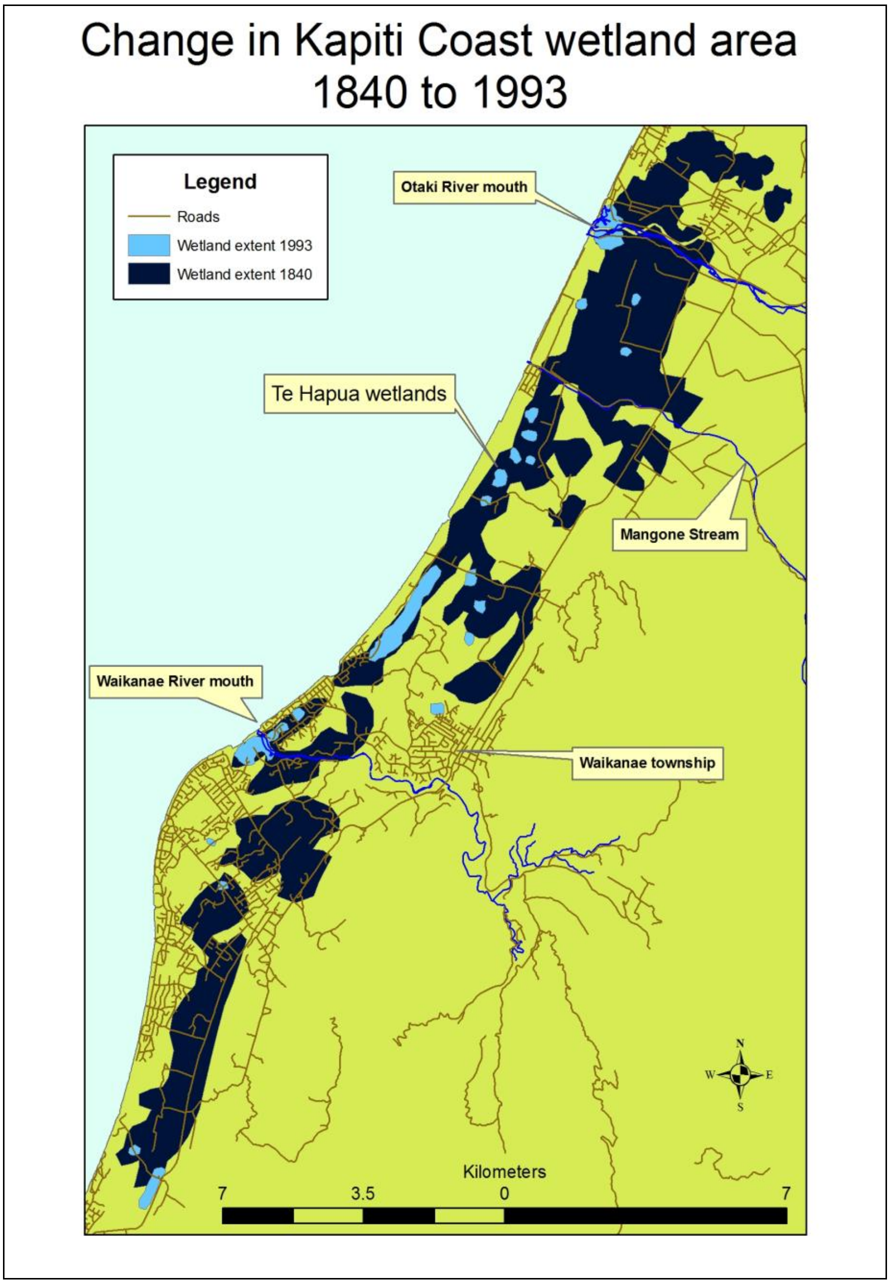


Figure 2.2.1: Kapiti Wetlands 1840 and 1993, reproduced from Fuller (1993).

[2] This is for the Manawatu / Wairarapa region, which includes Te Hapua in the Ausseil et al study.

2.3 Importance of wetlands

Perceived wetland values vary between countries. Table 2.3 summarises the main values that wetlands have in New Zealand.

Table 2.3: Values associated with wetlands in New Zealand. (Adapted from Stevenson et al (1983))

Ecology (discussed further in section 2.3.1)	Wildlife habitat Water purification / contaminant transformation Sanctuary for rare fauna and flora Biodiversity
Global warming (discussed further in section 2.3.2)	Carbon sink
Hydrological and physical environment (discussed further in section 2.3.3)	Flood mitigation Surface water base flow during drought Groundwater recharge / discharge Erosion mitigation Coastal protection
Social (discussed further in section 2.3.4)	Sport and recreation Aesthetic beauty Education Cultural links
Economic (discussed further in section 2.3.5)	Indirect water supply Income from shooting and fishing High quality soils for pasture Winter grazing for livestock Harvestable species (E.g. *Sphagnum*, Flax) Spawning and nursery for commercial and recreational fish (E.g. whitebait, eel)

2.3.1 Wetland ecology

Wetlands are invaluable as refuges for New Zealand bird species and are biodiversity hotspots. They cover less than 2% of the country's total land area yet harbour 12.1% of our rare and threatened plants, birds and fish (Cromarty & Scott, 1995). Of all permanent and migratory bird species that live in New Zealand 22% have wetlands as their primary habitat (Stevenson, et al., 1983). Another 5% depend on wetlands as their secondary home.

Adaptability varies from species to species. Some birds, such as the fernbird are totally dependant on unaltered wetland habitat for survival. Others like the introduced mallard duck, commonly associated with wetland environments as a game bird, can adapt and nest in modified environments like farm drains and effluent ponds (Stevenson, et al., 1983).

Runoff from grazed pasture, agriculture and urban areas will generally contain elevated amounts of nitrate, phosphorous, pesticides, heavy metals and industrial residue. These often bind to sediment that, following significant rainfall, is carried in suspension via surface water pathways. The pollutants remain in suspension until water velocities slow sufficiently for settling to occur (Buxton, 1991). If the surface water enters a wetland, the sediment (and nutrients / pollutants) will settle and be taken up by vegetation. The excess nutrients are subsequently denied access to downstream ecosystems where they would otherwise contribute to eutrophication (Sorrell & Gerbeaux, 2004). These downstream benefits are tempered by local problems. Too much nutrient loading in a wetland will reduce biodiversity as some species cannot cope with the elevated levels (Zedler & Kercher, 2005). This can bring about conditions favourable for exotic weed invasion.

Wetland vegetation adds oxygen to the water, helps to regulate water temperature by providing shade and acts as a sink in the wetland water balance via water loss through evapotranspiration (Mitsch & Gosselink, 2000).

2.3.2 Wetland carbon sources and sinks

One of the natural functions of wetlands is as a carbon sink (Hails, 2000b). Global warming is driven by the natural and anthropogenic release of greenhouse gases into the atmosphere. Carbon dioxide is one of the main greenhouse gases and is estimated to account for at least 60% of global warming (Burkett & Kusler, 2000; Hails, 2000a; Wetlands International, 2010).

Wetlands, which are currently estimated to cover between 4% and 8.5%[3] of the world's surface (Hails, 2000a), are thought to store 40% of the world's terrestrial carbon (Hails, 2000b; Mitsch & Gosselink, 2007). This is because carbon can be held for much longer under anaerobic conditions than in aerobic conditions, such as is found in saturated wetland soils (Burkett & Kusler, 2000). Bogs and peatlands are especially carbon rich because of their high acidity. Peatland develops in some but not all wetland environments. Covering approximately 3% of the world's land surface, peatland is estimated to hold 25% of the total global soil carbon (Hails, 2000b). Their degradation is estimated to contribute 7% of all fossil CO^2 emissions (Wetlands International, 2010).

[3] The uncertainty is due to variations between countries as to the definition of a wetland.

Lowering the water table in wetlands with highly organic soils (i.e. peatland) will have the effect of increasing decomposition rates and elevating the flux of CO^2 to the atmosphere (Burkett & Kusler, 2000; Hails, 2000a; IPCC, 1996).

Methane is another important greenhouse gas that is produced in wetlands. A drop in the wetland water table can have the effect of decreasing the formation of methane, which is reliant on anaerobic conditions (Burkett & Kusler, 2000). A current estimate of methane release from global wetlands accounts for more than 10% of total emissions (Zedler & Kercher, 2005). However this would not counter balance the increased release of carbon, the net result being increased greenhouse gas emission.

The amount of CO^2 and methane released is also related to temperature. An increase in temperature of the soil will result in higher emissions (Burkett & Kusler, 2000). It is possible that climate change will cause some wetlands, especially those at high latitudes, to change from being a net carbon sink into a net carbon source (Burkett & Kusler, 2000; Clair, et al., 1995).

2.3.3 Wetland hydrological values

The hydrology of a wetland helps to determine availability of water, pH level and distribution of nutrients. This will determine which plant species can grow where (Campbell & Jackson, 2004). The water regime, set out in table 2.2, is determined by variations in climate, topography, soil and underlying geology (see figure 2.5.1). Given an existing wetland, climate is arguably the principle variable that determines wetland water levels. Cyclic fluctuations in climate (and therefore wetland water level) may occur on a daily, seasonal, annual or much longer timescale (Campbell & Jackson, 2004).

As Mitsch and Gosselink (2000) state; "*Hydrology is probably the single most important determinant in the establishment and maintenance of specific types of wetlands and wetland processes.*"

Results from research into the role of wetlands in regional hydrology are contradictory. Earlier studies by Buxton (1991) and Stevenson et al (1983) describe wetlands as having a 'sponge-like' effect. They describe wetlands as providing a natural water storage basin during floods, which acts to slow, capture and store water spilled over

from nearby streams (Stevenson, et al., 1983). This may reduce the need for expensive engineering constructions that mitigate hydrological hazard in prone areas (Buxton, 1991). Hence reduction of wetland area may result in the removal of the buffer that protects homes, property and valuable crops from flooding in the wet season.
More recent research argues that the often saturated or near saturated soils of wetlands are not capable of taking up large volumes of additional runoff during storm events (Campbell & Jackson, 2004). Studies have shown flashy hydrographs for catchments with headwaters dominated by wetlands when compared to catchments with deep mineral soils or multiple aquifers (Campbell & Jackson, 2004). This may indicate water (at least some) is not stored but quickly pools and moves downstream as saturation overland flow.

Stevenson et al (1983) also found that during dry periods wetlands drain much slower than other surface water sources, concluding that they help maintain base flow in rivers, stabilise soil moisture, and recharge underlying aquifers (Stevenson, et al., 1983). Removal or reduction of wetland areas may equate to land and vegetation being more susceptible to damage and loss from drought, invasion by weeds, and poor stream water quality. Again there is literature to the contrary. Fahey et al (1998) found that the Otago wetland they studied did not contribute enough water to sustain the large volume of base-flow downstream (Fahey, et al., 1998). They concluded that the wetlands at this site are invariably the passage through which runoff moves from higher in the catchment.
Wetlands, given their diversity in classification and controls, should perhaps be considered in a case by case manner.

2.3.4 Economic value

Studies have been done that attempt to give a dollar value for individual wetlands given their specific resources. This can be compared to the value the area would have if drained and 'developed'. Resources taken into account in a study by Fuller (1993) were utility (water supply, flood protection, pollution reduction), commercial fishery habitat, and recreational values. One result showed that a wetland was worth 150 times more as a natural unaltered ecosystem than it would be if developed (Fuller, 1993). Another example is in Thailand, where intact mangroves are worth US$60,000 per hectare per year, compared to about US$17,000 per hectare per year if converted to shrimp farms (De Groot, et al., 2006). In Canada, intact freshwater marshes have a value of about

US$ 8,800 per hectare per year compared to US$ 3,700 per year for drained marshes used for agriculture (Balmford, et al., 2002). Additional costs of converted wetlands may include future work on ecological restoration and protection (De Groot, et al., 2006). In the Netherlands the government has begun a multimillion euro project to restore rivers and low lying areas to mitigate future hydrological risks because of sea level rise and extreme flood peak forecasts (De Groot, et al., 2006).

Whilst these studies on economic valuation are interesting and valuable in policy making situations, they can only be viewed on a case by case basis given high variability in resource values from wetland to wetland. No such studies have been done on the Kapiti Coast.

2.4 Human impacts on wetlands

Impacts that humans have on wetlands (figure 2.4.1) can be broadly split into three categories (Mitsch & Gosselink, 2000):

- Changes in water level or hydroperiod
- Changes in the amount of physical disturbance
- Changes in nutrient / sediment load

A 2007 study linked rate and extent of global wetland degradation / loss to problems with water allocation and distribution (Finlayson & Davidson, 2007). Increased demand for irrigation and hydropower has brought large scale change to regional hydrology and ecosystems in many areas. Lowering groundwater levels, saline intrusion, declines in biodiversity and reduced fish stocks are some of the resulting consequences of this development.

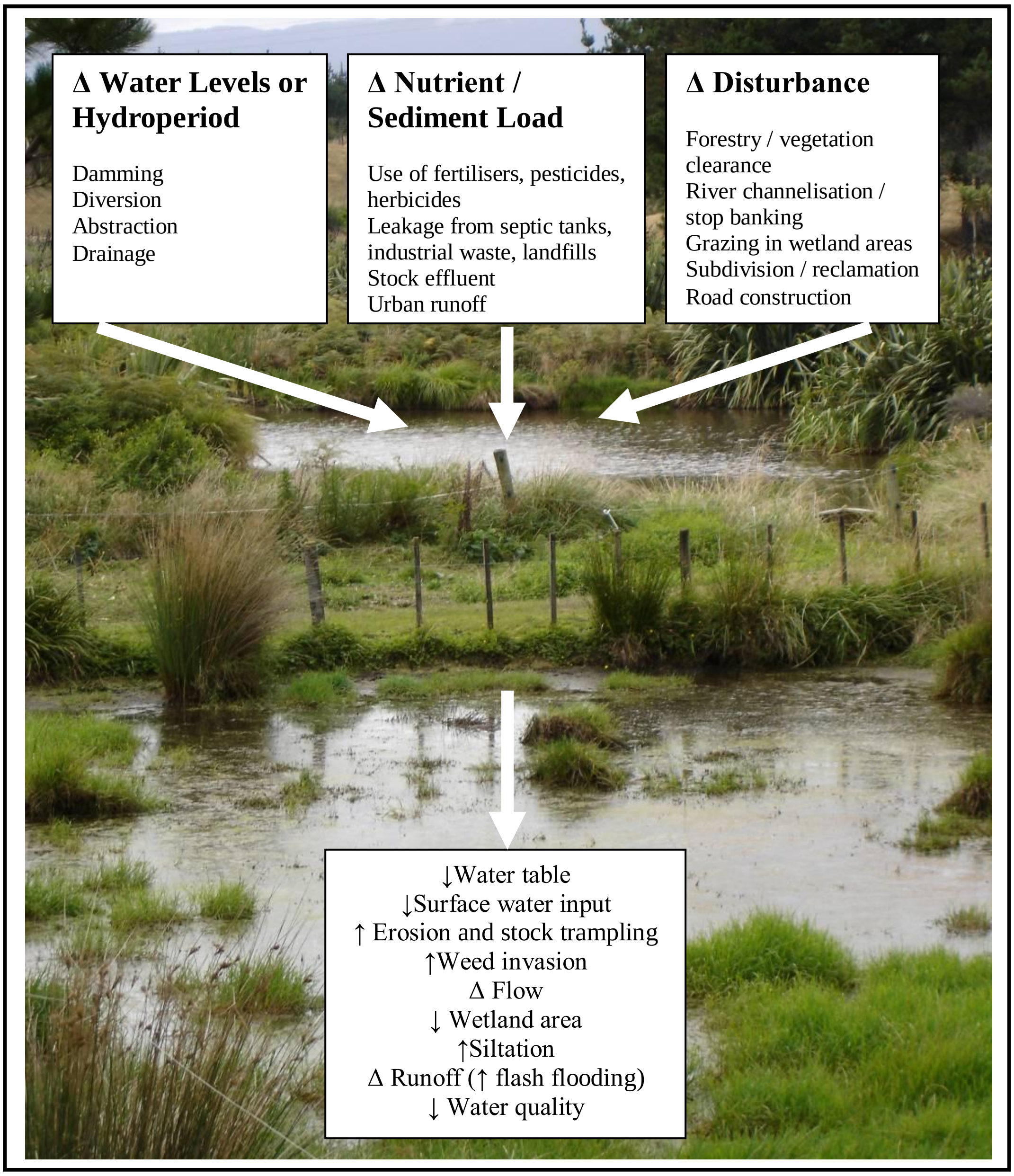


Figure 2.4.1: Human impacts on wetland systems. From: (Fuller, 1993). Photograph of Te Hapua wetland provided by Mari Housiaux.

Peat soils, often found in wetland areas, shrink and swell significantly with water loss and gain due to their high organic content and low density. Draining and subsequent compacting of peat soils for agriculture is often irreversible, so restoration may be impossible (McLay, et al., 1992).

"*Once a wetland system has been severely modified it is often difficult if not impossible to return the system to its natural state. Some of the values lost may be irreplaceable.*" (Ramsar, 1986).

2.5 Wetland hydrology

In a natural system the wetland presence is determined by the climate, topography, soil and underlying geology. Properties that define wetland class (as determined by Johnson & Gerbeaux in table 2.2) are determined by interactions between the hydrology, the physiochemical environment (soil and water chemistry), and the biota (fauna, flora etc). Figure 2.5.1 (below) illustrates these relationships.

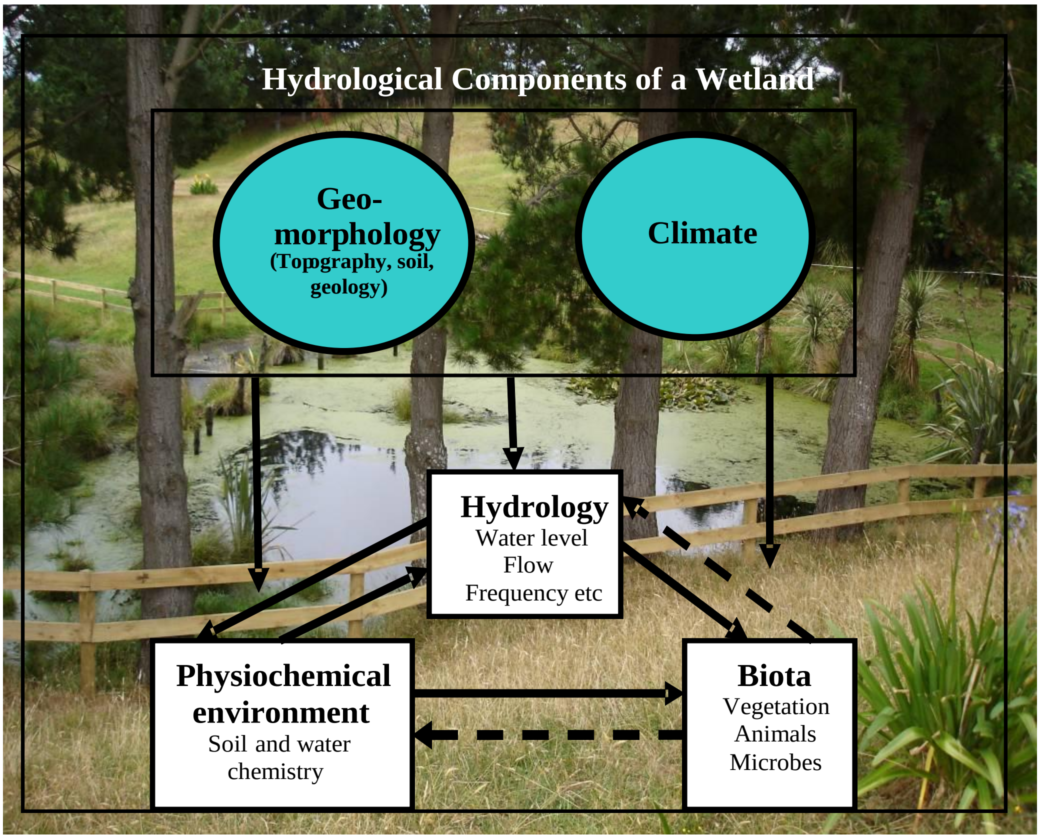


Figure 2.5.1: The components of wetland hydrology. Climate and geomorphology (topography, soil and geology) determine the water regime, physiochemical environment, and biota. The components are interdependent and there is significant feedback (dashed lines). Adapted from: Mitsch & Gosselink (2007). Photograph of Te Hapua wetland provided by Mari Housiaux.

Knowledge of these five main wetland components is fundamental for understanding individual wetland environments. If one was to change significantly then it is likely that it would bring about change in other parts or all of the system.

Wetland hydrology is central to wetland processes. Climate, topography, soil and underlying geology have brought water to the area via surface water, groundwater and / or local rainfall. Wetland hydrology is also influenced by adjacent landuse and the size of the catchment area (Sutherland, 1982). Hydrology controls the flow of nutrients, sediment and toxins into and out of the wetland, as well as the chemistry and nature of wetland soils. Through this it defines the species of vegetation capable of surviving in the environment and hence the variety of fauna that dwell there (Mitsch & Gosselink, 2000). Figure 2.5.2 shows how water enters the wetland as groundwater inflow, surface water inflow and / or rainfall, and leaves as evapotranspiration, groundwater outflow, or surface water outflow. This is the basis of any terrestrial wetland water balance.

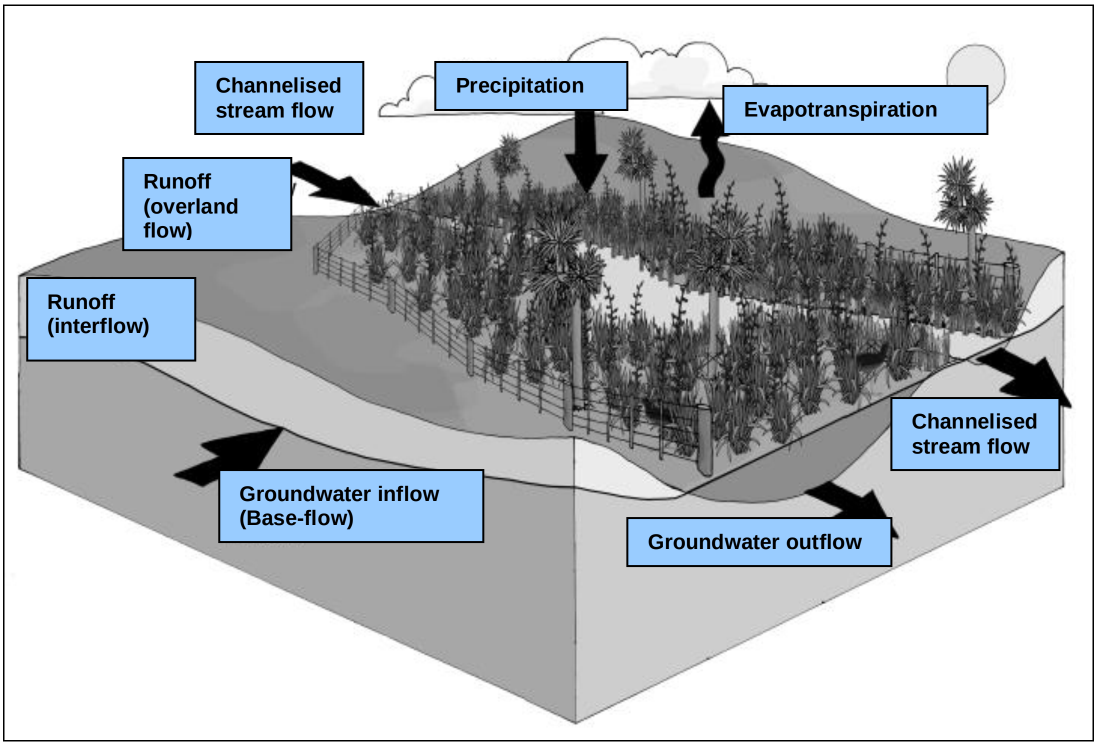


Figure 2.5.2: The main components of the hydrological cycle that feed into a wetland water balance. Surface water in/out flow encompasses channelised stream flow and overland flow. Groundwater in/out flow encompasses base-flow at the water table as well as through-flow. Adapted from: (WRC, 2005)

2.5.1 Water balance

Wetland hydrology can be broken down to the simple equation shown below (Equation 2.1). A water balance can be calculated for a wetland to establish the relative sources and sinks of water and whether the wetland is gaining or losing stored water over a set time period. Equations 2.1 and 2.2 below show a generalised water balance for a wetland.

Equation 2.1: ***General Systems Equation***

Input – Output = Change in storage

Or for wetlands:

Equation 2.2: ***Wetland Water Balance***

$$(P + Q_{in} + G_{in}) - (E + Q_{out} + G_{out}) = \Delta S$$

Where: ΔS = change in stored water within the wetland (mm); P = precipitation (mm); Q_{in} = surface water inflows (mm); G_{in} = groundwater inflows (mm); E = evapotranspiration (mm); Q_{out} = surface water outflows (mm); G_{out} = groundwater outflows (mm). (Campbell & Jackson, 2004)

Different classes of wetland have different components contributing to their water balance. For example, some wetlands on the South Island's West Coast have impermeable underlying substrates, so there is no exchange with groundwater (Johnson & Gerbeaux, 2004b). Te Hapua wetland has no significant surface water input, so the hydrology relies mostly on groundwater inflow and local rainfall. This influences the degree of nutrient input and the response to high rainfall events.

A water balance can be calculated for a given wetland by quantifying each of the inflows and outflows. When 'Δ Storage' is positive, the water table and / or soil moisture content will rise. Conversely, when 'Δ Storage' is negative, the water table drops and / or soil moisture declines (Campbell & Jackson, 2004). If the wetland pond level is connected to groundwater level, then this will also change.

Thus, to determine change in wetland pond level, we need to measure input from precipitation and groundwater, as well as outputs for evapotranspiration, surface water and groundwater. The Te Hapua complex includes 21 major wetland areas, so some of these in/outputs are present in one wetland and not in another.

2.5.2 Precipitation

All classes of wetland, regardless of whether they are fed by groundwater, surface water or neither, are dependant on precipitation. All water enters the hydrological cycle as precipitation and feeds into the system as shown in figure 2.5.2. Water may arrive at a wetland via a number of possible pathways, but they all stem from precipitation. Precipitation may fall directly on the wetland, arrive via runoff or channelised stream flow, or be discharged from groundwater after infiltrating and percolating down through the soil higher in the catchment. Precipitation may be in the form of rainfall, snow and ice of various types, or water deposited directly onto the ground surface as dew (Oke, 1987). However for the purposes of this study only precipitation from rainfall will be considered since snow and ice are not typically present in the catchment and the relative portion of dew is negligible.

2.5.3 Evapotranspiration

Evapotranspiration is important as it sometimes represents the largest output of water for wetland areas, depending on the class (Campbell & Jackson, 2004).

Evapotranspiration is all water lost via evaporation and transpiration and varies diurnally and seasonally due to changes in solar energy.

Evaporation is the water vaporised from freely exposed surfaces (Baird, 1997). This includes open water, exposed soil matrix, and plant surfaces. Transpiration is water loss from the stomata on leaf surfaces. The rate of evapotranspiration is essentially determined by the presence and amount of; heat energy (to supply the latent heat of vaporisation); air turbulence and humidity (to transport and mix the air above the surface); and water (to supply evaporative demand) (Ward & Elliot, 1995). Different species transpire at various rates, so species composition in a wetland may be important when quantifying evapotranspiration (Baird, 1997).

Evapotranspiration rates from an open water area can be estimated given the climatic parameters of the evaporative surface. Parameters required include temperature, wind speed, relative humidity and solar radiation (Oke, 1987). Evapotranspiration from soil is more difficult to quantify. Evaporation from an unsaturated soil will occur at the surface and at a depth depending on the climatic conditions and the physical properties of the soil. The continued evaporation depends less on climatic conditions and more on the hydraulic conductivity of the soil (Ward & Elliot, 1995).

Evaporation and evapotranspiration are complex processes because they depend on variables such as the amount of solar radiation reaching the surface, the amount of wind directly above the surface, the aperture of the stomates, the soil water content, the soil type and type of plant (Ward & Elliot, 1995). In a wetland, where areas of open water and nearby soil surfaces are usually at or near 100% saturation, evaporation will commonly proceed at or close to the potential rate. Potential evaporation (E_p) is defined by Ward and Elliot (1995) as "…evaporation from a surface when all surface-atmosphere interfaces are wet so there is no restriction on the rate of evaporation from a surface.…. E_p depends primarily on atmospheric conditions and surface albedo but will vary with surface geometry characteristics, such as aerodynamic roughness," (Ward & Elliot, 1995). Surface albedo estimates is the amount of solar radiation that is reflected from a given surface (Oke, 1987).

It is arguably safe to assume that potential evaporation can be used to estimate evaporation in a wetland water balance to simplify a given study (Baird, 1997;

Campbell & Jackson, 2004). However different wetlands have different soils, plant species and vegetation densities, so evapotranspiration in each wetland should be considered separately. The presence of peat together with certain vegetation, for example, may cause actual evapotranspiration to deviate considerably from the potential evapotranspiration (Campbell & Jackson, 2004). Campbell and Williamson (1997) found that although saturated, peat can exhibit actual evaporation rates at one third of the potential evaporation in northern New Zealand peat bogs (Campbell & Williamson, 1997). This was primarily because of the dominance of two types of native vegetation that have xerophyic (water conserving) properties. The species of concern, *Empodisma minus* and *Sporadanthus ferrugineus* were not listed as present at Te Hapua in a Wildlands ecological survey (Beadel, 2003b).

Other factors affecting evaporation in wetlands include the impact of grazing animals which remove vegetation cover, increasing evaporation from the now open water areas as well as from wet soil (WRC, 2005). When stock graze around wetland areas they trample and compact shallow soil layers which can slow percolation of precipitation and increase the likelihood of surface ponding. This may increase evaporation as less water is able to recharge to groundwater.

Exotic species like willow that are either introduced or colonise degraded wetland areas will increase evapotranspiration because they transpire significantly more than native species. In general, vegetated wetlands have lower evaporation rates than open wetland areas (Campbell & Williamson, 1997).

2.5.4 Surface Water

As depicted in figure 2.5.2, the main terrestrial pathways by which water can travel to and from wetlands are via channelised stream flow, runoff, and groundwater flow. The amount of water that stems from each of these pathways helps to define wetland class.

Runoff is the process that occurs following rainfall where water is moved into streams and open water areas such as lakes and wetlands (Freeze & Cherry, 1979). There are two main types of runoff – overland flow and interflow. Both are important to wetlands because of the high water table associated with wetland areas.

(a) Interflow (see figure 2.5.2) is water that travels laterally or horizontally through the unsaturated zone during or immediately after precipitation (Ward & Elliot, 1995). It is not well defined but can be described as either:

- *Through-flow* - lateral flow of the soil water in unsaturated conditions.
- *Subsurface storm flow* - lateral flow of the soil water in saturated conditions.
- *Translatory flow* - lateral flow of "old" soil water, pushed out by the freshly precipitated water. (Davie, 2004). See figure 2.5.5

(b) Overland flow (figure 2.5.4 and 2.5.5) can occur in one of three ways; Hortonian overland flow, saturation excess overland flow, or return flow.

- *Hortonian* or "*infiltration excess overland flow*' happens when the rate of rainfall exceeds the infiltration rate of the soil at the surface. This is important in areas surrounding a wetland where surface soil is compacted from vehicle tracks or livestock. (Davie, 2004).
- *Saturation excess overland flow* occurs when the soil is saturated through the profile so excess water cannot infiltrate down (Davie, 2004). This is important in wetland areas as the water table is often close to the surface.
- *Return flow* is water that is forced back to the soil surface after infiltrating. This may be caused by soil hydraulic characteristics and / or hillslope topography and may be important in wetlands surrounded by steep hills (Holden, 2008).

Base-flow (figures 2.5.2) is the portion of surface water maintained by groundwater discharge and represents the minimum flow during times of drought (Campbell & Jackson, 2004; White, et al., 2001). In low lying areas the pond level of a wetland may be considered the surface expression of groundwater level (White, et al., 2001).

Wetlands fed by stream flow can receive water either permanently or when in flood (WRC, 2005). Whilst it is not thought that Te Hapua receives significant surface water inflows, it is suspected that occasional flooding in the Mangone stream affects some wetland areas. Anecdotal evidence of the water regime at Te Hapua noted that in 2005 where a Mangone flood induced ponding in areas north of the wetlands restricted outflow from wetland areas. It is not clear if the wetlands were simply 'backed up' by the flooding, or if the flood waters moved from the Mangone stream into the wetland.

2.5.5 Groundwater

Understanding the movement of groundwater requires knowledge of the hydraulic properties of the substrates through which it flows. Groundwater flows through interconnected pore spaces, along cracks between grains, and through large scale fractures (Smith & Wheatcraft, 1993). Most near-surface water bearing materials are unconsolidated layers with varying degrees of; organic / inorganic content; sorting; density; and porosity. Flows through consolidated material are generally slower, depending on how fractured the rock is and the size of the fractures and the finer pores (see table 2.1).

Generally, layers nearer the surface that have morphological, physical, chemical, and mineralogical characteristics that differ from parent materials are called soils (Birkeland, 1999). Deeper layers (where there is less organic content) are called aquifers. Aquifers can be unconfined near the surface, or confined at depth (see figure 2.5.3). Aquitards are layers of material that restrict flow from one aquifer to another because of a lower conductivity compared to the material that defines the aquifer. Confined aquifers will have an aquitard above and below. If an aquitard is more or less impermeable, it's termed an aquiclude (Holden, 2008). The water table is the upper limit of groundwater, above which the soil is unsaturated.

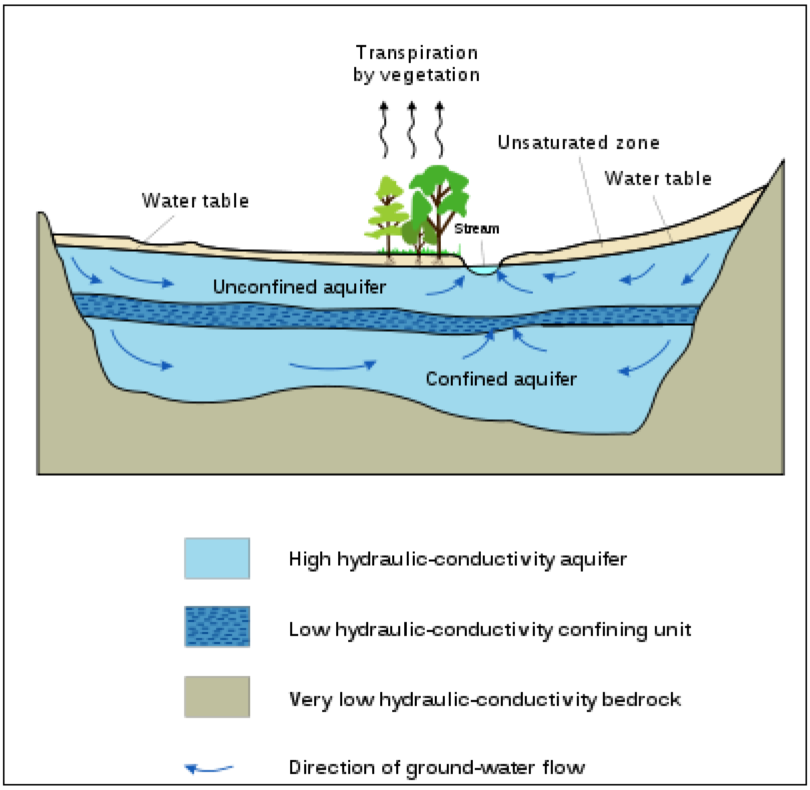


Figure 2.5.3: Confined and unconfined aquifers (Hillewaert, 2007)

2.5.6 Groundwater-surface water interaction in wetlands

Interaction between groundwater and surface water is common (White, et al., 2001). Groundwater can be recharged by wetlands, streams, lakes and seawater. Likewise, groundwater can discharge to surface water in the form of springs, seeps and subterranean flow. The relationship between groundwater and surface water is complex: recharge and discharge can interchange depending on surface flows and can occur simultaneously in different areas of the same system. Interactions are controlled by the porosity and conductivity of the underlying geology / soil, as well as the pressure gradient between the two waters (White, et al., 2001). Interactions between an inter-dunal wetland and groundwater are often transient and can reverse seasonally (Law, 2008; WRC, 2005).

In general it is thought that wetlands do not lose a significant amount of water to groundwater outflow (Campbell & Jackson, 2004). There are two reasons for this. One is that swamps and fens are typically found at the base of hill-slopes and low-lying areas where groundwater is emergent. The other is that the low permeability of the peat that lines many wetlands acts as a confining layer that limits water movement to deeper layers.

Groundwater inflow is an important input in some palustrine wetlands, yet in others it has little or no influence at all (see table 2.2). When trying to determine the source of wetland water, looking at the relative levels of wetland pond water and groundwater is useful. Figure 2.5.4 depicts the possible discharge – recharge relationships in wetlands with regard to groundwater.

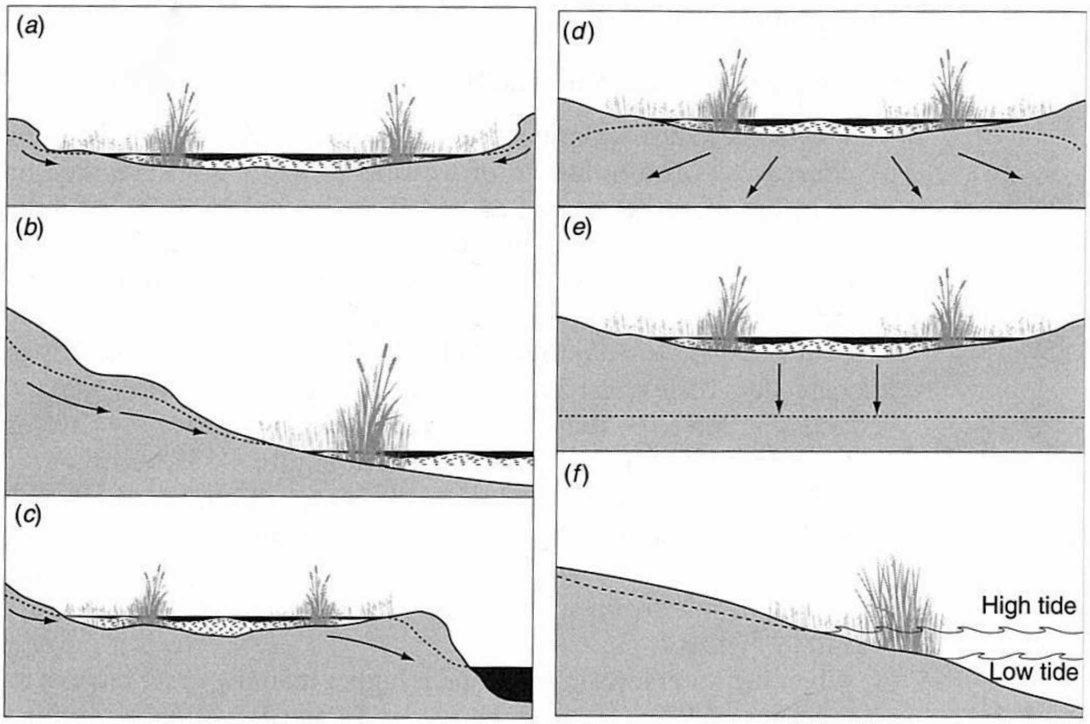


Figure 2.5.4: Possible groundwater / surface water relationships. Dashed lines indicate the groundwater level. (a) a marsh in a depression receiving groundwater inflow ('Discharge Wetland'); (b) a groundwater spring / seep wetland at the base of a slope; (c) a floodplain wetland fed by groundwater; (d) a marsh as a 'recharge wetland' which contributes water to groundwater; (e) a perched wetland or surface water depression wetland; (f) a groundwater flow through a tidal wetland. (Mitsch & Gosselink, 2007)

A 'discharge wetland' ((a) in figure 2.5.4) is a wetland that has a surface water level that is generally lower than the surrounding water table because the wetland is located in a topographic depression (Mitsch & Gosselink, 2007). Hydrology is therefore dominated by groundwater inflow which buffers the wetland from variations in water level, hence fluctuations are less dramatic than in surface flow wetlands (Law, 2008; White, et al., 2001). These types of wetland can occur in coarse textured glacio-fluvial deposits where the degree of interaction between ground and surface water is enhanced given a difference in the porosity of underlying sediments (Mitsch & Gosselink, 2007). Water level in a 'recharge wetland' ((d) in figure 2.5.4) is higher than the surrounding water table, so typically loses water to groundwater (Mitsch & Gosselink, 2007; White, et al., 2001). Water level in a 'perched wetland' ((e) in figure 2.5.4), is separated from the water table by an unsaturated zone (Mitsch & Gosselink, 2007). This wetland is influenced more by surface runoff and local precipitation.

Complex groundwater flow fields can develop if the underlying sediment varies in permeability (USGS, 1998). Figure 2.5.5 show how wetlands are more likely to develop where these zones of low permeability push groundwater toward the surface.

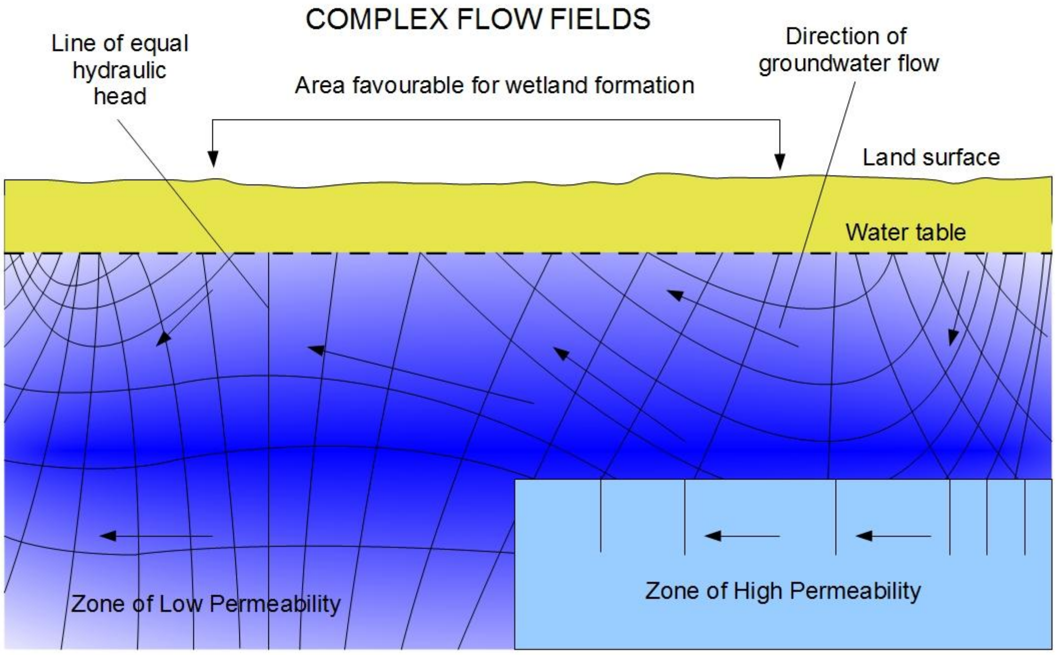


Figure 2.5.5: Complex flow fields caused by varying permeability of the underlying geology can bring about conditions favourable to wetland formation (Reproduced from (USGS, 1998).

The hydrological characteristics of lakes and wetlands in dune terrain are determined to a large extent by their position in respect to local and regional flow systems (USGS, 1998). The presence of dunes can alter the flow of local groundwater and contribute to the complex flow fields depicted in figure 2.5.5. Hummocky dune landscapes, like those found on the Kapiti Coast, typically have low lying areas between dune systems (Law, 2008). The build up of dune material and associated water table mounds can impede drainage of near surface groundwater flow (Preece, 2005; Winter, 1986). This brings the water table close to the surface in the inter-dunal depressions and allows the formation of wetlands (Preece, 2005), as shown in Figure 2.5.6. The Kapiti Coast has many such wetland areas where sand dunes have altered the flow of groundwater (URS, 2004). The mounding of water beneath dunes is more prevalent in dunes with small depressions as opposed to those that are single crested (Winter, 1986) (figure 2.5.6). One explanation of why the wetlands have formed in Te Hapua is that the development of dunes along the coast has hindered the passage of groundwater en route to the sea (Preece, 2005).

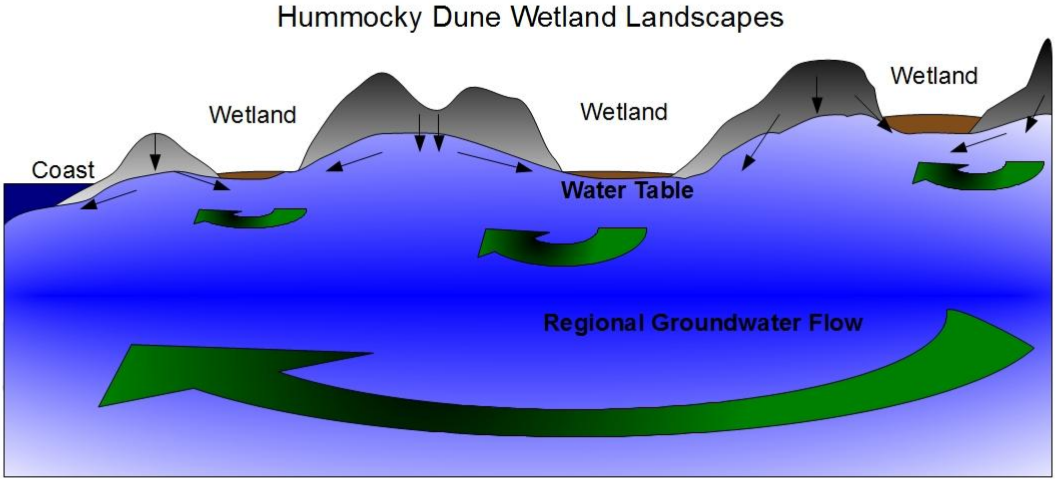


Figure 2.5.6: A cross section (perpendicular to the sea) through a hummocky dune landscape. Arrows show the direction of local and regional groundwater flow (Reproduced from (Winter, 1986).

2.5.7 Hydrogeology

The rate of water flow through soils and aquifers depends on (a) the energy gradient driving the flow; (b) the porosity / permeability of the material; and (c) the degree of saturation of the material (Baird, 1997).

Fluid pressure and elevation are the drivers of groundwater movement. Hydraulic head (or piezometric head) is the mechanical energy per unit weight of the fluid (Smith & Wheatcraft, 1993). Groundwater moves from areas of high hydraulic head toward areas where it is lower. Equation 2.3 and figure 2.5.7 show the equation and constituents of hydraulic head.

Equation 2.3: ***Hydraulic Head***

$h = z + h_p$

Where h = hydraulic head (in metres above datum); z = elevation (in metres above datum); h_p is the pressure head (m) (Smith & Wheatcraft, 1993).

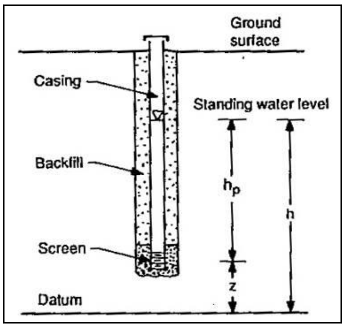


Figure 2.5.7: A piezometer showing the relationship between hydraulic head (h), pressure head (h_p), and elevation (z) (Smith & Wheatcraft, 1993).

Figure 2.5.7 shows a piezometer, commonly used to measure hydraulic head. Pressure head, $h_{p,}$ is expressed in units above (or below) atmospheric pressure (gauge pressure).

At the water table water pressure equals atmospheric pressure (i.e. h_p = 0). Above the water table soil water pressure is less than atmospheric (i.e. h_p < 0). Below the water table, soil water pressure is greater than atmospheric (i.e. h_p > 0) (Smith & Wheatcraft, 1993). This is important in groundwater flow because water does not necessarily flow with gravity – a fluid under pressure (for example a confined aquifer) can flow up or down relative to gravity. Figure 2.5.8 gives an example of how this might happen. An artesian aquifer is a confined aquifer that has enough natural pressure for water to flow above the upper limit of the aquifer. The water may reach the ground surface, then termed an artesian well or spring (Freeze & Cherry, 1979)

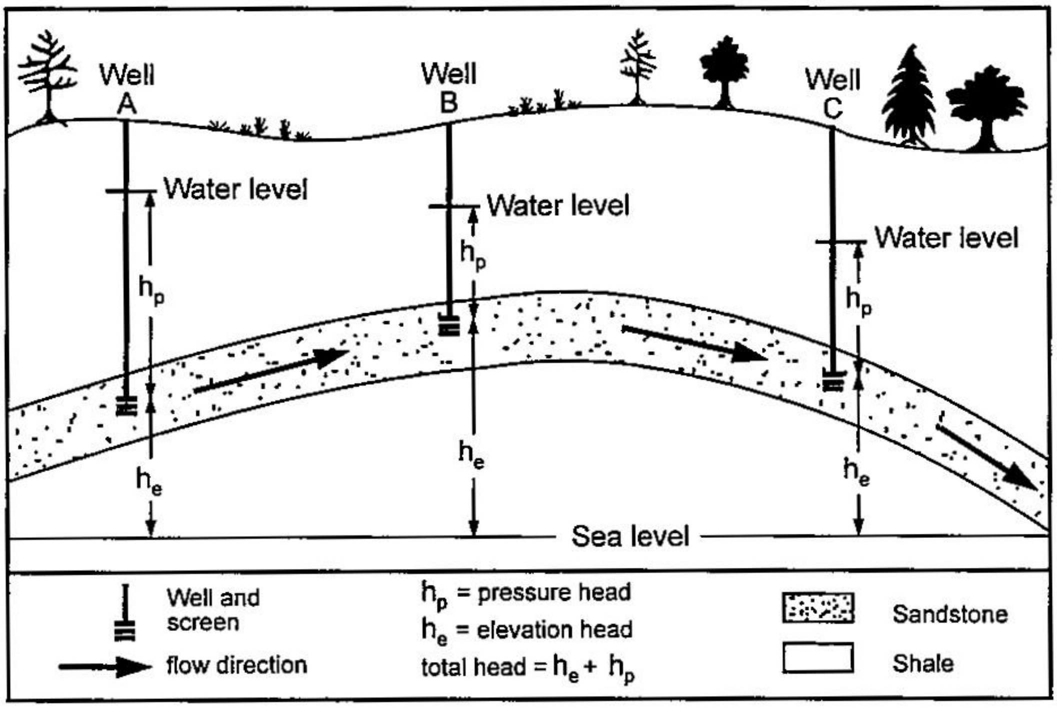


Figure 2.5.8: Components of total hydraulic head, elevation head and pressure head controlling flow in a sandstone aquifer (Scott, 1995).

Measurements of hydraulic head from the same aquifer can be connected to make contour maps. These maps can be used to infer groundwater flow direction; given that water will move from areas of high hydraulic head to low. The difference in hydraulic head between two or more measurements over a given distance is called the hydraulic gradient (Smith & Wheatcraft, 1993).

In most groundwater modelling studies Darcy's Law is used to measure water movement through a porous medium. Darcy's Law (equation 2.4 below) measures the rate of water flow through a saturated sediment or soil with a given hydraulic gradient and area. Hydraulic conductivity is a measure of the ability of a fluid to move through a sediment or rock, see table 2.4 (Smith & Wheatcraft, 1993).

Equation 2.4: ***Darcy's Law***

$$Q = K.i.A$$

Where Q is the rate of flow (in length^3/time); K is the hydraulic conductivity (in length/time); i is the hydraulic gradient (in length); and A is the cross sectional area (in length^2)

(Freeze & Cherry, 1979).

Darcy's Law states that the flow of groundwater is proportional to (a) hydraulic gradient and (b) the hydraulic conductivity (Law, 2008).

This is important because we can apply Darcy's Law to calculate the relative groundwater inflow and outflow for an area of interest. However, using Darcy's Law for peat soils may be problematic because pores are often blocked by gas bubbles that form as a result of microbial activity in the anaerobic environment. This can block water flow in an unpredictable way and hence some scientists have questioned whether Darcy's Law can be applied to wetlands (Baird, 1997; Campbell & Jackson, 2004). Peat soils are also different in that pores decrease in size and permeability with depth due to being more decayed and compacted in deeper layers (Campbell & Jackson, 2004), though this can be included in calculations using Darcy's Law. Given this, whilst it may be possible to calculate groundwater flow near a wetland, using Darcy's Law where peat soils preside over sandy soils is questionable. Some values for conductivity in peat are given in table 2.4. The dominant species of vegetation also influences conductivity in peat (Mitsch & Gosselink, 2007).

Porosity is the fraction of void space per unit volume of material (Smith & Wheatcraft, 1993). It can be expressed as a percentage or as a value between 0 and 1. It approximates the volume of water that a given material can hold. The intrinsic permeability of particular sediment describes the size of the pore openings. The smaller the sediment grain size, the more surface contact there is. Intrinsic permeability will therefore be lower in sediments with small grain size because frictional resistance to flow will be higher (Fetter, 2001). Table 2.4 compares different sediment types.

Table 2.4: Hydraulic characteristics of various sediment and rock types (Freeze & Cherry, 1979; Mitsch & Gosselink, 2007; Smith & Wheatcraft, 1993).

Sediment or rock type	Porosity (%)	Permeability (m^2)	Hydraulic conductivity (m/day)
Peat - UK bog	Not available	Not available	10^{-4} to 10^{-5}
Peat – Russian fen	Not available	Not available	10^{-3} to 10^{-1}
Clay	40% to 60%	$10^{-19}$to 10^{-15}	10^{-7} to 10^{-3}
Silt	35% to 50%	$10^{-16}$to 10^{-12}	10^{-4} to 10^{-0}
Sand(coarse, aeolian)	15% to 45%	$10^{-14}$to 10^{-9}	10^{-2} to 10^{-3}
Sandstone	5% to 35%	$10^{-17}$to 10^{-12}	10^{-5} to 10^{-0}
Unfractured igneous rocks	0.01%	10^{-21} to 10^{-17}	10^{-9} to 10^{-5}
Fractured igneous rocks	1% to 10%	10^{-17} to 10^{-13}	10^{-5} to 10^{-1}

Clay for example generally has a high porosity yet a very low permeability and conductivity due to a very small grain size. Clays are known to act as aquitards given their low hydraulic conductivity. Coarse sands have relatively high porosity and permeability, so have high conductivity. Aquifers containing coarse sands are known to be capable of providing high yields of water from abstraction. The shallow unconfined aquifers of the Kapiti Coast are dominated by coarse grained aeolian dune sands with moderate permeability (10^{-4} to 10^{-6} m^2) (Law, 2008).

Darcy's law is effective for determining flow rates in a saturated medium. If the sediment is unsaturated however, water will flow differently, in which case Richard's Equation is more suitable. The hydraulic properties of soils are important because they affect the relationship between Δ Storage and water table fluctuations. They also affect the degree of through-flow and movement to deeper aquifers (Campbell & Jackson, 2004).

Variations in groundwater levels and moisture content of an unsaturated wetland soil are closely linked because the water table is so near the surface. Water evaporated from shallow subsoil is quickly replaced by groundwater (Campbell & Jackson, 2004). Peatland soils retain soil moisture as high as 90% given the soil's hydraulic properties and shallow water table (Campbell & Jackson, 2004; Thompson, et al., 1999).

'Transmissivity' (T) is a measure of how much water can flow from an aquifer, given the thickness of the aquifer and conductivity of the sediment (Freeze & Cherry, 1979;

Singh, 1992). Transmissivity is important when assessing the safe yield for aquifers, as well as the yield and spacing of wells.

Equation 2.5: ***Transmissivity***

$T = Kb$

Where K is the hydraulic conductivity; *b* is the thickness of the aquifer (Freeze & Cherry, 1979; Singh, 1992)

The 'Specific Yield' (S_y) is the percentage of water an aquifer releases from storage via gravity, per unit surface area of aquifer, per unit drop in water table following saturation of the unconfined aquifer. (Freeze & Cherry, 1979; Singh, 1992). The 'Safe Yield' of an aquifer is the amount of water that can be taken from a groundwater basin annually without causing detrimental effects (Freeze & Cherry, 1979). Safe yield is used in water resource management to create limits of groundwater abstraction across a groundwater zone.

III Regional setting and site description

3.1 The Te Hapua Wetland Complex

Te Hapua wetland is situated approximately 75 km north of Wellington on a coastal plain called the Kapiti Coast (see Figure 3.1). This plain lies between the townships of Paraparaumu / Raumati to the south and Otaki to the north, and is approximately 720 km^2 in size (Hughes, 1997). It is flanked to the east by the axial Tararua Ranges and to the west by the Tasman Sea. Averaging approximately 5km in width between the foothills of the Tararua Ranges and the sea, the Kapiti coastal plain sits at about 20 metres above sea level with a topography dominated by low rolling dunes.

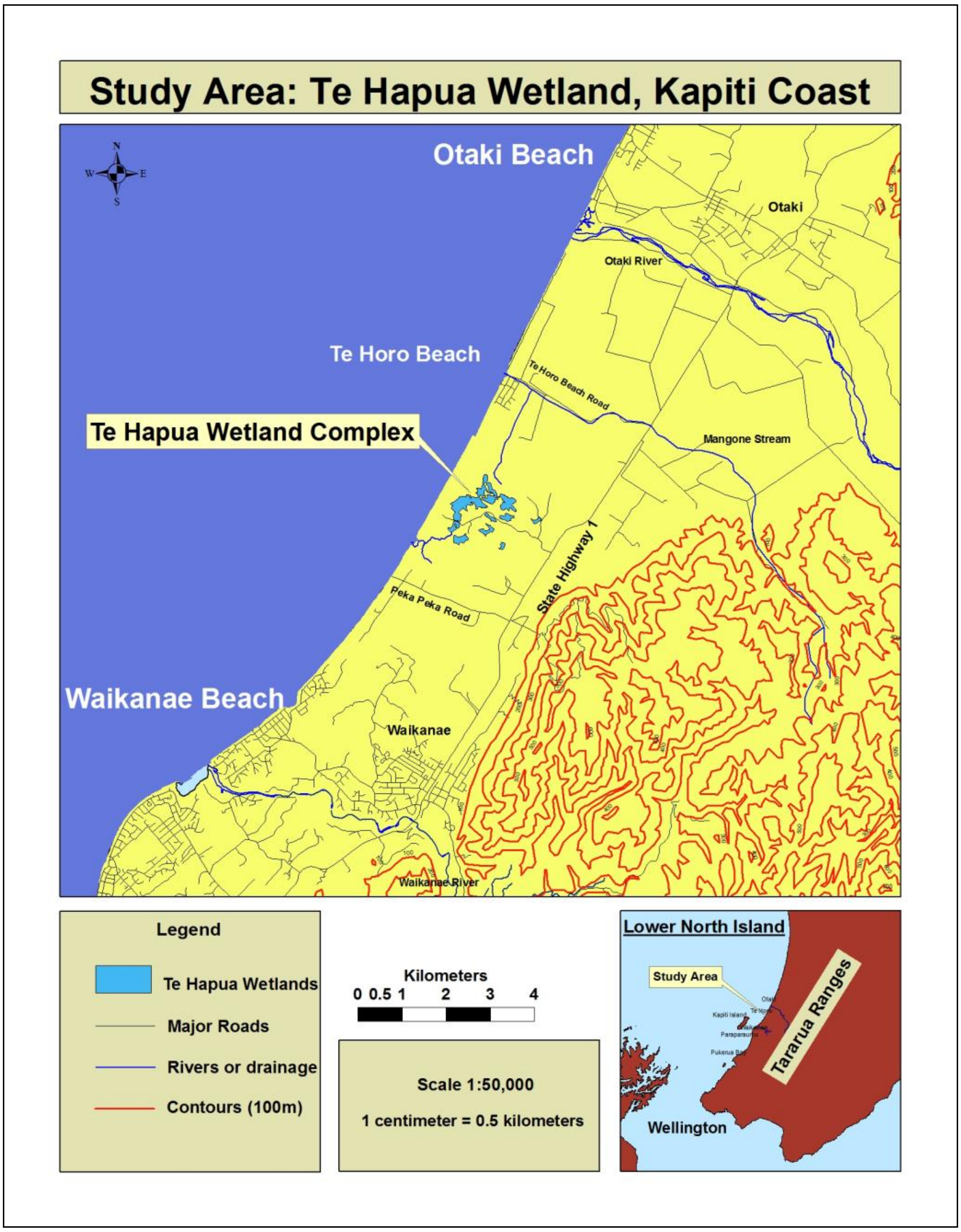


Figure 3.1: The study area, Te Hapua Wetland. The wetland is situated 75km north of Wellington on the Kapiti Coast, close to Waikanae.

The Te Hapua wetland complex is a group of small wetlands with a total area of approximately 59.6ha (Ausseil, et al., 2008; Preece, 2005). Te Hapua wetland is on the Kapiti Coast, 7 km north of Waikanae, close to the northern limit of the Wellington region (as defined by Greater Wellington Regional Council). The wetlands occupy inter-dunal depressions east of the coastal foreshore, with the Tararua foothills rising 3km further east. The complex itself consists mostly of small remnant wetlands that vary in size and class (Preece, 2005).

Part of a DOC conservancy called the *Foxton Ecological District*, Te Hapua wetland lies in a coastal zone characterised by an elongated belt of sand dune country with several estuaries, wetlands and dune lagoons covering about 1,100km^2 (Ravine, 1992). The climate is generally warm with moderate seasonal rainfall and often windy conditions (Preece, 2005).

Before 1900, a large coastal swamp spanned from Paekakariki in the south to beyond Otaki in the north. Known as '*The Great Swamp*', it is thought to have covered nearly 2,000ha. By 1990, heavy modification and drainage is estimated to have reduced the swamp area to around 300ha (Fuller, 1993). See Figure 2.2.1, chapter II.

Previous studies in the area by Ravine (1992) from the Department of Conservation; Beadel (2003) of Wildlands Consultants; Preece (2005) from Wetlands NZ; and Ausseil et al (2008) of the Department of Conservation / Landcare Research; looked mostly at the wetlands' ecological significance and biodiversity. Of the four studies found, three grouped the complex as a single wetland class, classifying the Te Hapua area accordingly as a '*swamp*' (refer to Chapter II for definitions of wetland class). Ausseil et al describe it as mostly '*swamp'* with some '*marsh*' areas whilst Beadel and Ravine describe it as '*swamp'* only (Ausseil, et al., 2008; Beadel, 2003a; Preece, 2005; Ravine, 1992). When Preece (2005) did an ecological survey of privately owned wetlands within the complex he found the hydrology "*complex and in need of study*". He noted "*…not all wetlands in the complex (are) swamp…at least one is better described as a fen*". However Preece then provisionally designated all the wetlands in the complex as swamp "*….in line with previous studies*" (Preece, 2005). This confusion is probably due to a lack of detailed study, by each of the authors, when looking at the hydrology of the wetlands. The Te Hapua complex has more than twenty separate wetland areas and study of the hydrology throughout is incomplete.

Ravine's 1992 survey recommended that Te Hapua wetland be targeted for restoration and protection with 'Priority 1' status. The purpose of the survey was to identify and protect wetlands within the Foxton Ecological District that are currently at risk using the Department of Conservation's Protected Natural Areas Programme. This programme aims to preserve a full range of indigenous biological and landscape features in New Zealand (Ravine, 1992).

Beadel's 2003 survey for Kapiti Coast District Council noted Te Hapua's significance as one of the best examples of what were once extensive wetland communities in the Foxton Ecological District (Beadel, 2003a), citing previous work by Ravine. Also noted was the presence of a significant number of native wetland species, some of which are uncommon. *Hypolepis distans,* a native fern, was found in a fenced area. This fern has a "*very patchy distribution"* around the country (Anderton, 2006). Beadle suggested the wetland be included in Kapiti Coast District Council's list of Ecological Sites, be fenced and undergo weed control measures. This recommendation was followed up by the council with Te Hapua now a designated Kapiti Coast Ecological Site "with regional significance" (as opposed to 'local' or 'national' significance).

The most recent assessment was by Landcare Research in 2008. This work was undertaken for the Department of Conservation as part of a nationwide study to identify wetland ecosystems of national importance for biodiversity. Using indexes across a range of environmental indicators, the survey aimed to "…develop a ranked list of wetlands of national importance that would protect a full range of wetland biodiversity and provide guidance on the most immediate conservation management needs" (Ausseil, et al., 2008). Te Hapua was ranked 9th in the region, and designated as a 'Nationally Important' wetland (Ausseil, et al., 2008).

Parts of the wetland complex are included in Wellington Regional Council's *Key Native Ecosystems Programme.* This programme targets areas that are considered to have exceptionally high ecological value / biodiversity, and are situated on private land, giving support by way of pest control, restoration and advice (WRC, 2009).

Areas surrounding Te Hapua wetland have been drained to provide pasture for livestock. In 2003 the complex was described as having had "most of the wetland heavily browsed and trampled" (Beadel, 2003a). Ravine (1992) speculated that draining and conversion of most of this area to provide pasture for grazing animals has had the effect of lowering the water table over the entire coastal plain (Ravine, 1992). Also noted was that there had been "……large changes to natural hydrology (where) human influences drive entire wetland ecosystem processes…… but the wetland will persist if the influence is removed" (Beadel, 2003a).

Ravine notes that in 1992 all wetland areas (visited) had at some point been open to grazing by cattle. This resulted in invasion of exotic pasture plants around the edges of wetland areas and trampling of wetland vegetation. Beadel (2003) estimates the percentage of non-native plant cover at less than 25% and mostly confined to the edges. Other possible impacts on the wetlands given the change in landuse to pasture include water quality degradation due to agricultural chemicals and increased sediment load given vegetation loss and increased surface area for erosion (Phreatos, 2002). There has been extensive excavation in some parts of Te Hapua to create habitat for water fowl such as ducks for game shooting (Ravine, 1992). Also, the building of access roads, farm tracks, drains and culverts in the area is thought to inhibit natural flows within the wetland.

The area has been farmed for the last 50 – 100 years and has recently been developed into lifestyle blocks. All of the wetlands found at Te Hapua are on private land. Much of the private land containing wetland area now has QEII covenant protection[4]. The Te Horo area is one of the most covenanted regions for wetland reserves in New Zealand (personal communication with Peter Ettema, QEII National Trust Wellington, December 3rd 2009). Two of the larger wetlands have been converted into waterfowl habitats for recreation and hunting (Ravine, 1992), one of which is still used for duck shooting.

Local community conservation group '*The Friends of Te Hapua Dunes and Wetlands*' has been involved in conservation and planting efforts for some years. Landowners have used private funding as well as grants from the Department of Conservation, Wellington

[4] The 'QEII National Trust' provides, among other things, expertise on the legal protection of private land to protect and enhance valued New Zealand landscape for landowners.

Regional Council, Kapiti Coast District Council and QEII Trust for fencing, weed and pest control and the planting of native vegetation.

Te Hapua soils are sandy with peat in low-lying areas. Historical vegetation is thought to have been coastal swamp forest, given the remains of charred totora logs (Ravine, 1992). Today there are few remaining native forest areas left in the district (none at Te Hapua) and the majority of the dune areas have been modified at some time (Preece, 2005). Many of the district's dunes have been planted with marram, lupin and pine forest. Less than 5% of the area is now covered in native vegetation (Preece, 2005). There are no streams flowing into the area and rainfall into this catchment is not considered sufficient to maintain the wetlands (Preece, 2005). This study therefore focuses more on the interaction of shallow groundwater and wetland surface water in response to local rainfall. Current topographical maps and GIS analysis (see chapter V) indicate that there are two surface water outflows. One, a northbound drain, moves water from northern wetland areas into the Mangone Stream where it goes out to sea at Te Horo Beach. The other is a natural break in the dunes just south of the Te Hapua wetland complex (see Figure 3.1).

Population increase on the Kapiti Coast is well ahead of the national average (see Figure 3.2). Whilst urban growth is currently restricted to the main centres, large blocks of land in the Te Hapua area have been subdivided a number of times since the early 1990s into smaller 'lifestyle blocks'. The impact of this disturbance was discussed earlier in this section. In January 2010 the Coastal groundwater zone was 8% allocated. Conversely, the neighbouring Waikanae groundwater zone was 86% allocated (data retrieved via personal communications with Wellington Regional Council, February 12th 2010). Given this, a question remains about how to meet future water requirements for the growing population.

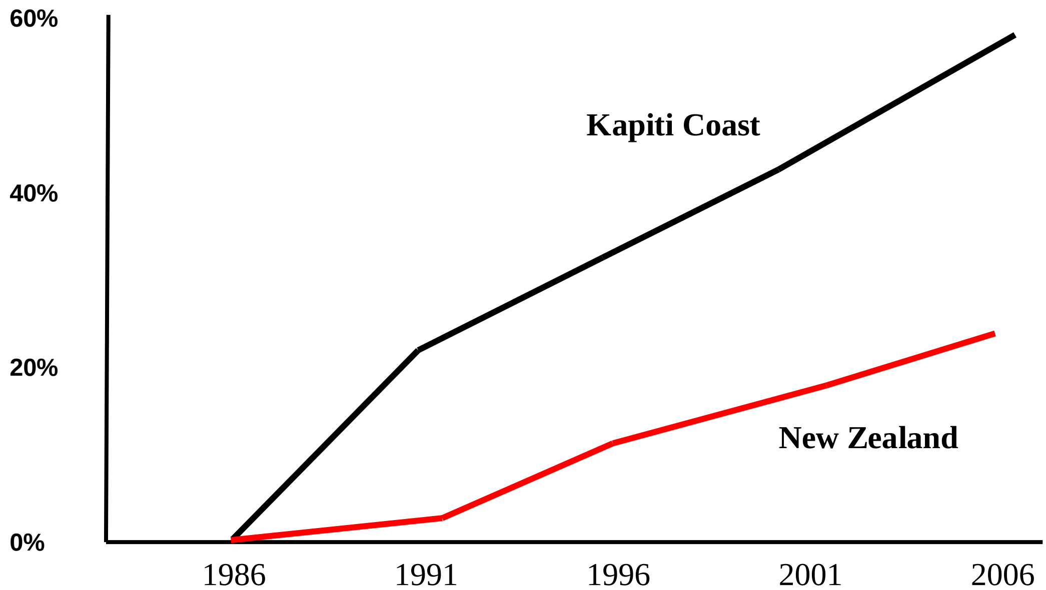


Figure 3.2: Population growth on the Kapiti Coast and in New Zealand from 1986 to 2006 (Statistics NZ, 2006).

3.2 Geology

The north – south oriented Tararua Ranges are the result of uplift created from the convergence of the Indo-Australian and Pacific plates (Begg & Johnston, 2000). Extensive folding and faulting of the 190 – 240 million year old greywacke and argillite basement rock has taken place producing a series of ridges and valleys that climb to a maximum elevation of over 1500m (Heron & Van Dissen, 1992; Hughes, 1997).

The geomorphology and underlying depositional sequence of the Kapiti Coast is the product of geological processes during the quaternary period (the last 2 million years), in particular the past 300,000 years during which three distinct glacial periods have been identified (Hughes, 1997). These periods were interspersed with warm interglacial / postglacial periods and associated changes in sea level, together defining the dominant depositional processes and resultant hydrogeology.

During cold periods, water accumulated in vast ice sheets in mountainous areas, dropping sea levels by up to 200m below their present point (Hughes, 1997). As sea level dropped, fine marine sand and silts were transported by the prevailing westerly wind and deposited as loess (Heron & Van Dissen, 1992). High rates of erosion dominated the Tararua Ranges as glaciers carved their way down valleys and vegetation receded given the cold alpine climate (Heron & Van Dissen, 1992). The large volume of glacial derived sediment, frost-shattered scree and silt was transported toward the coast accumulating in poorly sorted alluvial fans and river flood plains – see Unit X Figure 3.3 (Heron & Van Dissen, 1992; URS, 2003)

During the warm interglacial periods glaciers melted and vegetation returned to cover bare rock surfaces. This greatly reduced erosion and hence sediment and silt transport to rivers (Kampman & Caldwell, 1985). Major rivers were then able to entrench the underlying alluvial layer and worked to sort sediments on river floodplains (Morgan & Hughes, 2001). The re-working of glacial period outwash sorted sediments with finer material being deposited downstream – possibly beyond the area where they had been deposited by glacial outwash. The end result was higher permeability in outwash zones near major rivers (WRC, 1994). This sequence of events created a depositional environment with good potential to form permeable water bearing layers (Kampman & Caldwell, 1985). As sea levels rose, layers of fine marine sand, clay and peat were deposited on the fluvial sediments and sand, silt and clay accumulated along the coastal zone (Kampman & Caldwell, 1985). High interglacial sea level eroded into alluvial fans left by previous glaciations forming interglacial cliffs (Figure 3.3). The layering process continued as subsequent glacial periods deposited further layers of alluvial material on top of the marine sand layers (Heron & Van Dissen, 1992).

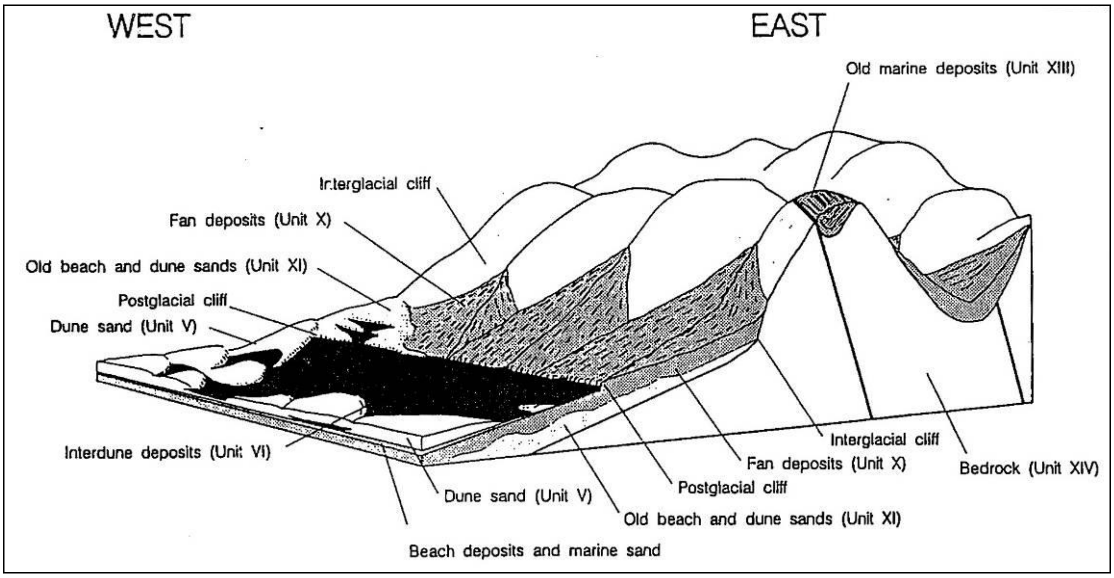


Figure 3.3: Distribution of main deposits of the Kapiti coast (Hughes, 1997).

In more recent times, the end of the last glacial period approximately 14,000 years ago allowed sea levels to rise and rivers to rework and entrench fluvial fans and terraces (Kampman & Caldwell, 1985). By about 6500 years ago the sea had encroached as far as 3.6 km inland from its current position and eroded the base of alluvial fans and glacial deposits (Unit X, Figure 3.3) to form postglacial sea cliffs and a marine terrace that can be traced along the entire coastal plain from Paraparaumu to Otaki (Heron & Van Dissen, 1992; Morgan & Hughes, 2001). Note also Unit VI, the '*inter-dune deposits*' which are defined as low lying areas between dunes where the water table is close to the surface and vegetation growth facilitates the development of peat soils.

A steady supply of sediment from major rivers on the coast and tectonic uplift combined to naturally prograde the coastline to form what is now known as the coastal plain (Kampman & Caldwell, 1985). By about 5000 years ago the coastal boundary had expanded to its present state, leaving deposits of marine and aeolian sands across the coastal plain up to 50m thick (Morgan & Hughes, 2001). This sits on top of the layers of unsorted glacially derived alluvial deposits, interglacial marine sediments, and well sorted interglacial fluvial sediments, together forming a maximum thickness of 165m (Heron & Van Dissen, 1992). It is this alternating sequence of fluvioglacial and alluvial gravels that make up the aquifers of the Kapiti Coast. Figures 3.4 and 3.5 show the approximate layers of sediment in a cross section near Te Horo, 2 km north of Te Hapua Wetland (Kampman & Caldwell, 1985).

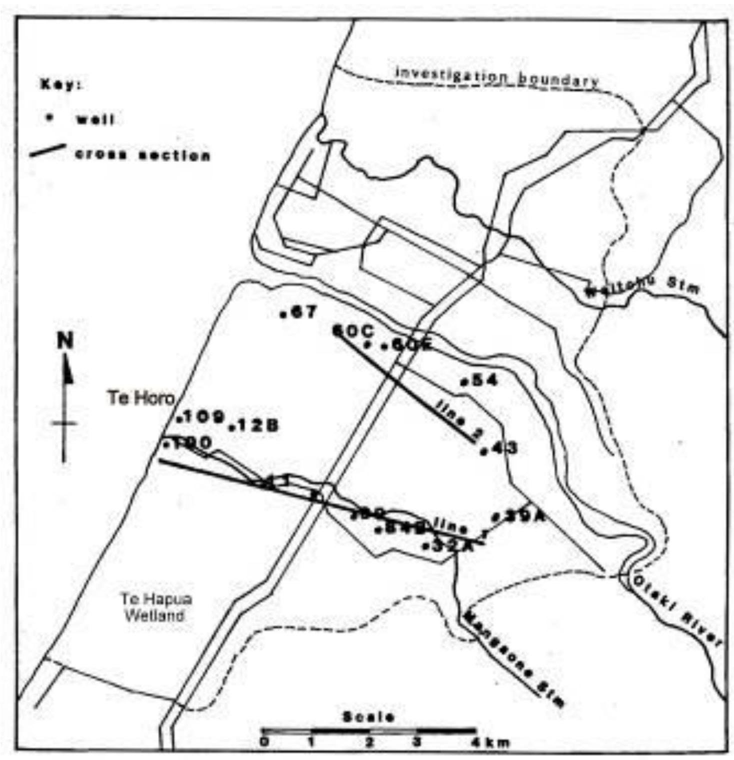


Figure 3.4: The position of cross sections. Te Hapua wetland is approximately 3km south of Te Horo. (Kampman & Caldwell, 1985).

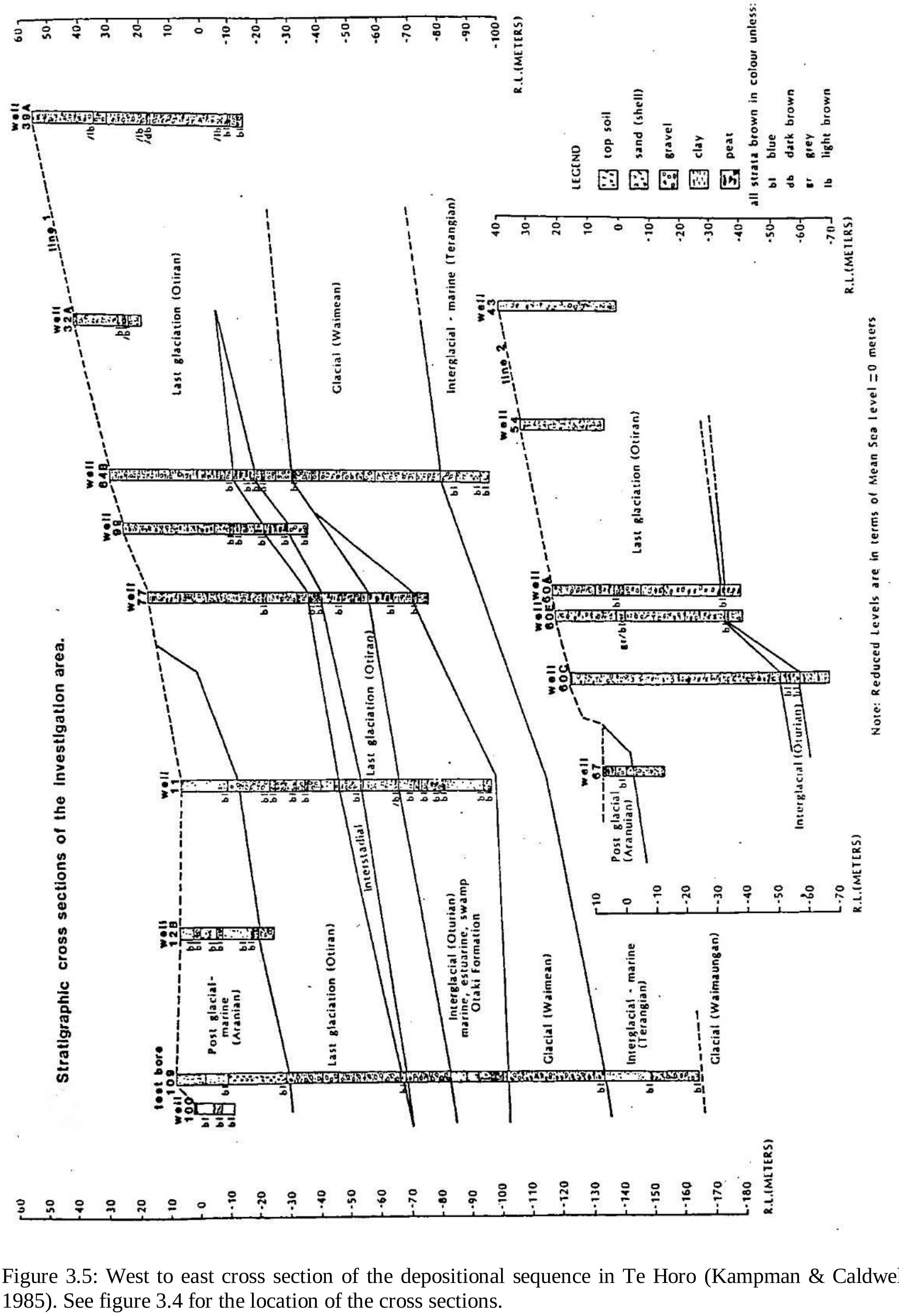


Figure 3.5: West to east cross section of the depositional sequence in Te Horo (Kampman & Caldwell, 1985). See figure 3.4 for the location of the cross sections.

Dunes developed on the coastal plain, the tallest of which are 20m above surrounding flat lands (Heron & Van Dissen, 1992). It was in low lying areas between these dunes that conditions allowed the development of wetland areas (also known as inter-dune deposits – Unit VI Figure 3.3). The thickness of the deposits varies along the coast, but is generally a layer of peat between 1 and 4m thick with high water content (Moar 1954). Whilst Moar (whose study looked at peat bogs in Plimmerton, approximately 35km south) did not specify what "high" was, wetlands can have unsaturated soil moisture content of up to 90% when the water table is high (Campbell & Jackson, 2004). When the water table is low peat can have a moisture content as low as 14-30% (Campbell, et al., 2002). Peat significantly shrinks and swells depending on the water content, which equates to peat soils being vulnerable to irreversible shrinkage and compaction after being drained and grazed with agriculture (McLay, et al., 1992).

The peat layers are not always at the surface – a borehole in Te Horo had a 2.5m thick silty-peat layer at a depth of 5m overlain by aeolian dune material (Kampman & Caldwell, 1985). When dunes are stabilised with vegetation, peat soil may develop in low lying inter-dunal areas where water accumulates (see Chapter II). When dunes become unstable, for example if vegetation is removed or dunes are eroded, sand blows over the peat soils to form new dune systems and perched peat / soil layers (McFadgen, 1997).

3.3 Hydrogeology

Groundwater levels follow seasonal fluctuations in rainfall (see table 5.1 and figures 4.2.2 to 4.2.9, Chapter V for seasonal fluctuations in rainfall and groundwater level). Groundwater recharge comes from direct rainfall on the coastal plain as well as infiltration through alluvial fans that have formed between the Tararua foothills and flat lands. Major surface water sources such as the Otaki and Waikanae rivers (see Figure 3.6) are thought to be hydraulically connected to shallow groundwater *(Morgan & Hughes, 2001)*. Te Hapua wetland is considered to be outside of this zone of surface water influence (Preece, 2005). Close to the Tararua foothills groundwater levels vary by as much as 8 to 9m. Coastal areas show fluctuations of less than 1m. Permeability increases toward the coast, as does the degree of channelised groundwater flow (WRC, 1994).

Reynolds (1992) defined the groundwater zones of the Kapiti Coast into areas of similar hydraulic character by comparing patterns of postglacial re-worked gravels (Figure 3.6). There are six zones in total – Waitohu, Otaki, Hautere, Coastal, Waikanae and Raumati / Paekakariki (Reynolds, 1992). The Te Hapua wetland complex sits towards the southern end of the ‘Coastal Zone’. The eastern edge of the coastal zone follows the line of the post glacial sea cliff and State Highway 1 northward, where it ends at the terrace on the edge of the Otaki river zone.

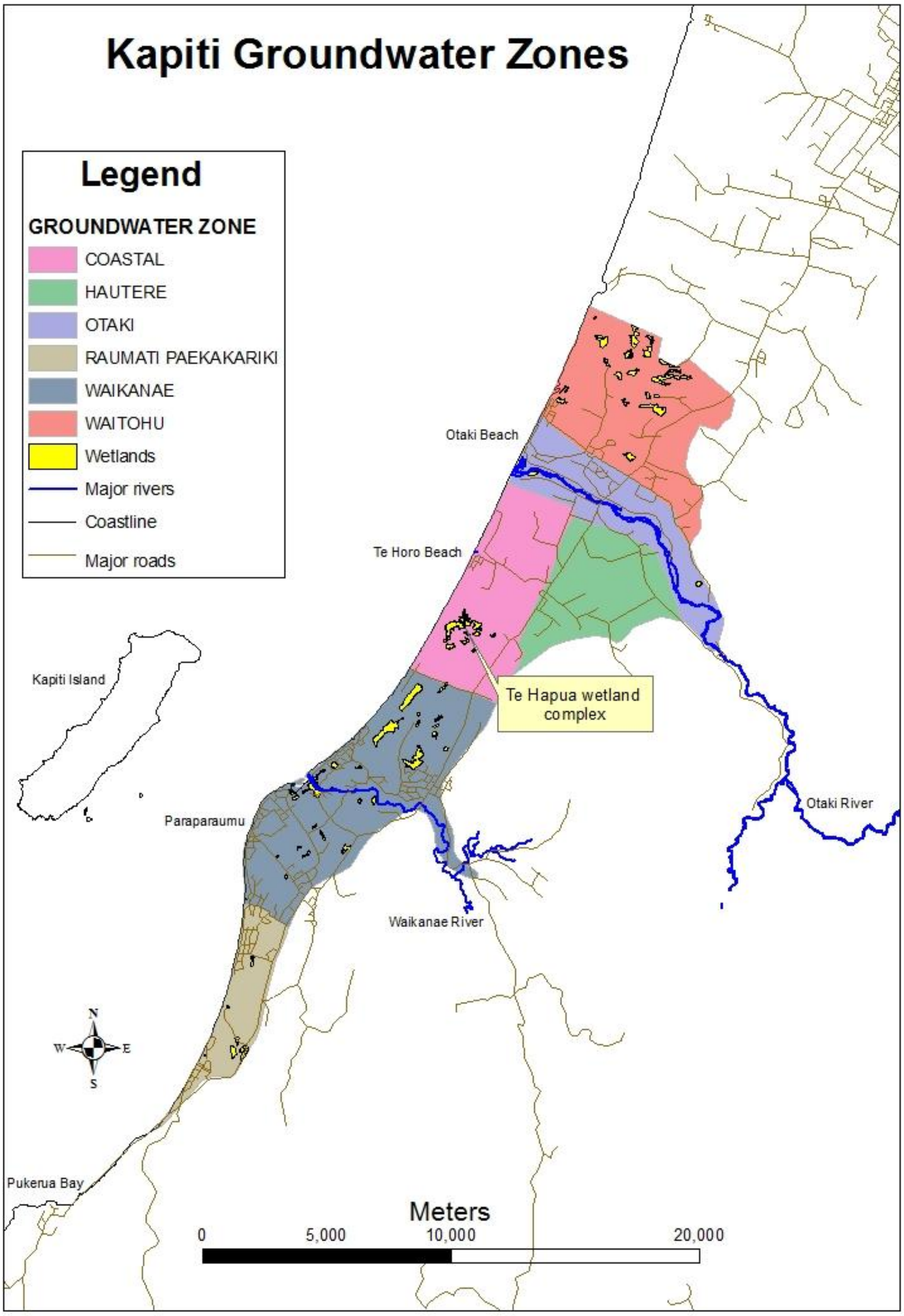


Figure 3.6: Kapiti Groundwater Zones (adapted from Hughes 1997)

The Coastal Groundwater Zone extends from the terrace beside the Otaki River in the north, to Peka Peka and Hadfield Roads in the South. The eastern boundary follows the line of the 6500 year sea cliff (where it meets the Hautere Zone) before crossing State Highway 1 and heading south at the base of the foothills (WRC, 1994).

As a result of the geological and paleo-climatic history, a stratified aquifer system has developed in the Coastal Groundwater Zone. Figure 3.7 is a bore log from Te Horo which shows and describes the aquifers present. The sequence of poorly sorted fluvioglacial sediments, re-worked alluvial gravels (deposited during inter-glacials), marine sands, silts, clays and accumulated interdunal peat, together combine to present four main aquifers in the Coastal Groundwater Zone (Jones, 2002; WRC, 1994). These four aquifers, described below, are underlain by a greywacke basement (Unit XIV, figure 3.3).

Table 3.1: Kapiti Coast aquifer depth and sediment type (WRC, 1994).

Aquifer Name	**Depth (m below ground level)**	**Dominant sediment**
Surface Aquifer (unconfined)	5 to 30	Sand and gravel
First Confined Aquifer	35 to 56	Gravel (overlaid with silt, clay and sand)
Second Confined Aquifer	100 to 107	Sand and gravel
Third Confined Aquifer	164 to 172	Gravel

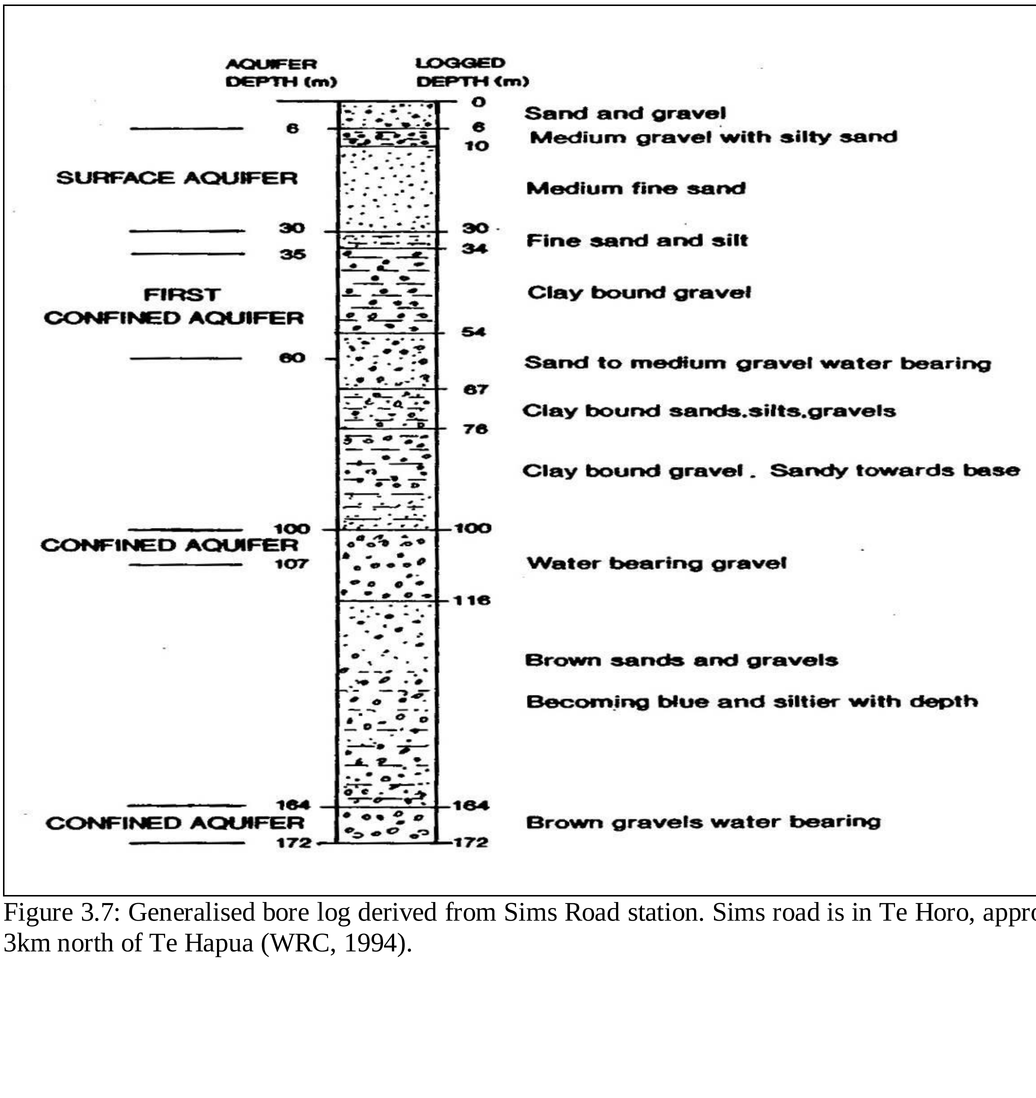


Figure 3.7: Generalised bore log derived from Sims Road station. Sims road is in Te Horo, approximately 3km north of Te Hapua (WRC, 1994).

3.4 Hydraulic Properties

Recharge to the shallow unconfined aquifer comes largely from local rainfall (Cussins, 1994; Kampman & Caldwell, 1985). Cussins (1994) calculated rainfall recharge to the shallow unconfined aquifer of the Otaki – Te Horo area by taking into account evaporation, runoff, hydraulic conductivity, transmissivity and hydraulic gradient. His estimate was that approximately 27% of incident rainfall recharges to groundwater. A quarter of this recharges to the shallow unconfined aquifer, the rest percolating down to deeper layers (Cussins, 1994). This equates to an average daily volume of 17,800m^3/day of rainfall recharge to the shallow aquifer in the coastal zone. This compares to a similar study in Waikanae where up to 25% of local rainfall was estimated to recharge the shallow aquifer (Reynolds, 1992).

Nine springs and through-flow from the neighbouring Hautere aquifer also contribute to recharge in the shallow unconfined aquifer, but this may slow or stop during dry periods (WRC, 1994). The details of this have not yet been studied. There may also be recharge from upward leakage via the 172m aquifer (WRC, 1994). Adjacent bores at Te Horo beach (one at 60m and one at 172m) showed that hydraulic head is higher in the deeper confined aquifer – where groundwater level was up to 1.5m higher above sea level in the 172m bore compared to the 60m bore (WRC, 1994). This may indicate upward leakage from deeper aquifers into overlying layers as water is pushed down and out from the mountains (Kampman & Caldwell, 1985).

There is anecdotal evidence of occasional surface water input from the Mangone Stream, but there is generally thought to be no regular flow of surface water into the wetland or nearby shallow groundwater (Preece, 2005).

Given a low hydraulic gradient throughout the north-westward sloping Coastal Groundwater Zone, groundwater moves slowly away from the Tararua foothills toward the sea (see Figure 3.8) (WRC, 1994). Salt water tracer tests found velocities in the shallow unconfined layer of less than 0.1m / day (Cussins, 1994). Velocities in the confined layers are thought to be an order of magnitude higher (Cussins, 1994), possibly due higher transmissivity (see table 3.2) and increased hydraulic head found in the deeper aquifers which are recharged from waters higher in the hills.

Wells north of Te Horo Beach road are relatively low yielding (regardless of depth) with transmissivities of less than 100m^2 /day. Toward the southern end of the coastal zone wells situated in the 40-50m deep gravels have a slightly higher yield of up to 200m^2/day (WRC, 1994), but are generally low – especially toward the coast. Measured and interpolated transmissivities are displayed in figure 3.9. Wellington Regional Council has calculated the transmissivity and storage coefficient for each aquifer in the coastal zone. These are summarised in Table 3.2.

Table 3.2: Aquifer parameters calculated by Wellington Regional Council for the four aquifers in the coastal groundwater zone (WRC, 1994).

Aquifer Depth (metres)	Transmissivity (m^2/day)	Storage Coefficient
5-30	10	0.3
35-56	120	5 x 10^{-4}
65-110	170	3 x 10^{-4}
164-172	150	1 x 10^{-4}

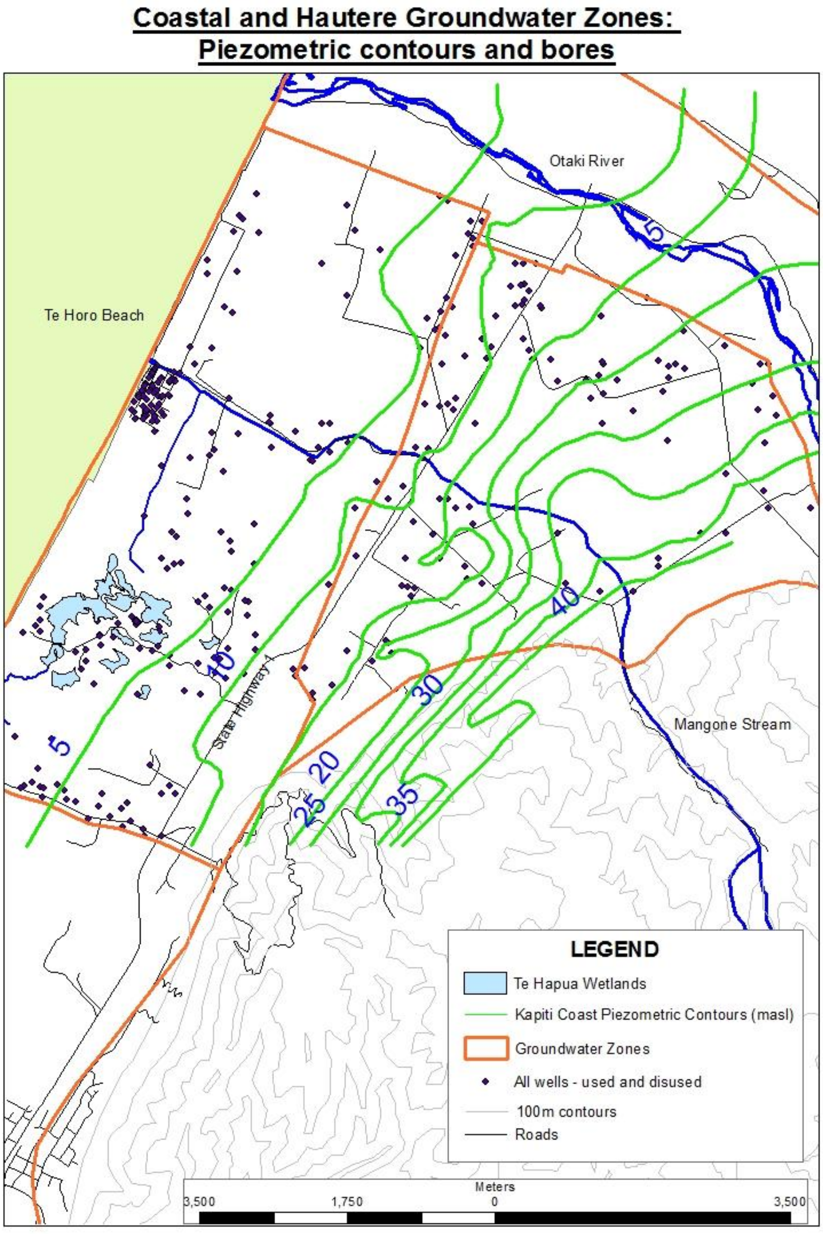


Figure 3.8: Groundwater piezometric contours for Hautere and Coastal Groundwater zones (WRC, 1994)

Given the low hydraulic gradient in the coastal groundwater zone, through-flow is also relatively low. Table 3.3 summarises estimated through-flow for each of the aquifers.

Table 3.3: Through-flow and Safe Yield Estimates for Aquifers in the Coastal Groundwater Zone (WRC, 1994)

Aquifer Depth (metres)	Through-flow (m^3/day)	Estimated Safe Yield Range (m^3/day)
5-30	200	200-12000
35-56	2200	2200-8000
65-110	3000	3000
164-172	2700	2700

Also displayed in Table 3.3 is the estimated safe yield for each of the aquifers. These are maximum rates only as abstraction is usually limited by the local drawdown at the well (i.e. defined by the surrounding geology). Well drawdown is important as transmissivities are often very low, especially in the shallow unconfined aquifer (WRC, 1994).

The assumed maximum 'safe yield' of groundwater from the coastal groundwater zone is 25,700 m^3 per day (6,917,000 m^3 per year) (WRC, 1994). 8% of the safe yield is currently allocated to 8 individual resource consent holders (these data were supplied via personal communications with Wellington Regional Council in June 2009). The consent holders have stakes of between 34m^3 per day and 1900m^3 per day that can be used for irrigation or household purposes, up to the amount stipulated on the consent.

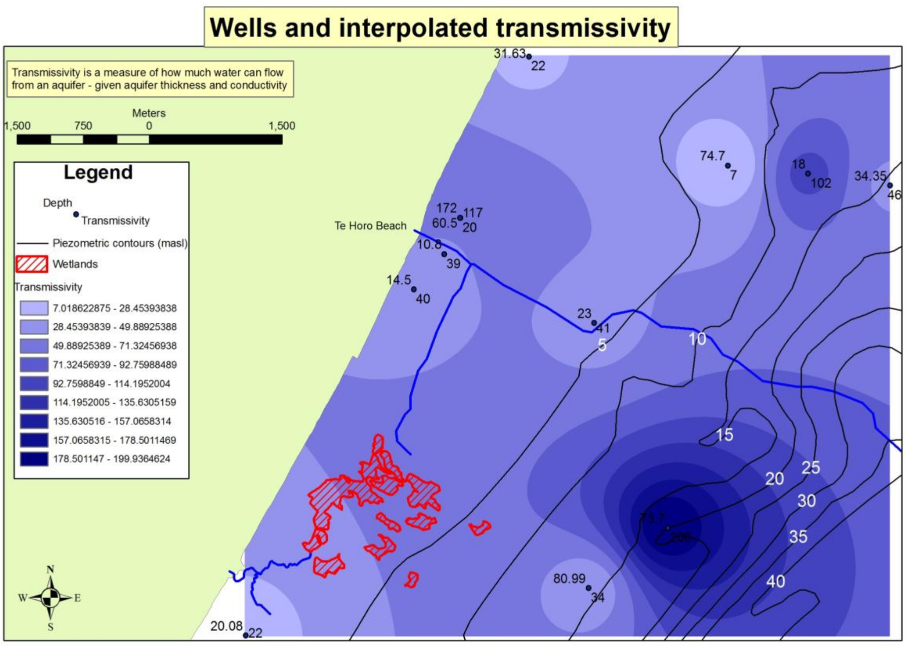


Figure 3.9: Inverse Distance Weighted interpolation for transmissivity measurements for the region. The expected transmissivity in the aquifers below Te Hapua is between 28.45 and 71.32. Produced using data supplied by Wellington Regional Council, May 2009).

The hydraulic properties of dominant local soils are also relevant to wetlands, especially with regard to recharge from local rainfall. Table 3.4 outlines the properties of soils found close to Te Hapua wetland. Figure 5.3.3 in chapter V shows the distribution of soil types around the wetland.

Table 3.4: Characteristics of soils surrounding Te Hapua wetlands (Law, 2008; McFadgen, 1997; Palmer & Wilde, 1990)

Soil Type		**Waitarere Series**	**Motuiti Series**	**Foxton Series**	**Omanuka Series**
Accumulation began		150 to 400 years BP	900 years BP	6500 years BP	N/A
Parent Material		Quarto-feldspar wind blown sand of greywacke origin. Pumice.	Quarto-feldspar wind blown sand of greywacke origin	Quarto-feldspar wind blown sand of greywacke origin	Organic
Texture		Coarse	Coarse	Coarse	N/A
Permeability		Very Rapid	Rapid	Rapid	Moderately rapid
Soil Drainage Class		Excessively drained	Somewhat excessively drained	Somewhat excessively drained	Very poorly drained
Flooding		Nil	Nil	Nil	Ponding
Total Porosity	**Topsoil**	Moderate	Moderate	High (60%)	Very High (75-92%)
	Subsoil	Moderate	Moderate	Moderate (50%)	Very High (75-92%)
Macro-Porosity	**Topsoil**	High	High	Moderate	Very High (17-30%)
	Subsoil	High	High	Very high	Very High (17-30%)
Water holding capacity		Low	Low	Low to moderate	N/A

Six main soil types are found in the Coastal Groundwater Zone. Three of these (Waitarere, Motuiti and Foxton) are derived from sand of various age and together cover around 60% of the Coastal Zone (Cowie, 1963; Wilson, 2003). The fourth dominant soil type is Omanuka, which covers 35% of the Coastal Zone. This soil is derived from inter-dunal swamp and is therefore highly organic. The properties of these main soil types (table 3.4) play an important role in rainfall recharge within the Coastal Zone. Comparing the drainage class, Omanuka is quite different in that it is 'very poorly drained', whilst the sand based soils are 'excessively' or 'somewhat excessively drained.' Resistivity soundings conducted in Te Horo by Wilson (2003) found the Omanuka soils had relatively high earth resistivity readings. Further results from resistivity depth soundings suggested that the peat soils are widespread beneath the dunes, which may reduce or possibly inhibit infiltration to the shallow aquifer (Wilson, 2003).

3.5 Wellington Regional Council's Te Hapua Wetlands monitoring sites

Wellington Regional Council (in conjunction with Kapiti Coast District Council) installed four new wetland monitoring sites at Te Hapua in April 2009. Figure 3.10 shows the location of the four new sites. Three of the sites – Jill and Joy's, Shoveler and Pateke; have a shallow bore (down to around 6m), as well as a wetland pond level stage recorder. The locations for these sites were selected to give a spatial context for study. The site at Pateke has historically been used for data collection via 6 shallow bores and a pond stage, so a reasonable record already existed. The Jill and Joy's and Shoveler sites were chosen because they are on the western side of the complex which was known to have drainage patterns with water moving south and north respectively. Monitoring in the pre-existing deep bores (R25/5171 and R25/5262) was commenced at the same time as the wetland sites to attempt to gather data on relative water levels in the context of a layered aquifer system where leakage is possible but as yet undefined. The Trotters site measures pond stage only and was installed by GWRC to assess the influence of the culvert that joins Jill and Joys pond with Trotters beneath Te Hapua Road. Also pictured is a third deep bore nearby that has no monitoring equipment installed.

Appendix 8 provides a more detailed view of each site in the form of a TIN elevation map, as well as a profile of the land between the bore and pond stage sites.

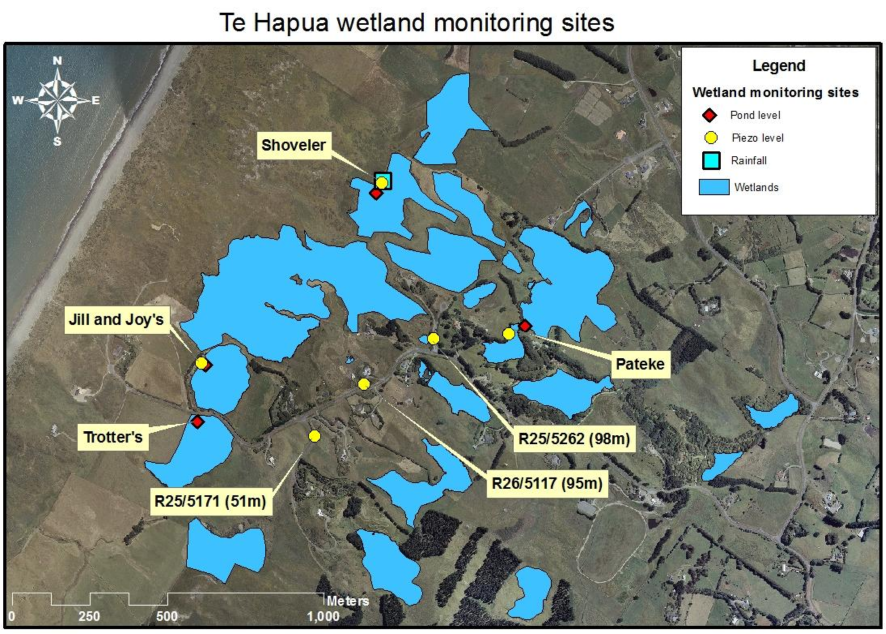
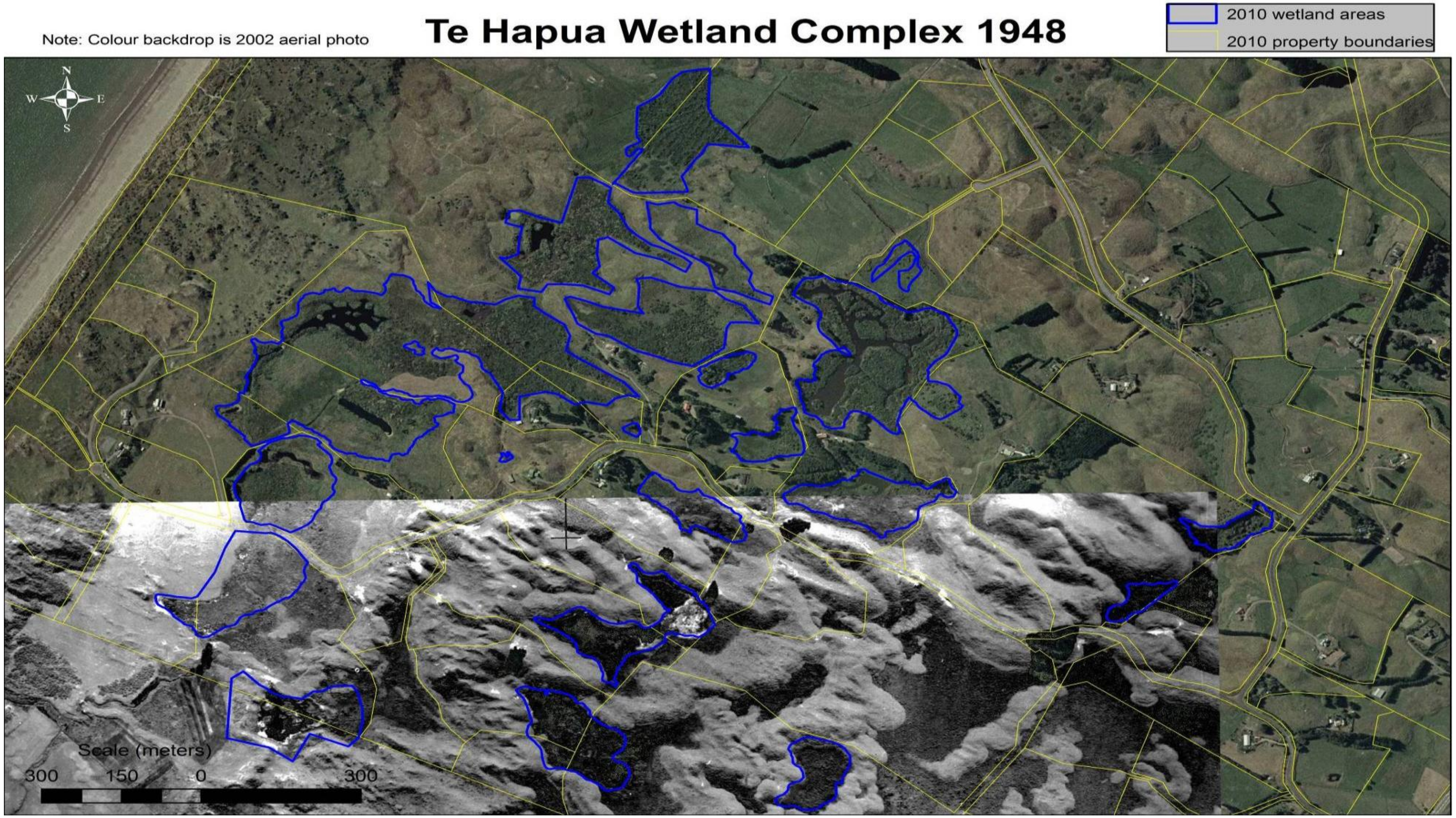


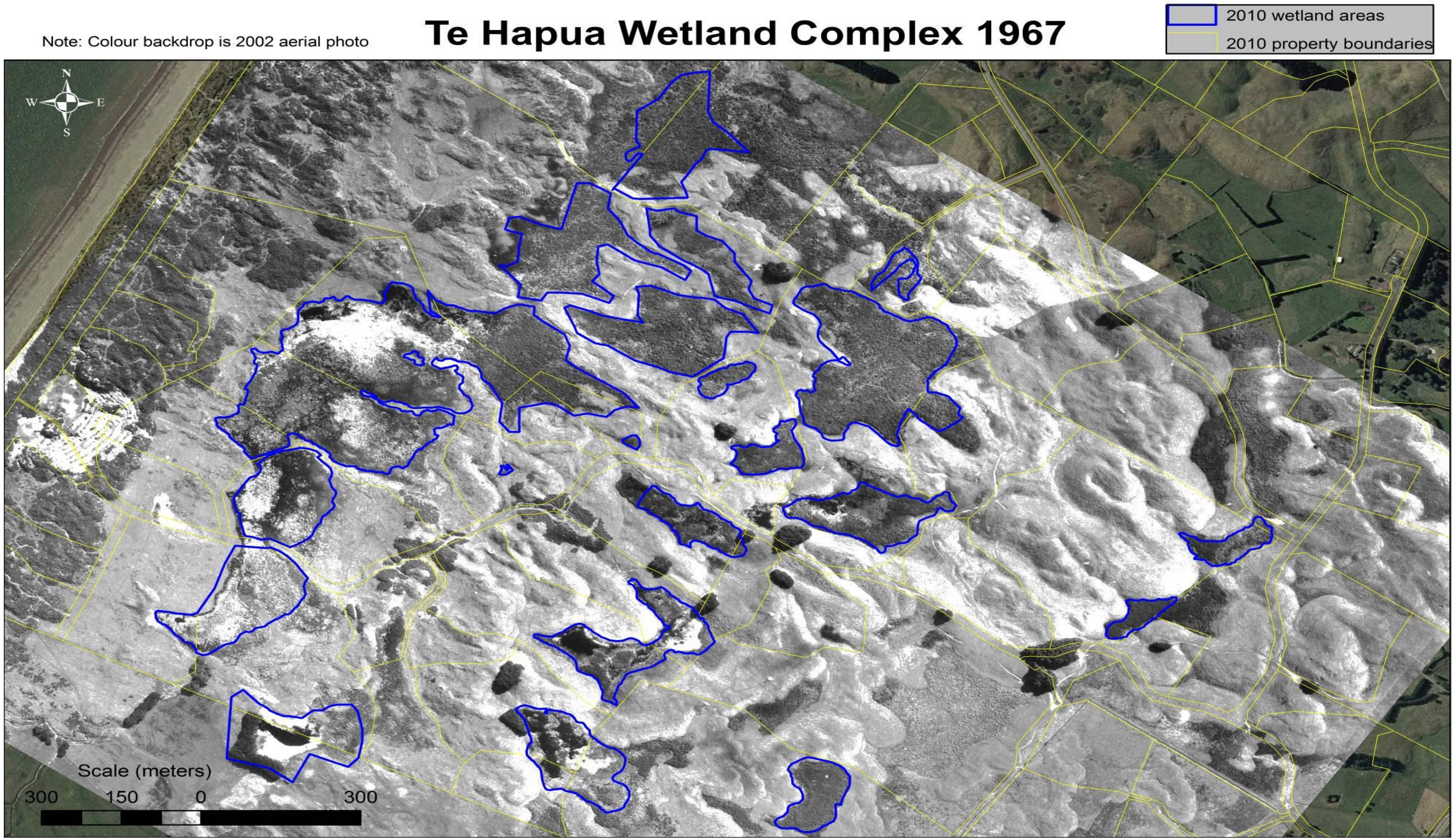
Figure 3.10: Locations of the three primary Te Hapua wetland monitoring sites (Shoveler, Pateke, Jill and Joy's). Trotters is a fourth pond stage site but was not used for this study. The three deep bores (R25/5171, R25/5262 and R26/5117) were used in conjunction with the main monitoring site data.

3.6 Historical Aerial Photo Series

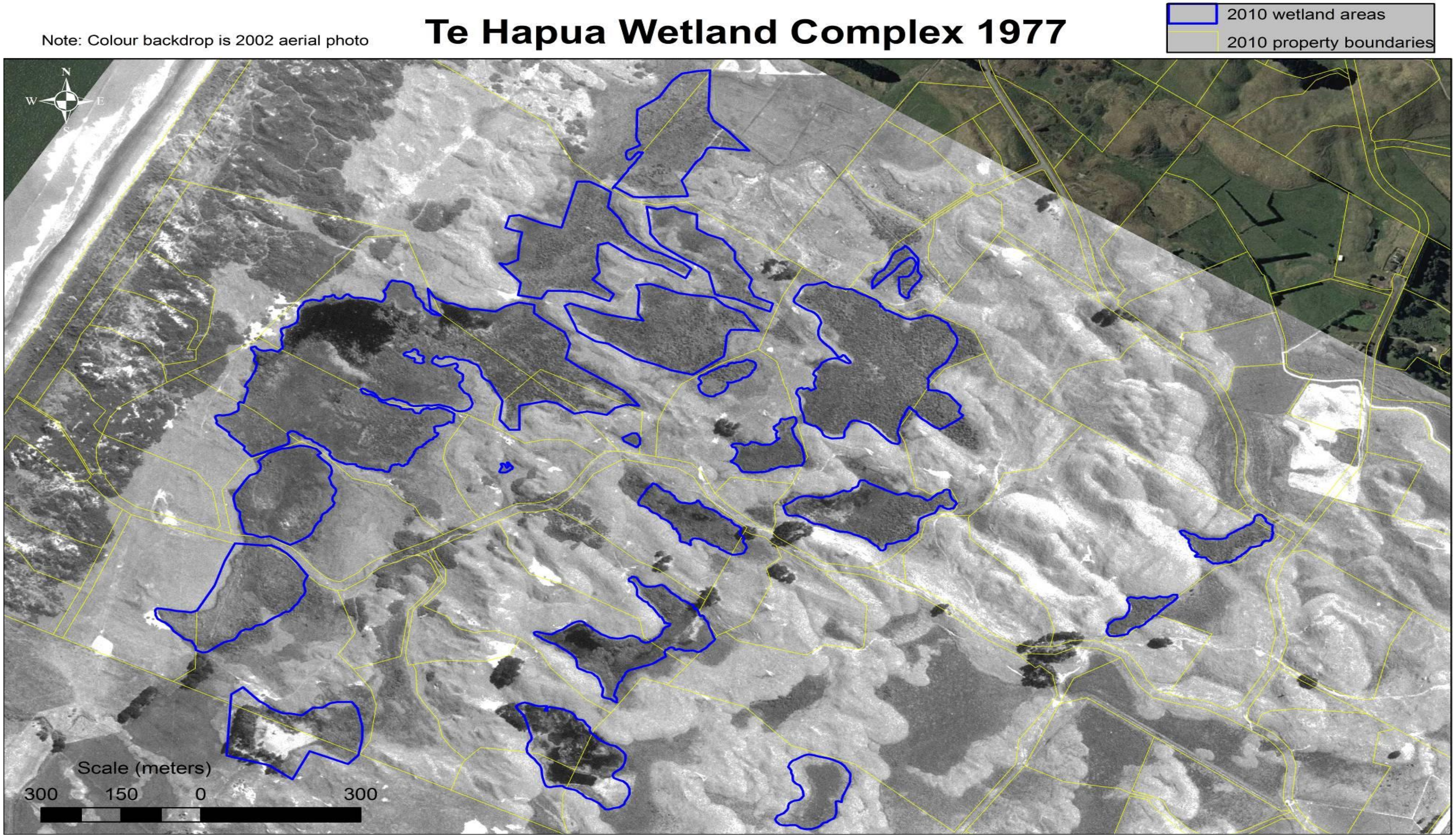
Aerial photographs from 1948, 1967, 1977, 1993, 2002 and 2007 are shown in the following pages. The approximate present day wetland extent is outlined in all of the images, so areas of wetland loss are visible in earlier photos where wetlands extend outside of these boundaries. Modifications relevant to the monitored wetlands are described in detail in chapter V, section5.2.1. Photos care of Jon and Gendy Stevenson.



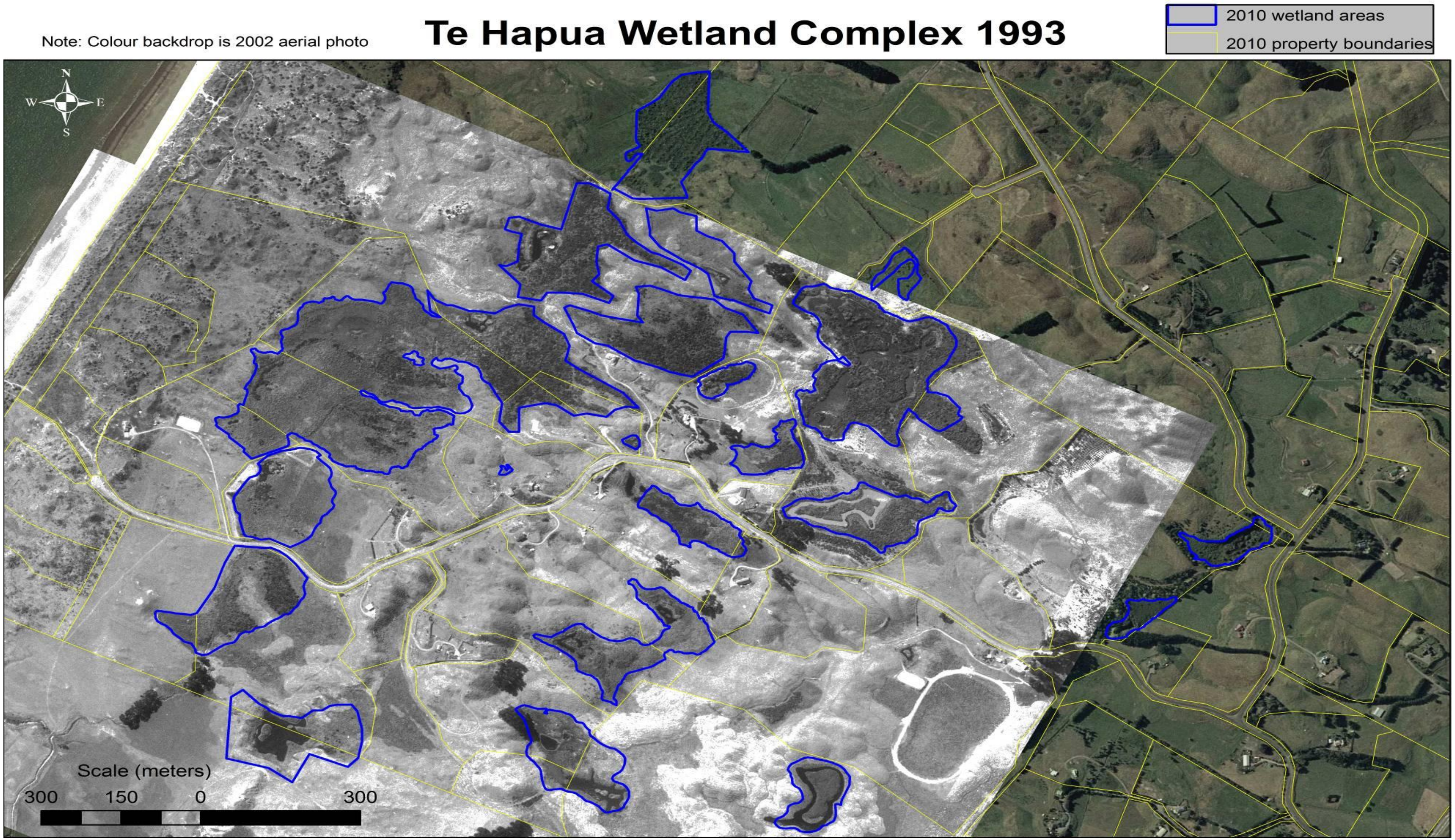
Te Hapua wetland complex 1948



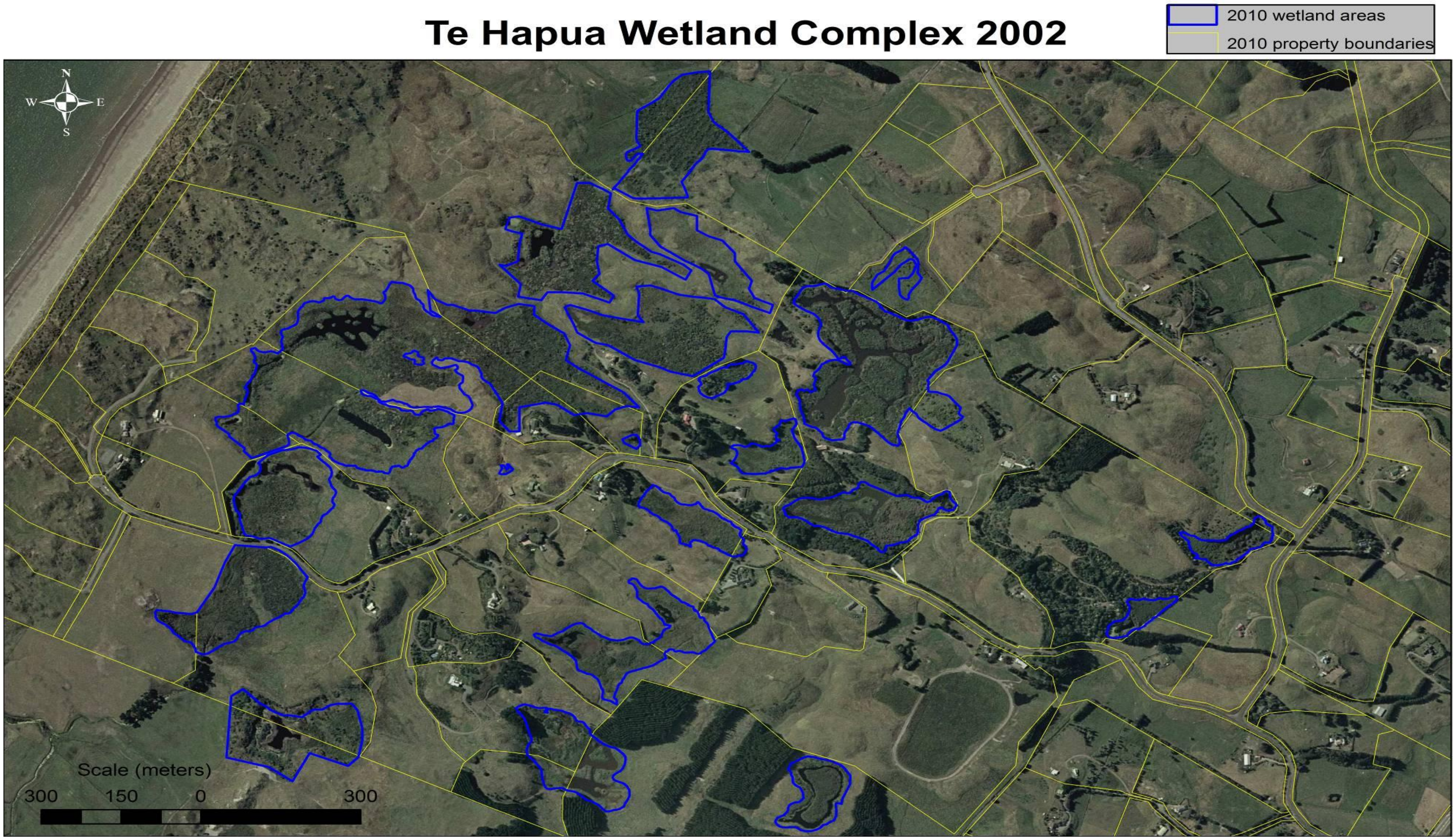
Te Hapua wetland complex 1967



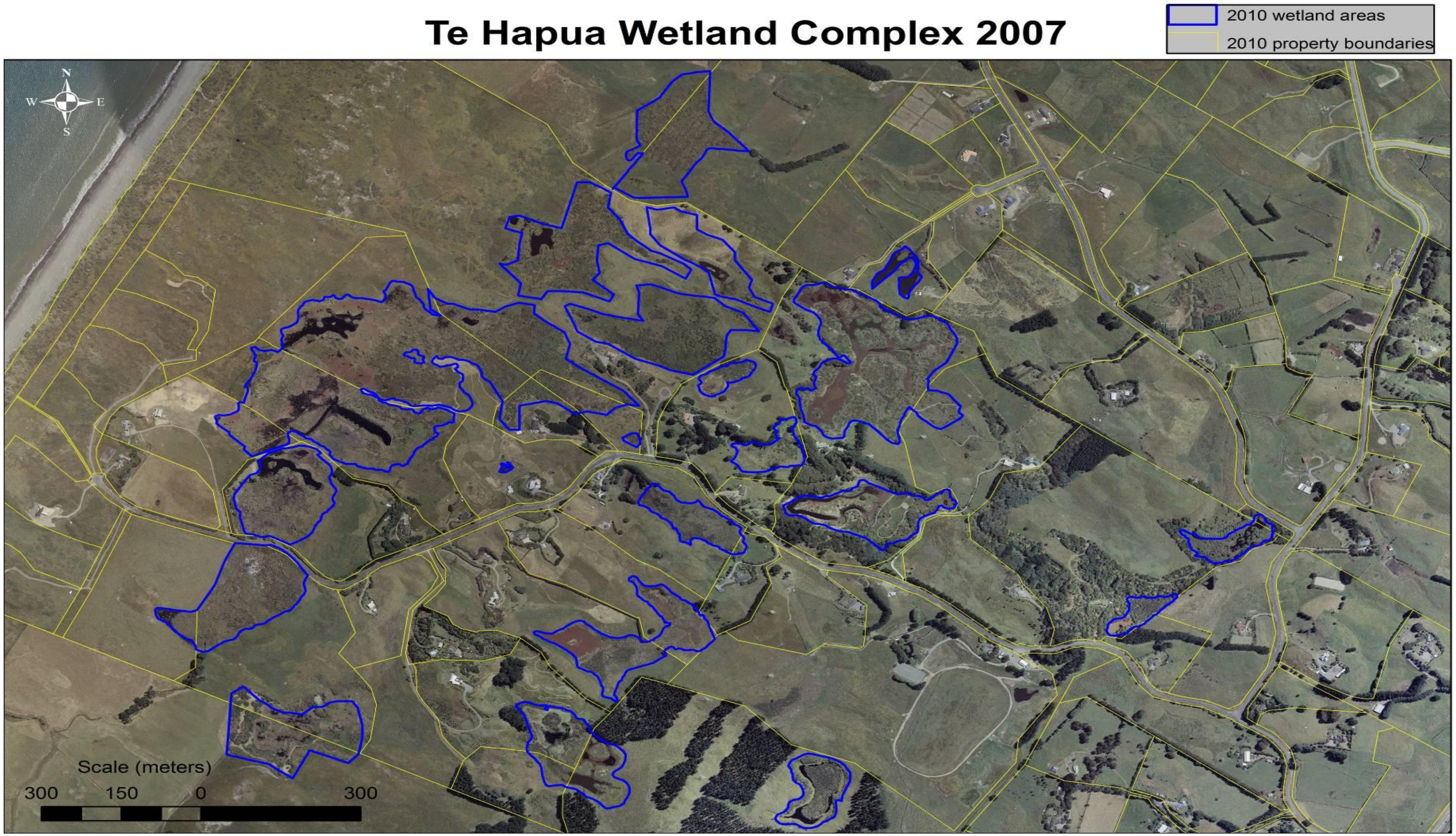
Te Hapua wetland complex 1977



Te Hapua wetland complex 1993



Te Hapua wetland complex 2002



Te Hapua wetland complex 2007

IV Results 1: Hydrology and climate of the wider region

4.1 Introduction

This chapter features an analysis of existing data to provide background information deemed important when considering the key questions and objectives of this study. Some of the literatures reviewed in chapters II and III have defined the 'region' differently. For the results and discussion that follow, the term 'region' refers to the area that includes both the Coastal and Hautere Groundwater Zones, as defined by Reynolds (1992) in figure 1.1. The Te Hapua complex is situated in the Coastal Zone; with the Hautere Zone adjacent to the east on the foothills of the Tararua Ranges. These zones therefore represent the most likely recharge area for shallow aquifers that underlie the wetlands and hence have the potential to influence surface water levels within the complex.

Section 4.2 describes the results of an analysis of regional groundwater data supplied by Wellington Regional Council and NIWA. First, 2009 rainfall data is compared to the historical average. The long term trends in groundwater levels are then analysed and temporal and spatial patterns are assessed. A geological cross section is drawn through the wetland complex using bore drill logs and the approximate position of the underlying aquifers deduced.

Section 4.3 looks at global climate change predictions from the IPCC Fourth Assessment Report as well as downscaled reports for New Zealand and the Kapiti Coast. Climate change is discussed in the context of threat to the hydrological cycle and wetlands.

4.2 Analysis of Existing Data

4.2.1 Rainfall Analysis

The closest reliable long term rainfall record to Te Hapua is from the Paraparaumu Airport climate station which has been recording climate data since 1951. The site is 13km south west of Te Hapua wetlands and is at a similar distance from the coast but closer to the mountains by 1km. A new rain gauge was installed at the Te Hapua (Shoveler) site on March 30th 2009. Daily rainfall in Paraparaumu correlates reasonably well with Te Hapua rainfall records, with an R-Square value calculated at 0.82. However the record from Te Hapua is less than one year long, so it is uncertain how representative the 2009 data is of the local long term average[5].

The Te Hapua rainfall recording site uses a tipping bucket rain gauge (model number OSK 15180T) connected to a Campbell Scientific datalogger. One disadvantage of this rain gauge model is that rainfall is recorded in increments of 0.5mm. A source of error can therefore be attributed to the data for rainfall events that were less than 0.5mm, as they will not be recorded. If the rain stops before the bucket tips, some may be lost to evaporation (Ward, 1967). Another possible source of error occurs during heavy rainfall events, when the bucket tips several times per second (World Meteorological Organisation, 1994). The number of bucket tips per second varies from gauge to gauge, but the level of accuracy for model used is estimated to be within 2% at a rainfall rate of 100mm/hr (NIWA, 2010). At a rainfall rate of 150mm/hr the gauge will under-read by approximately 2.5%.

The Paraparaumu rainfall data is collected and read manually with a measuring glass graduated at 0.1mm. Given that the Te Hapua gauge can only measure to 0.5mm, error will be introduced when using one to infer the other. Also, glass beakers can be easily misread or the sample spilled.

Table 4.2.1 and figure 4.2.1 summarise the average monthly and annual rainfall for Paraparaumu from 1951 through to 2009, as well as monthly rainfall from Paraparaumu and Te Hapua for 2009. Overall, 2009 was slightly drier than usual, Paraparaumu receiving 97% of the historical average. Autumn and winter rainfall at Paraparaumu was relatively low, receiving 21.7% less than the historical average (April through August). Rainfall at the Te Hapua site over the same period was 34.2% less than Paraparaumu’s

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[5] The R-Square value was calculated using data from March 30th 2009 to January 30th 2010.

historical average. Spring and early summer was much wetter than winter. Paraparaumu received 27.1% more rain than the average, whilst Te Hapua received 32.9% more than the Paraparaumu historical average.

Table 4.2.1: Rainfall Summary for Paraparaumu Airport and Te Hapua (mm). (Data retrieved from the NIWA Climate Database and Wellington Regional Council (January 2010).

	JAN	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**Annual**
Paraparaumu Aero Average 1951-2009	70.7	63.3	72.9	75.7	96.7	103.9	105.7	90.6	83.4	101.4	86.1	84.4	**1034.8**
Paraparaumu Aero 2009	33.7	122.8	25.6	57.6	97.5	41.8	56.1	117.1	92	147.6	106.2	105.8	**1003.8**
Te Hapua 2009	N/A	N/A	N/A	63.0	91.0	49.0	67.0	41.0	112.5	127.0	93.5	139.0	N/A
Paraparaumu 2009 Vs Average (%)	47.7	194.0	35.1	76.1	100.8	40.2	53.1	129.3	110.3	145.5	123.3	125.4	**97.0**
Te Hapua 2009 Vs Paraparaumu Average (%)	N/A	N/A	N/A	83.3	94.1	47.1	63.4	45.3	134.9	125.2	108.6	164.8	N/A

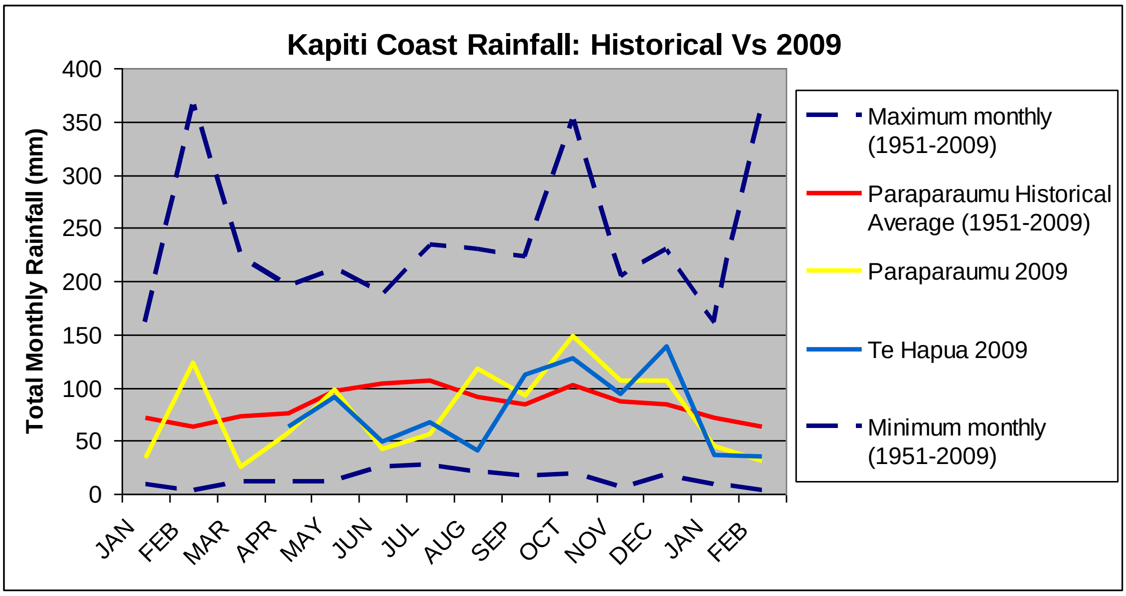


Figure 4.2.1: 2009 monthly rainfall at Te Hapua and Paraparaumu airport compared to the Paraparaumu maximum, minimum and average monthly rainfall between 1951 and 2009.

4.2.2 Long term trend in groundwater levels across the region

17 of the region's bores with records spanning 5 years or more were analysed for long term trends in water level. These were plotted with trendlines and 95% confidence intervals, giving approximate total and annual rise / fall. Table 4.2.2 summarises the average annual rise / fall for each of the 17 bores. Four of the bores showed a significant increase in water level (see blue text on table 4.2.2). Four more bores showed a significant decline in water level (red text, table 4.2.2). Looking at table 4.2.2, the column labelled '% annual rise/fall of range' puts the amount of water level change

each bore has into context. These values were calculated by dividing the average annual rise / fall by the total range of values observed at the bore for the duration of the record (and then converted to a percentage). This is important because of the difference in seasonal fluctuation between bores close to the sea and bores nearer to the Tararua Ranges. For example, an average annual drop of 102.5mm at R25/5111 seems high compared to the 13.5mm annual drop found at R25/5100. However when adjusted for the much larger range at R25/5111, the annual drop is only 1.8%, compared to 1% at R25/5100.

Looking at figure 4.2.2, three of the four bores that show an apparent declining trend in groundwater level are within 1500m of the Te Hapua wetland complex. These are R25/5111, R25/5100 and R26/6747). Figures 4.2.4 through 4.2.11 show the water level and trend in bores that significantly rose or fell. Hydrographs for the 9 bores where groundwater level did not change significantly are displayed in Appendix 2.

A problem with some of these data and data analysis is that the length of the data record is not long enough to be able to robustly identify any medium or long-term trend in groundwater level that may be present. Also, some of the shorter records may not have enough data for a statistical trend analysis to confidently pick up the annual variation, giving an inaccurate trend line.

Table 4.2.2: Bore records for each of the four aquifers. Note bores with an average increase in groundwater level are in blue font; decrease are in red; and bores that have been steady or show no significant rise or fall at 95% confidence are in black font.

Aquifer	Bore #	# Years Sampled	Total rise / fall (mm)	Average annual rise/fall (mm)	Total range (mm)	% annual rise/fall of range
<35m	R26/6881(7.5m)	5	0	0	1304	0
	R25/5123 (13m)	16	+136	+8.5	3947	+0.2
	S25/5204 (22m)	8	+180	+22.5	1868	+1.2
	S25/5215 (21m)	12	-460	-38.5	9574	-0.4
	S25/5203 (20m)	7	-20	-3	5051	-0.1
	S25/5256 (30m)	16	-157	-10	9988	-0.1
35-60m	R25/5117 (49m)	7	+66	+9	2537	+0.4
	R25/5110 (47m)	3.5	+200	+33	2218	+1.5
	R25/5136 (41m)	7	+54	+9	3052	+0.3
	S25/5200 (46m)	16	+753	+47	12757	+0.4
	R25/5100 (48m)	8	-110	-13.5	1297	-1.0
	R25/5111 (49m)	16	-1643	-102.5	5691	-1.8
60-120m	R25/0003 (60m)	24	+20	+1	877	+0.1
	R25/5135 (93m)	27	-200	-10	3480	-0.3
	R26/6747 (69m)	27	-270	-10	2085	-0.48
120m+	R25/5152 (172m)	8	+85	+11	364	+3.0
	S25/5208 (192m)	17	-1143	-64	2790	-2.3

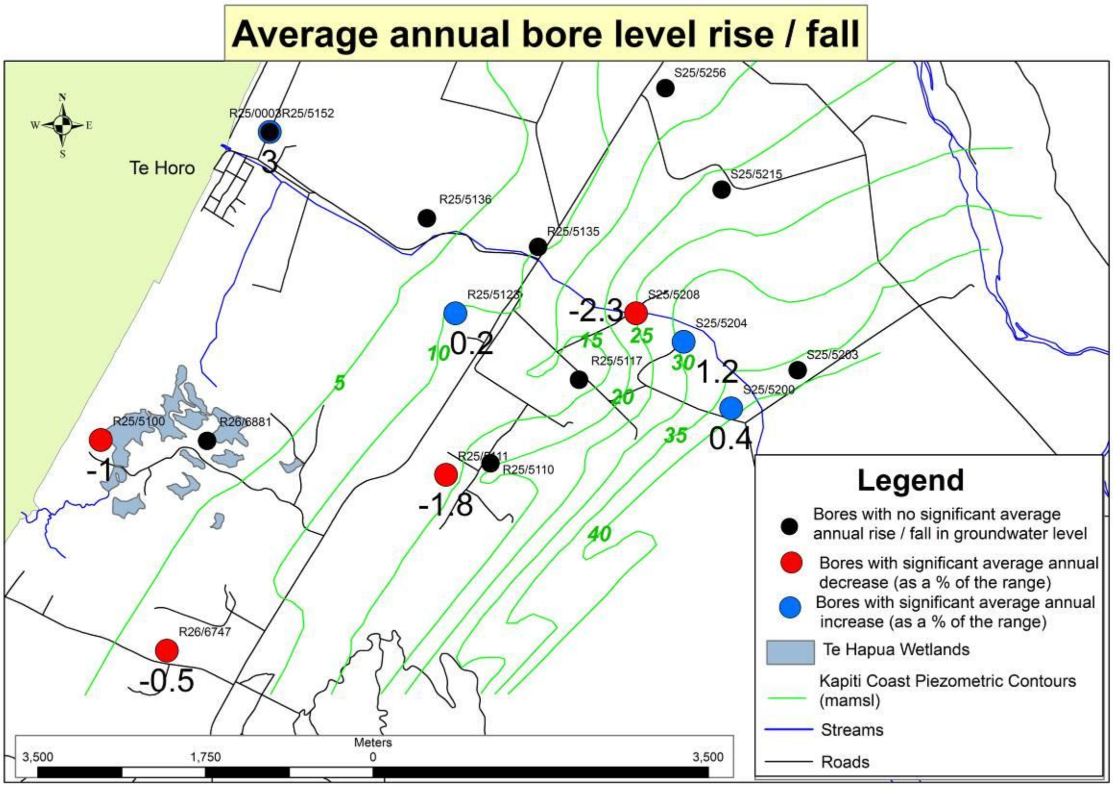


Figure 4.2.2: Bores in the area show a mix of falling and rising trends. There is no obvious strong spatial pattern, but three of the four bores closest to Te Hapua appear to be in decline.

Two of the six shallow bores (<35m) in the region showed significant change in groundwater level since 1993. Both of these were seen to increase annually by 0.2 to 1.2% of the range (figures 4.2.4 and 4.2.5). Both of these sites are close to the Mangone Stream. Three of the six bores in the first confined aquifer (35-60m) showed significant change in water level. Two of these were in decline (figures 4.2.9 and 4.2.10), and one was increasing (figure 4.2.6). One of the three bores in the second confined aquifer (60-120m) had a significant decrease in water level. This bore, R26/6747, dropped by 0.48% of the range annually (10mm per year). In the deepest confined aquifer (120m+), both bores showed significant change in water level. Water level in S25/5208 fell by 2.29% of the range annually (64mm per year) for 17 years (figure 4.2.8). The other deep well, R25/5152, rose 3.02% of the range annually (11mm) for 7.5 years (figure 4.2.7).

Explaining these trends is not easy given the limited length of the data set. The two deepest bores had the greatest change in water level across the region. This was the only obvious pattern in the data when comparing bores of different depths. The deepest bores penetrate deep regional flows that may be more likely to have long term cyclical flow patterns that cannot be recognised without a longer record.

Some patterns are apparent when looking at bores from all aquifers together (i.e. irrespective of depth). Shallow bores close to the Mangone Steam appear to show slightly rising groundwater levels. There are a number of possible explanations for this, including changes in precipitation patterns, changes in landuse and modification of farm drainage in the area. Any of these could induce an increase in stream volume and hence increase in shallow groundwater level.

One of the bores in the first confined aquifer, R25/5111, dropped 1643mm (1.8% of the range / 102.5mm per year; figure 4.2.10). Breaking this time series down however, it looks like this drop occurred almost entirely over one summer (1997-98). The hydrographs either side of this summer (i.e. 1993 to 1997 and 1998 to 2009) both show a gradually rising groundwater level (see figure 4.2.10b). The large drop observed in R25/5111 may be due to some small scale change in the local hydrology. It is possible that nearby land was drained. Conversations with both current and former local residents gave conflicting accounts regarding drainage of nearby wetlands at that time. Some residents recall an extended dry period that summer, yet rainfall records from Paraparaumu airport say otherwise (figure 4.2.10c). Regional council records do not note a change in the well casing depth at that time. Note that breaking down a time series in this way was done with caution, as one could split results to attempt a fit for a preferred conclusion. In this case however, the drop was observed in one bore only, so it is not likely to have been caused by natural variation. The only other bore with an obviously odd looking hydrograph was R26/6747 (figure 4.2.11). In this case there was a 9 year gap in the data with quite different levels either side. Once split however the end result was the same – an annual drop of around the same value.

S25/5208 – the 192m deep bore that penetrates the third confined aquifer has declined at the rate of 2.3% of the range per year since records began. This is the bore record that had raised concerns at Wellington Regional Council over whether the groundwater in this region has a general declining trend. The 17 year record used to calculate this rate of decline may not be long enough to pick up long term trends in fluctuation. It is possible that, with reference to the last two years of data, the downward trend has started to reverse.

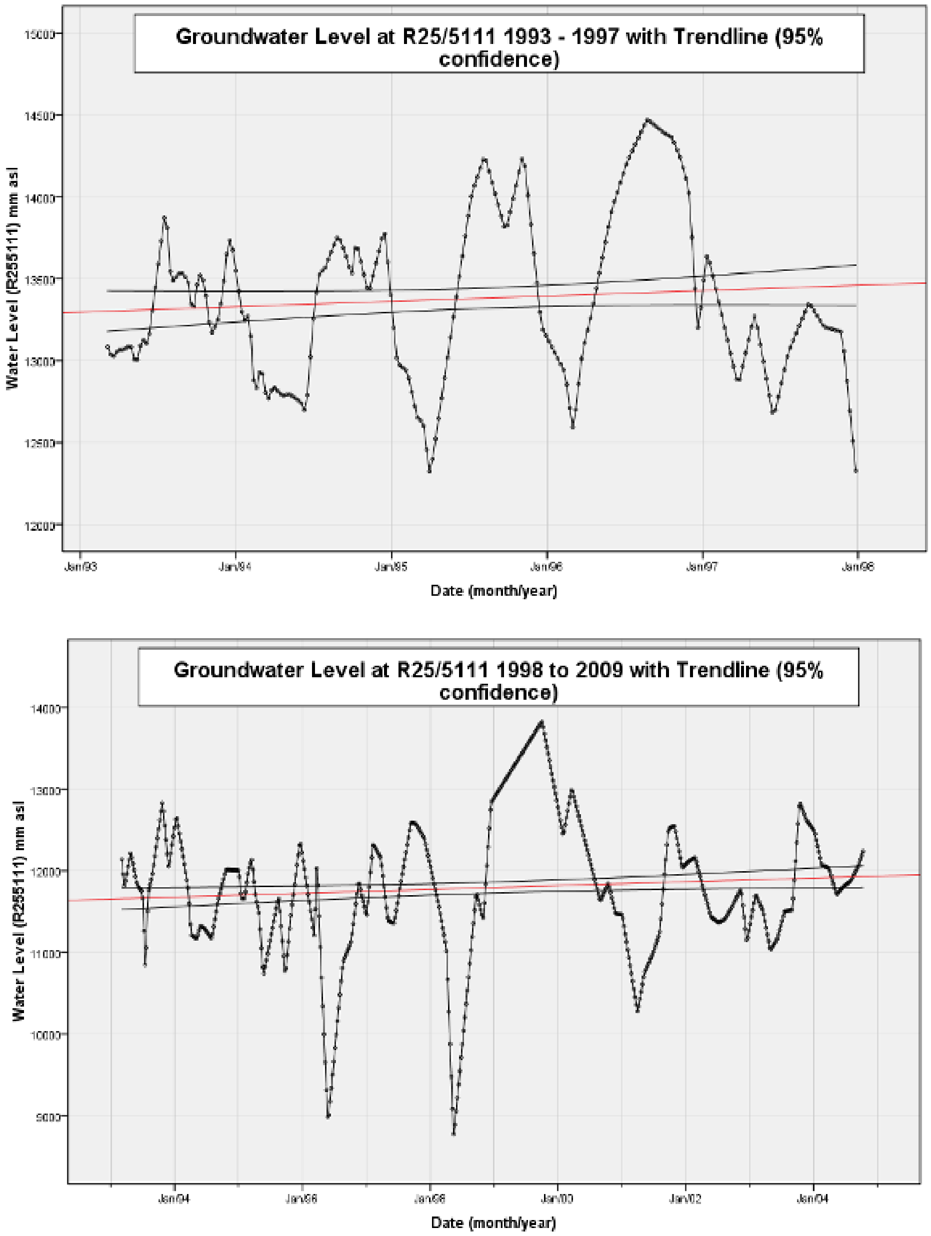


Figure 4.2.10b: The hydrographs for R25/5111 for the periods before and after December 1997.

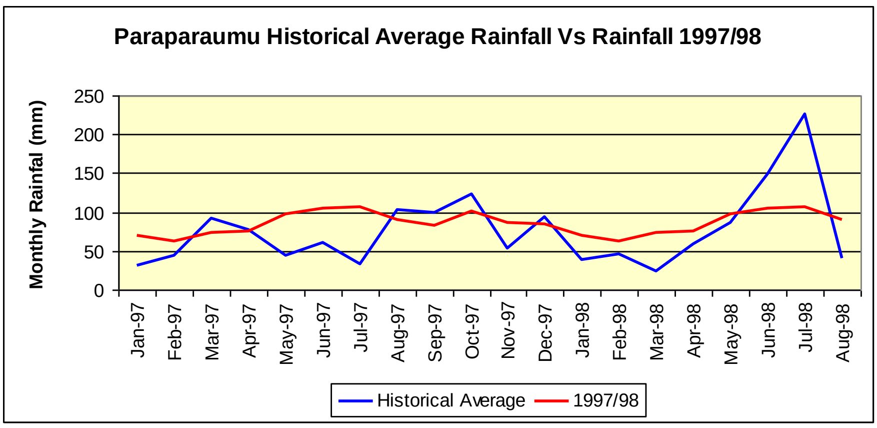


Figure 4.2.10c: Paraparaumu rainfall during 1997/98. (Data source: NIWA Climate Database, retrieved October 2009).

Another notable pattern is reflected by the regional soil type. All of the bores showing decline are located on the coastal plain. Looking at the soils map (figure 4.2.3), the two declining bores that are closest to the wetland (R25/5100 and R26/6747) are in areas where the predominant parent material is peat and sand. This soil composition indicates that this area is or was at one time inter-dunal wetland (also see figure 2.2.1). Studies by Ravine (1992) and Beadel (2003) found that there has been extensive drainage in the area to make way for agricultural farmland (see chapter 2, section 2). It is possible that drainage of wetland areas over the past 25 years has contributed to a lowering of the water table, and hence a decline in water level in these bores. This, however, seems doubtful given their depth: the bores penetrate to 48m and 69m respectively and would thus be in the first confined aquifer. There is a confining layer below the wetland at a depth of 25 to 40m (see figure 4.2.20 and 4.2.21) that would, in theory, separate drained surface areas from this aquifer. This is discussed in more detail in chapter VI.

The groundwater level trend can be projected using the same time series data from figures 4.2.4 to 4.2.11. If groundwater levels were to continue to drop at the same rate, then in 70 years time the water table at R25/5100 would be 0.98m lower than it is now; 0.7m lower in R26/6747; and 4.48m lower in R25/5208. If bores showing significant groundwater rise were projected, in 70 years time S25/5123 would be 0.63m higher; S25/5204 would be 1.54m higher; S25/5200 would be 3.29m higher; and R25/5152 would be 0.77m higher. However in reality natural trends do not follow linear patterns. The projections are done with no knowledge of medium to long term groundwater cycles, so are therefore purely speculation. Climate also varies significantly over time and predicted climate change would need to be factored in.

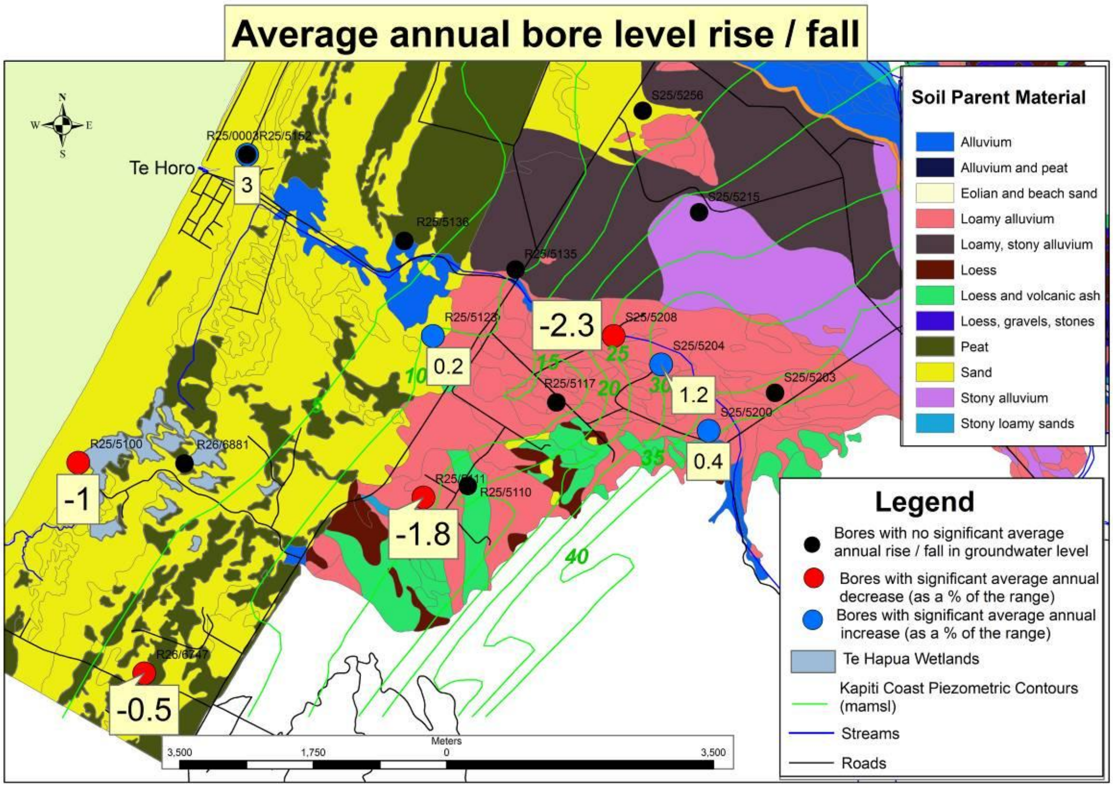
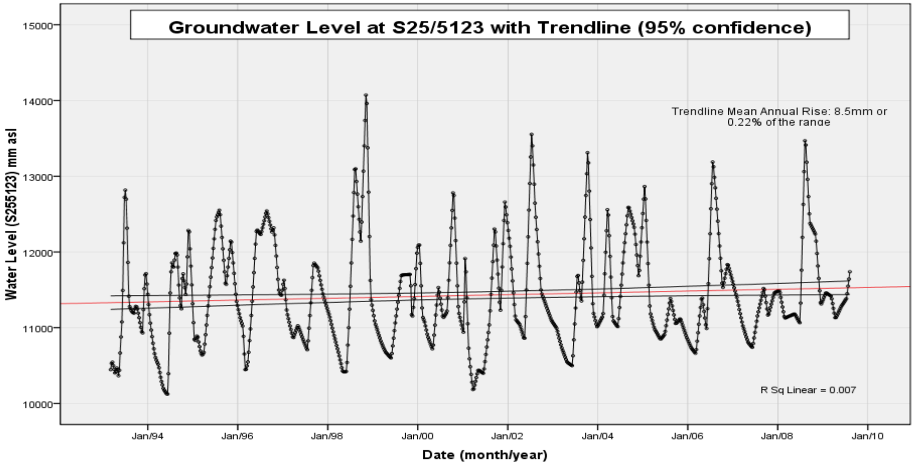


Figure 4.2.3: Parent material of soils surrounding the bores.

This analysis of time series groundwater level data is highly auto-correlated with strong seasonal trends. It is likely that groundwater level is also affected by broader cyclical influence such as ENSO, IPO and QBO. Given this, the statistical method chosen for this analysis, least squares linear regression, is questionable given the assumptions required. This may be evident in figure 4.2.10, which may be picking up some longer term trend. After discussing the use of time series analysis for this thesis with university statistician Dennis Dawson, I was advised to keep the analysis simple. Time series analysis is a specialist skill set and given the aims and objectives of this thesis, would be beyond the scope of this study.



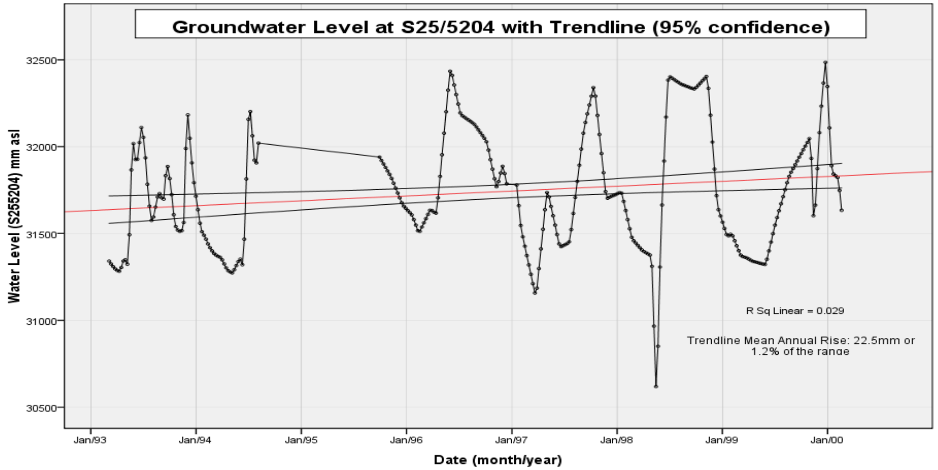
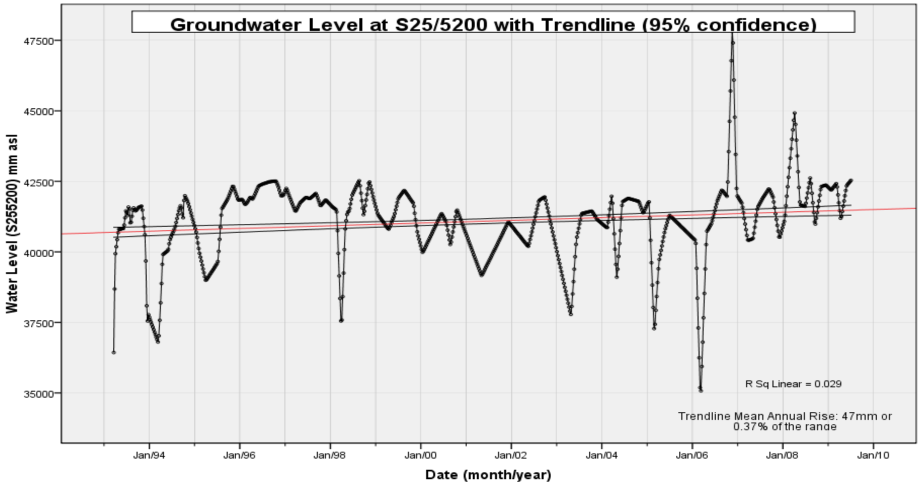


Figure 4.2.4 (left): The record from R25/5123 shows a rise of 8.5mm / year for 16 years. This equals 0.22% of the range. Well depth: 13m
Figure 4.2.5 (right): The record from S25/5204 shows a rise of 22.5mm / year for 8 years. This equals 1.2% of the range. Well depth: 22m



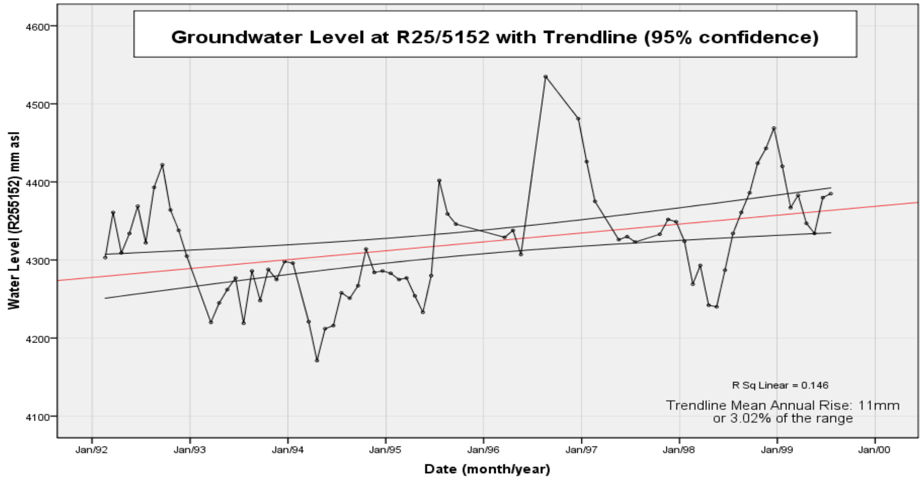
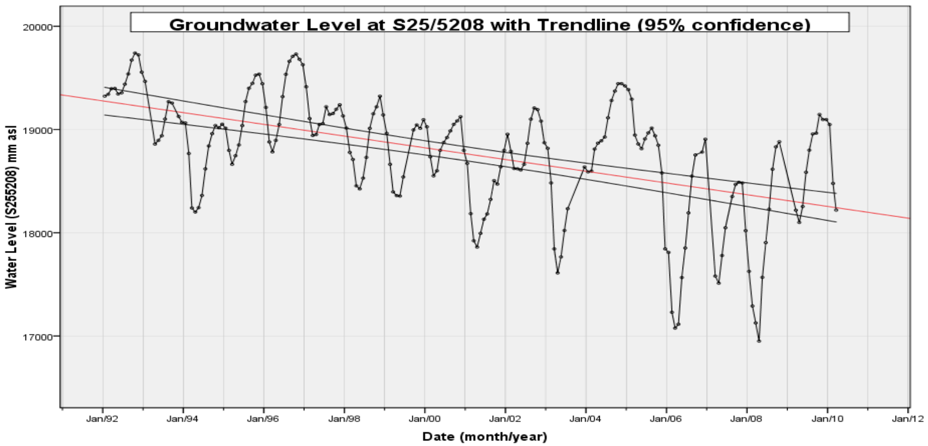


Figure 4.2.6 (left): The record from S25/5200 shows a rise of 47mm / year for 16 years. This equals 0.37% of the range. Well depth: 46m
Figure 4.2.7 (right): The record from R25/5152 shows a rise of 11mm /year for 8 years. This equals 3.02% of the range. Well depth: 172m



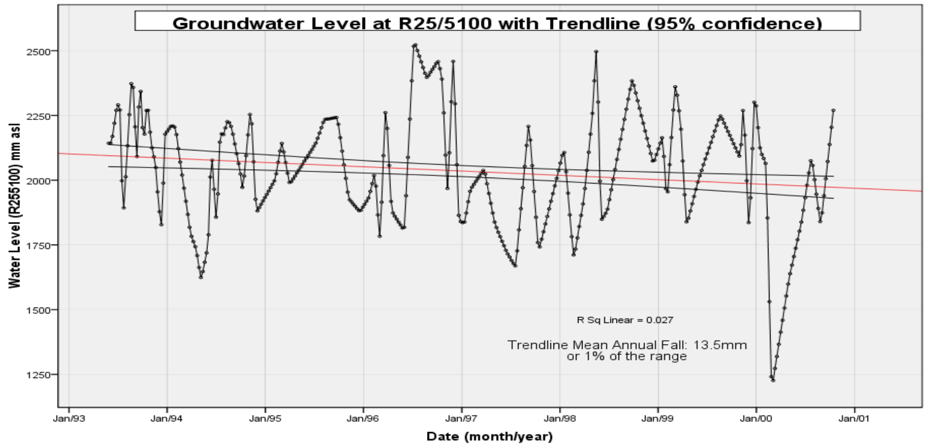
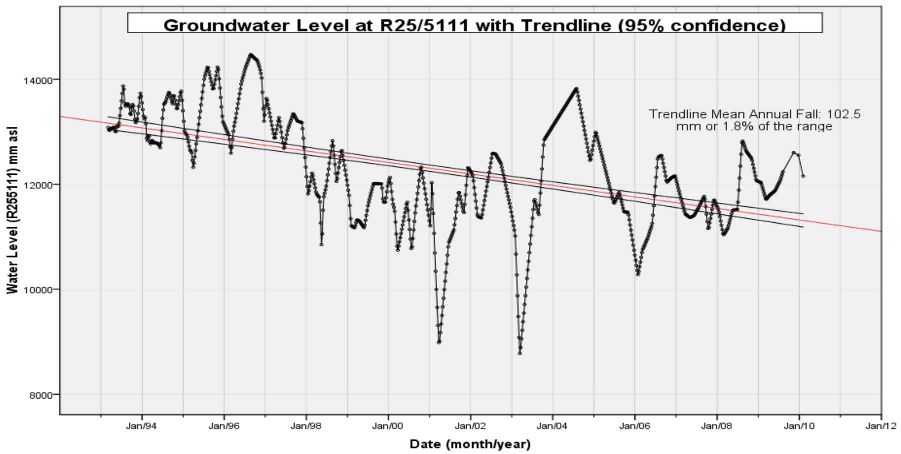


Figure 4.2.8 (left): The record from S25/5208 shows a drop of 64mm/year for 17 years. This equals 2.29% of the range. Well depth: 192m
Figure 4.2.9 (right): The record from S25/5100 shows a fall of 13.5mm / year for 8 years. This equals 1% of the range. Well depth: 48m



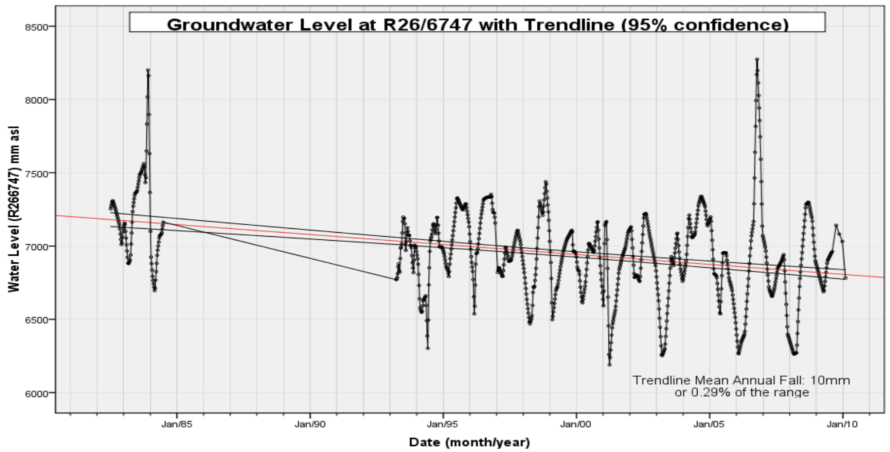


Figure 4.2.10 (left): The record from R25/5111 shows a large annual drop in the water table since records began in 1994, but this may be misleading. Well depth: 49m.
Figure 4.2.11 (right): The record from R26/6747 shows a drop of 10mm / year for 27 years. This equals 0.48% of the range. These two figures do not show a gradual decline. They are broken down further in figures 4.2.10b and 4.2.11b. Well depth: 69m.

4.2.3 Spatial and temporal groundwater patterns across the region.

Methodology

To determine the nature of the aquifers that underlay Te Hapua wetland, regional bore records from each aquifer were analysed to look for changes in groundwater level according to season; proximity to mountains, coast and major rivers; level / fluctuation with respect to bores in the same aquifer; and level / fluctuation with respect to bores in adjacent aquifers. This was done by comparing time series plots for different bores and using ArcGIS to map recognised spatial patterns.

The sampling interval of the data supplied by Wellington Regional Council varied. 19 bores have been read manually every 4 to 10 weeks. A further 8 bores have high resolution data loggers recording level every 15 - 30 minutes. The longest record dates back to 1982 and the shortest back to 2004. A summary of bores used and their sampling histories is provided in Appendix 6.

When some of the wells in the region were installed, a pump test was conducted and values for yield, drawdown and transmissivity were recorded. These bores were mapped using ArcGIS and the data interpolated using the *Inverse Distance Weighted* method. Inverse distance weighted interpolation estimates cell values in a raster from a set of sample points that have been weighted so that the farther a sampled point is from the cell being evaluated, the less weight it has in the calculation of the cell's value (Wade & Sommer, 2006). This was chosen because the method assumes that the variable being mapped decreases in influence with distance from the sampled location (from ArcGIS Desktop Help). Given this, the values for locations between the bores changes gradually, as it would be assumed to do with movement of groundwater and groundwater parametres.

The GIS layer named *Kapiti Coast Piezometric Surface* was provided by Wellington Regional Council on September 2nd 2009.

General spatial patterns associated with groundwater level fluctuations

Hydrographs from bores in the wider region were overlaid to look for patterns of similarity. Bores with levels that rise and fall with similar timing were grouped together and assumed to be potentially hydraulically connected. Figure 4.2.12 shows the main groupings of bores that have similar hydraulic characteristics – one near the Mangone

Stream and toward the Otaki River (Group A - blue); another westward toward Te Hapua wetlands (Group B - yellow); and finally a lone bore (Group C - red) where the hydrograph did not follow fluctuations seen in any other bore.

As discussed in Chapter III, the Otaki River has a wide flood plain and associated layers of well sorted sediment. The piezometric contours (see figure 4.2.12) indicate that areas within 1500m of the Mangone stream are also associated with well sorted sediment. This may explain the water level patterns in Group A, figure 4.2.12. Bores located in similar sediments have similar patterns of groundwater fluctuation. Other factors worth considering are the influence of elevation (figure 4.2.13) and the type of soil / parent material (figure 4.2.14). Group A bores are generally found at relatively high elevations, where Groups B and C are nearly all at lower elevations and are closer to the coast. This means the Groups B and C are often located in the coastal dune and peatlands, where as Group A are mostly in soil derived from 'Loamy Alluvium' material (figure 4.2.14). It is likely that the loamy alluvium soil allows percolation and groundwater movement at a different rate to the sand and peat.

Availability of bores with transmissivity values in the area is limited, but an indicative interpolated surface is shown in figure 4.2.15. Given that few data points were available to use for the IDW interpolation of transmissivity, the accuracy of figure 4.2.15 should not be highly regarded. Instead it provides a reasonable range of IDW values given the existing data. All said, the estimated transmissivity for aquifers that underlie Te Hapua wetland is between 28.45 and 71.32 m^2/day. The spatial pattern of interpolation does not match well with other spatial patterns, namely Groups A, B and C from figure 4.2.12. However, IDW interpolation assumes spatial similarity, not pattern. Visual spatial / temporal patterns such as proximity to rivers, mountains and coast, the influence of tides, well depth, and response to rainfall are not considered in the IDW interpolations. These are discussed in detail later in the section.

Specific yield (figure 4.2.16) and drawdown (figure 4.2.17) data were much more abundant than transmissivity. Aquifers below Te Hapua wetland have an estimated specific yield of between 0.16 and 2.24%, and the expected drawdown in wells is between 0.06 and 12.31m. WRC (1994) described the coastal aquifer as having a low hydraulic gradient.

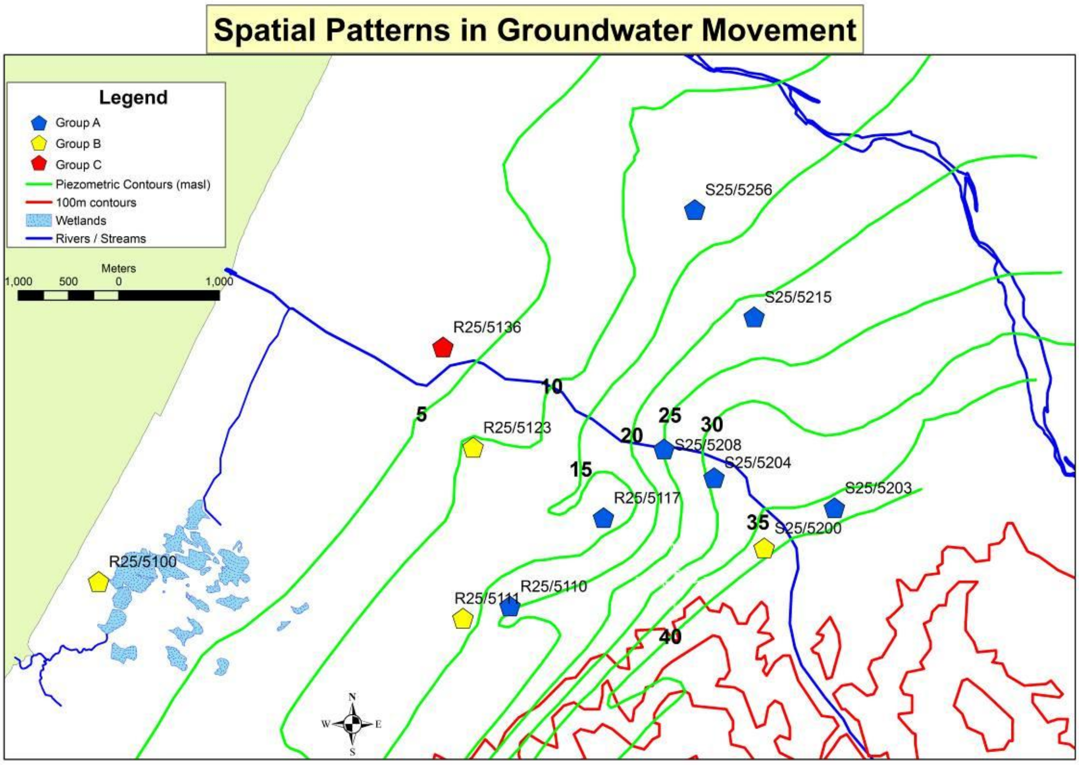


Figure 4.2.12: Bores with similar patterns of seasonal fluctuation.

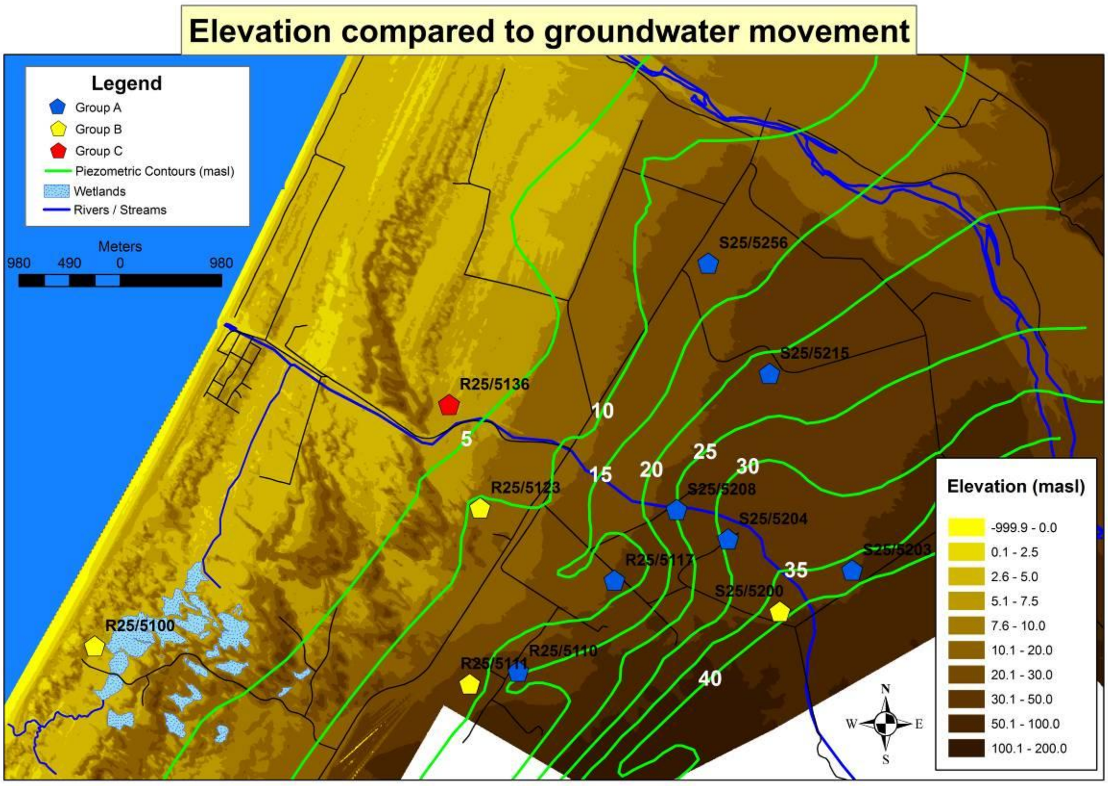


Figure 4.2.13: Bores with similar patterns of seasonal fluctuation compared to elevation contours for the area.

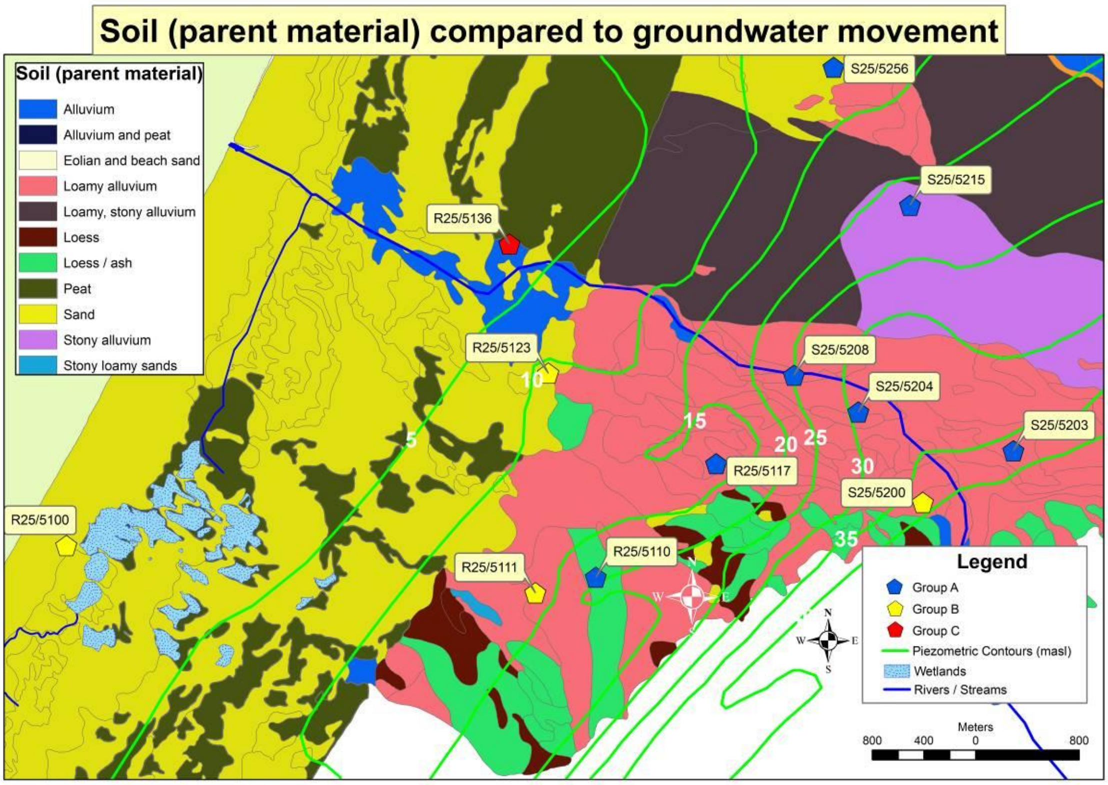


Figure 4.2.14: Bores with similar patterns of seasonal fluctuation compared to the parent material of soils.

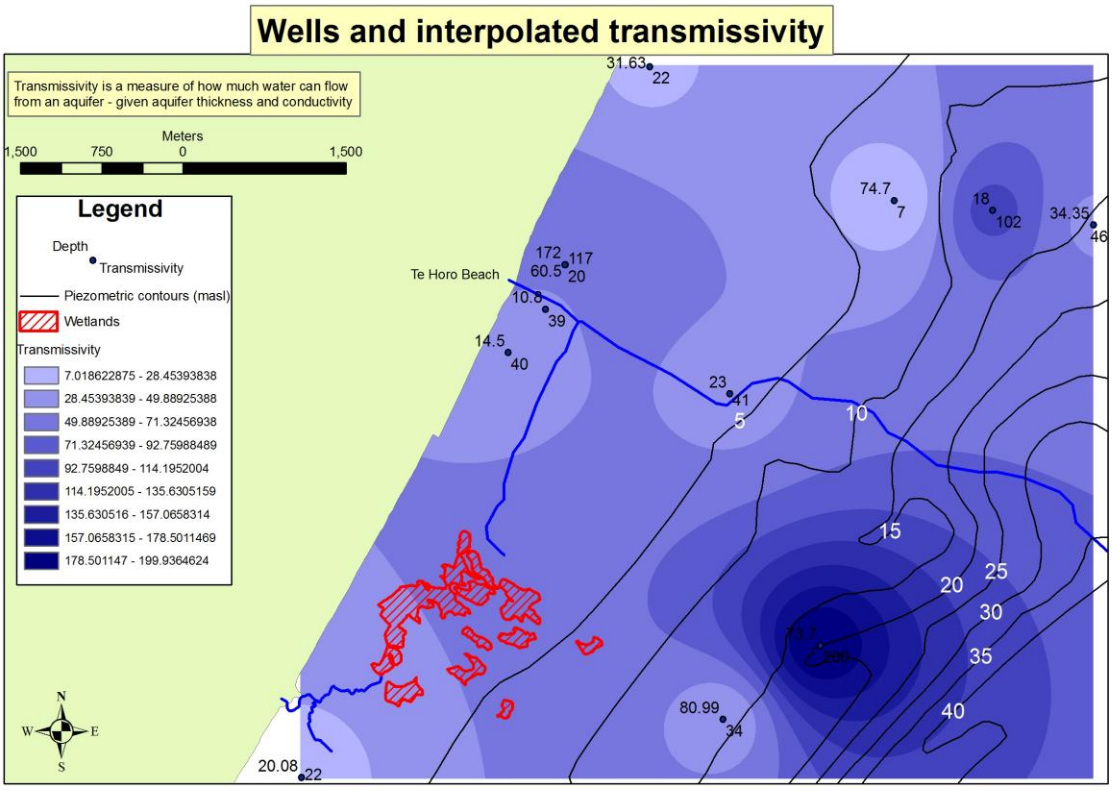


Figure 4.2.15: Inverse Distance Weighted interpolation for transmissivity measurements for the region. The expected transmissivity in the aquifers below Te Hapua is between 28.45 and 71.32.

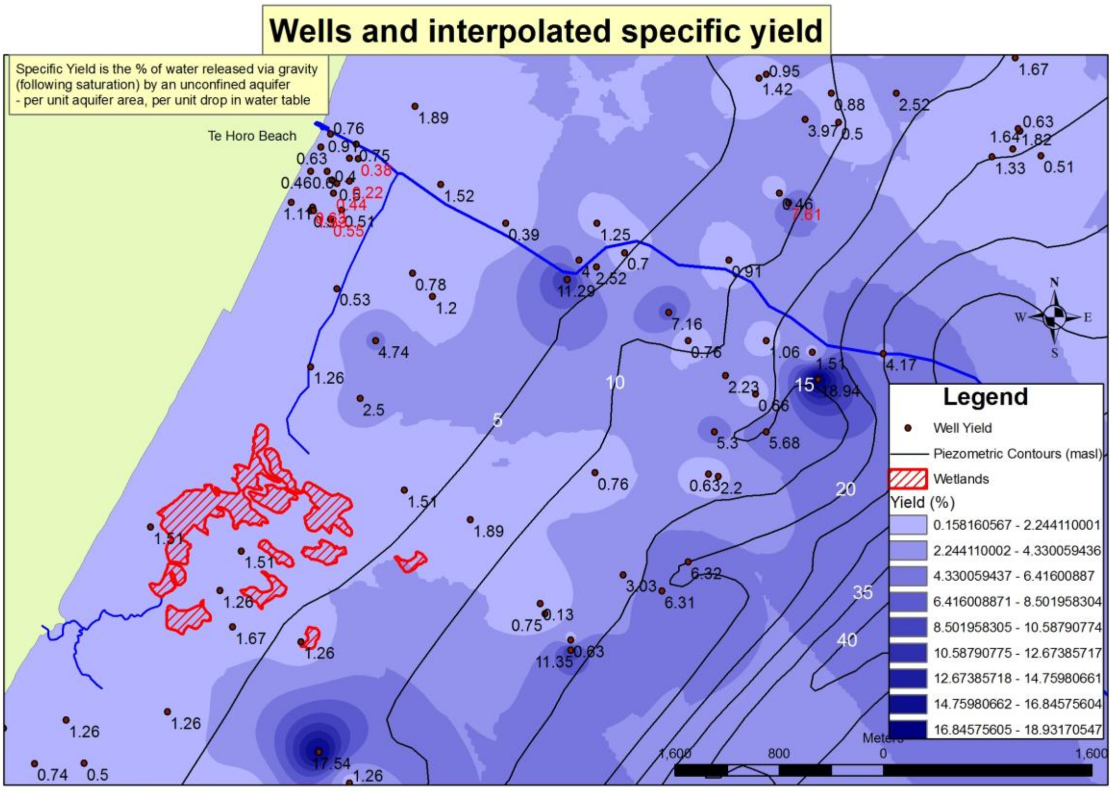


Figure 4.2.16: Inverse Distance Weighted interpolation for specific yield measurements for the region. The expected specific yield in the aquifers below Te Hapua is between 0.16 and 2.24.

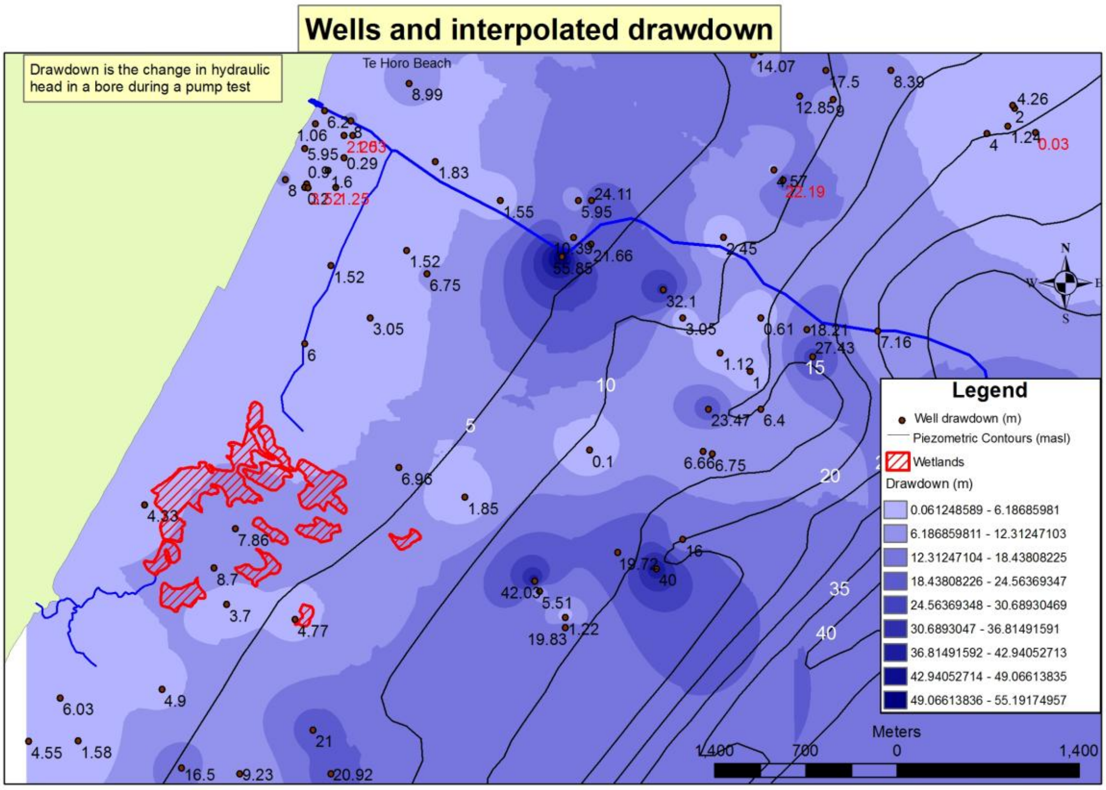


Figure 4.2.17: Inverse Distance Weighted interpolation for drawdown measurements for the region. The expected drawdown in aquifers below Te Hapua is between 0.06 and 12.31.

Distance from the Coast

The range of groundwater level fluctuation increases with measurements made further from the coast. Several factors may contribute to this. Rainfall records from various sites in the region indicate that coastal areas receive less annual rainfall than inland areas, probably due to orographic lift. Also, the groundwater near the coast is constrained by the ocean, hence reducing the degree of groundwater fluctuation. As groundwater flows down from the mountains onto the broad coastal plain it spreads laterally and percolates into deeper layers. Figure 4.2.18 summarises the total range observed for each of the bores and table 4.2.3 gives the distance from each bore to the coast. Bore S25/5200 (46m), for example, is 5,900m from the coast and has an annual range of 12.8m; where as bore R25/5100 (48m) is 300m from the coast and has an annual range of 1.3m.

Tides also influence groundwater level. Patterns of tidal fluctuation can be seen in high resolution data from all four aquifers. Table 4.2.3 outlines the maximum tidal range observed in each bore with high resolution data. Within the two deepest aquifers, tidal influence is greatest closer to the coast. The amount of tidal fluctuation in the shallow aquifer does not appear to be influenced by distance from the coast (though there are only two monitoring bores). Comparing the four aquifers, the second deepest bore (172m deep, 400m from the coast and located in the third confined aquifer) showed the largest diurnal range of tidal surge. This would be caused by a pressure response from the mass of water overlying the aquifer. The deeper aquifer probably extends further offshore than the shallower aquifers and so is ‘exposed’ to a larger area of ocean mass. Tidal fluctuation in the shallower aquifers may be the result of a similar pressure response, or a direct connection with the sea along the saltwater-freshwater interface. This, however, is purely speculation and no literature could be found on the subject. There is not enough data to say how far inland the tide can influence groundwater level, but the furthest observed response was 4.6km from the coast. In the deepest bores, tidal response decreased from around 1m (close to the coast) to 16mm 4.6km inland.

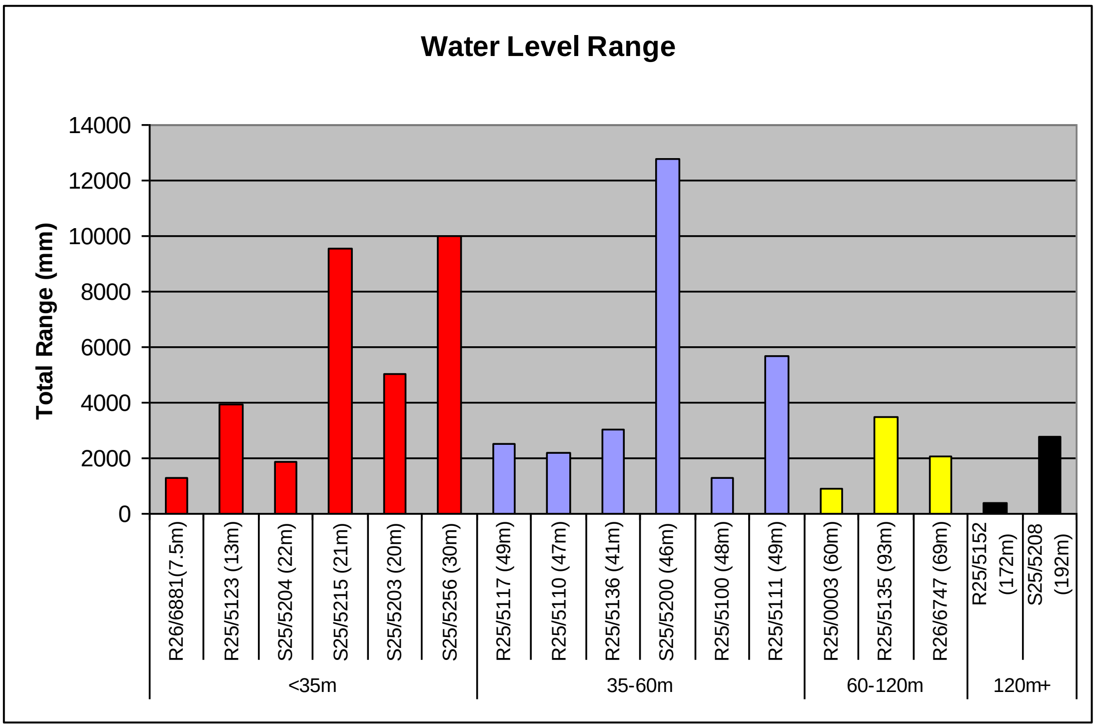


Figure 4.2.18: The total range of water level observed in bores across the wider region.

Table 4.2.3: Bores with high resolution data showing; the range of water level recorded since they were installed; the degree of influence from tides; and the temporal response to significant rainfall.

Aquifer / Bore #		**# years sampled**	**Total range of Water Level (mm)**	**Distance from Coast (m)**	**Maximum tidal range (mm)**	**Response Time after rainfall event**
0 to 35m	R25/6881 (7.5m)	5	1304	1330	15	< 1 hour
	S25/5215 (21m)	12	9574	3900	15	< 1 hour
35 to 60m	R25/5171 (51m)	<1	N/A (record <1 year)	980	90	Too difficult to see
60 to 120m	R25/0003 (60m)	24	877	400	230	3 hours
	R25/5262 (98m)	<1	N/A (record <1 year)	1147	50	1 to 2 hours
>120m	R25/5152 (172m)	8	364	400	1000	1 to 6 hours
	S25/5208 (192m)	17	2790	4660	16	1 to 6 hours

Distance from the Otaki River

The ranges of groundwater level from bores that are closer to the Otaki River are higher than other bores. For example, shallow bores S25/5215 and S25/5256 are both within 2 km of the Otaki River channel and have a water level range of 9.5m and 10m respectively. R25/5123 and S25/5203, two shallow bores further south have a range of 4 to 5m (they are at a similar distance from the coast). This is possibly a consequence of the change in parent material with elevation as well as increased sediment sorting nearer the Otaki River. Nearby bores are hydraulically connected to the Otaki River.

Depth

Looking at the total range of water levels for bores at different depths (figure 4.2.18) the deepest bores look to have the least variance whilst the shallowest bores have the most. This is almost certainly because the shallow unconfined aquifer is more closely connected to surface water systems, such as the Otaki River, which carry large volumes of water during heavy rain. Deep aquifers may still be hydraulically connected to regional surface layers via change in fluid pressure following significant rainfall. However they are less affected by individual events (especially local scale events) as the thickness of the overlying sediment 'buffers' their response, and hence the range is comparatively small.

Response to rainfall

Table 4.2.3 summarises the change in groundwater level in each aquifer following a significant rainfall event. The response time in an unconfined aquifer will generally be influenced by how well connected the aquifer is to the surface – the faster the response the better the hydraulic connection. In a confined aquifer, a response in water level following significant rainfall indicates a change in fluid pressure within the aquifer material, where the magnitude of response depends partly on the hydraulic properties of the material (Bardsley & Campbell, 1994). Note though that an unconfined aquifer may not be fed close to where the well is located, so rainfall in the vicinity of the well may be quite different to that in the aquifer's source. In this situation, bores in the shallow unconfined aquifer responded in less than 1 hour, where as deeper bores had varying rates of response. The data indicate that response time is also influenced by the tide and previous rainfall, where response is faster when the tide is high, and / or if there have been other recent significant rainfall events.

Shallow Te Hapua bores are strongly influenced by local rainfall. Groundwater levels rise slightly before significant rainfall registers higher in the catchment, hence the rise at Te Hapua is likely to be from local rain.

4.2.4 Geological cross sections

Geological cross sections were drawn through the Te Hapua complex and surrounding topography. Cross section 1 (figure 4.2.19 and 4.2.20) uses deep bores in a northwest – southeast direction (perpendicular to the coast). Three more cross sections were drawn but they did not add significantly to what can be see in cross section 1, so are displayed in appendix 3. Cross section 2 runs parallel to and a few km north of cross section 1.

Cross section 3 runs parallel to the coast. Cross section 4 runs west – east and looks at shallow bores only.

All of the geological records from bores used in the cross sections had layers of clay and peat at depth. The clay / peat layers are generally no thicker than 2.5m, though some layers have a mixture of clay and gravel up to 6m thick. Figures 4.2.20 and 4.2.21 show that the position of the first confining layer is between 25m and 40m below sea level. Another confining layer can be seen in the geological record from the two deep wells at a depth of between 65m and 80m below sea level. Other features prevalent through the cross section are layers of blue sand and gravel, some water bearing, as well as brown gravels and more clay layers nearer the mountains. The clay layers in sediments surrounding bores closer to the mountains are closer to the ground surface. These layers of clay and water bearing sediment are at similar depths to those found in Te Horo (figure 3.7, Chapter III) and indicate the same aquifers generally recognised on the Kapiti Coast.

As discussed in chapter II, clay and peat are known to act as aquitards in groundwater systems. Given the geological history of the area (described in chapter III), the depositional sequence of sediment is not uniform and continuous across the entire coastal plain. It is likely that the clay layers noted in some of the bores in cross sections 1 to 4 are also not continuous. This means the aquifers may be leaky given a difference in hydraulic head in underlying aquifers. WRC (1994) confirmed upward leakage from deeper aquifers into overlying aquifers, noting the hydraulic head in the third confined aquifer in Te Horo is up to 1.5m higher than that in the first confined aquifer.

To investigate potential for leakage in the aquifers that underlie Te Hapua, pressure head was compared in local bores. Groundwater level was measured in all Te Hapua bores as part of pump testing conducted and described in section 5.2 (though the level in R26/5117 was taken from the drill record because the well head is sealed). Figure 4.2.21 shows the position of the pressure head in wells within the wetland at this time. Similar to discussion by WRC (1994), pressure heads for wells in the second confined aquifer are higher than those from wells in the first confined aquifer and shallow unconfined aquifer. If leakage does occur, it would be an upward leakage because hydraulic head in deeper layers is higher than shallow layers.

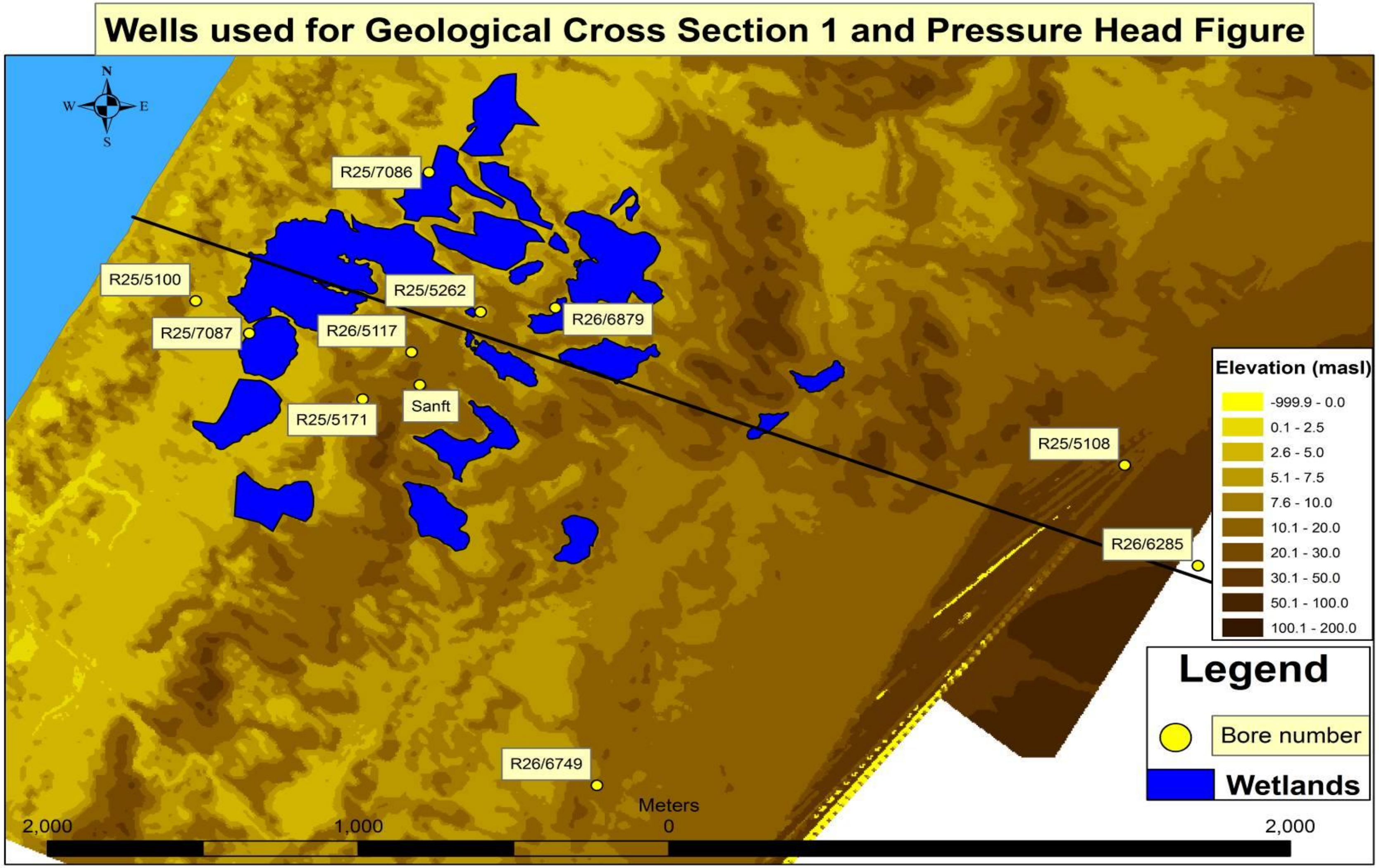


Figure 4.2.19: Locations of wells used for the cross sections in figures 4.2.20 and 4.2.21.

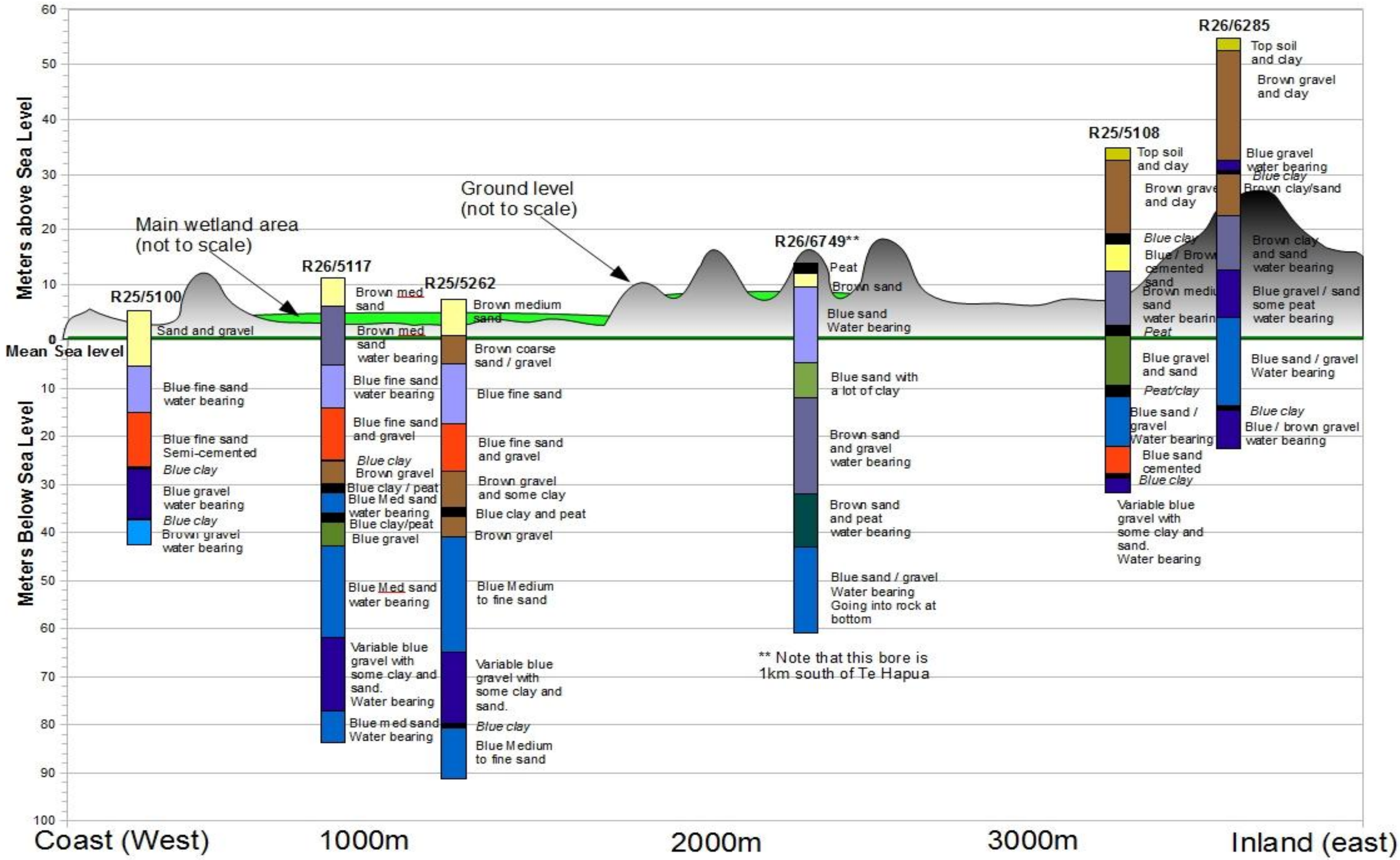


Figure 4.2.20: Geological cross section / bore log data through Te Hapua – perpendicular to the coast from West to East. Geological cross sections 2, 3 and 4 are in Appendix 3. Note that the ground level is drawn in approximately to fit the transect line – the wells did not align perfectly on the transect line so do not match the ground surface exactly.

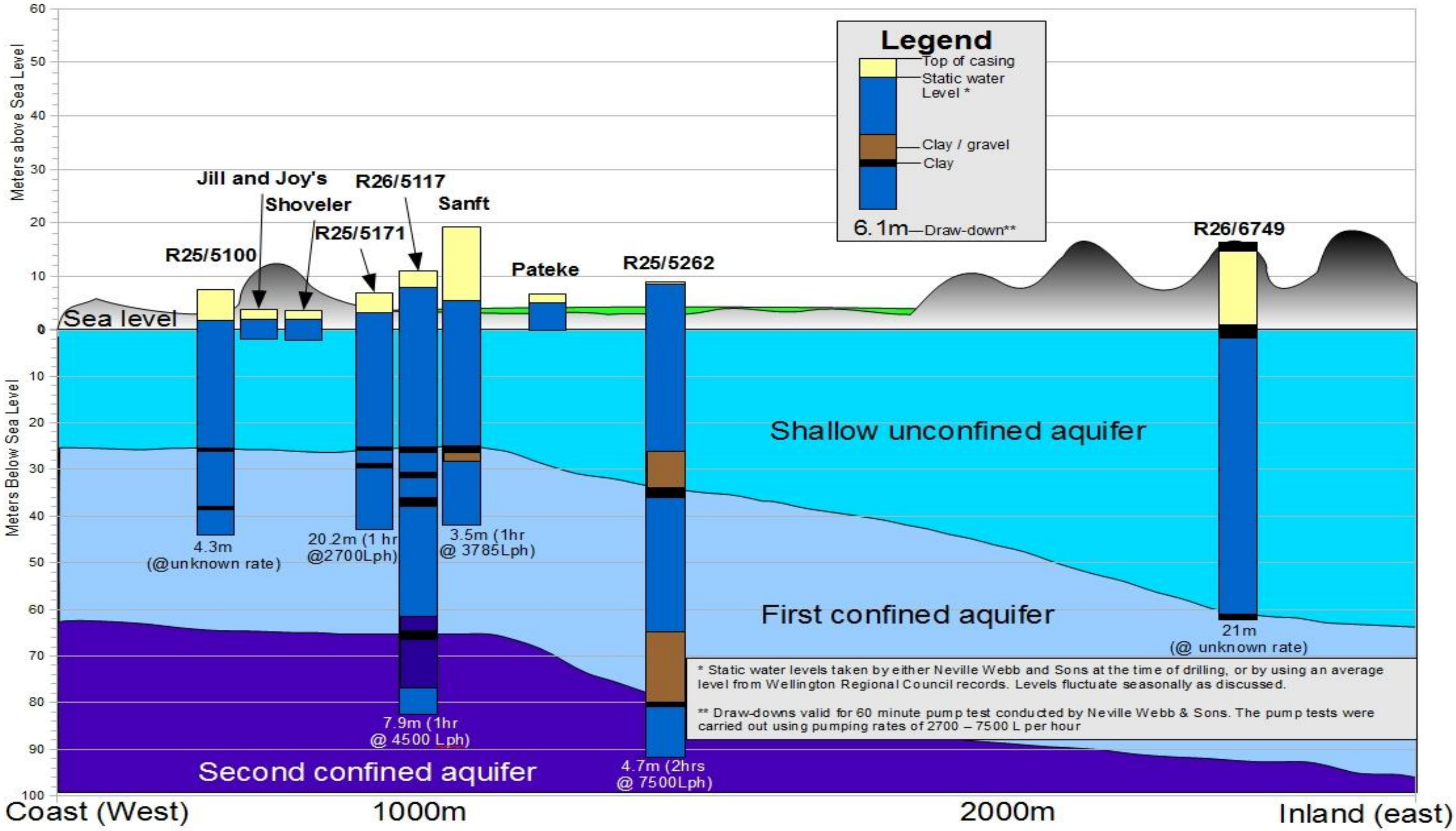


Figure 4.2.21: The position of aquitards in geological bore records and inferred position of the aquifers underlying Te Hapua wetland. Also visible is the pressure heads in bores penetrating different aquifers. The pumping rate unit is Lph (litres per hour). Note that the ground level is drawn in approximately to fit the transect line – the wells did not align perfectly on the transect line so do not match the ground surface exactly.

4.2.5 Summary

Higher than average 2009 spring rainfall on the Kapiti Coast maintained higher than usual Te Hapua wetland water levels. The general trend of long term groundwater level data shows that water level in four of the bores in the region has significantly declined; whilst another four have significantly increased over the years. Of the four bores that showed significant long term decline in groundwater level, two look like they may have started to reverse this trend and are now increasing annually. One of these is the well that penetrates the third confined aquifer and the bore record that had raised concerns at Wellington Regional Council over whether the groundwater in this region has a general declining trend. Another of the four bores showing decline is situated near the Te Hapua complex in the first confined aquifer. This bore was only monitored for eight years and monitoring ceased in 2000, hence it is not currently possible to know if the bore is still in decline or not. The fourth bore that has shown a declining water level trend has been monitored for 28 years. Water levels have declined on average at a rate of 10mm per year, or 0.48% of the range annually.

The water level records used for this analysis are relatively short and may not be long enough to be able to recognise long term trends. Bores in the third confined aquifer are likely to be penetrating a deep regional flow system. Both of the bores drilled to this depth showed the largest rise / fall in groundwater level of the 17 bores analysed.

Hydraulic properties were interpolated from historical bore record data from the region. Transmissivity was estimated at 28.45 to 71.32m^2/day; specific yield was estimated at 0.16 to 2.24%; and drawdown was estimated at 0.06 to 12.31m. Piezometric contours indicate a low hydraulic gradient. These values together combine to show that the aquifers are relatively low yielding.

Temporal analysis of groundwater level data in response to rainfall indicates that the shallow Te Hapua bores are strongly influenced by local rainfall. During some rainfall events that registered on the Te Hapua gauge, shallow groundwater levels rose slightly before significant rainfall registered at rain gauges higher in the catchment (Mangone Stream at Transmission Lines).

Analysis of geological records from bores within the wetland complex area revealed that two or three confining layers lie between 25 and 40m below sea level. Another one or two confining layers lie between 65 and 80m below sea level. These represent the upper / lower limits of the first and second confined aquifers. Water bearing layers are medium blue sands or gravels. Pressure heads in bores that penetrate the second confined aquifer generally appear to be higher than those from bores in the first (uppermost) confined aquifer. It is not known if this ever reverses, but a study carried out in Te Horo, 5km north indicates that pressure head in the third confined aquifer is higher than the first confined aquifer (WRC, 1994). This report states that upward leakage occurs; moving water from the third confined aquifer into overlying aquifers, but does not specify which ones.

4.3 Climate change predictions

Wetland responses to climate change are still poorly understood and are often not included in global models of the effects of climate change (Clair, et al., 1995). It is generally accepted, however, that increases in temperature, sea-level rise, and changes in precipitation will impact on wetlands (Bergkamp & Orlando, 1999; Mullan, et al., 2008). The vulnerability of wetlands to changes in climate depends on their position within the hydrologic landscape (Winter, 2000). Given the wide range of wetland types that exist and the range of scenarios and levels of uncertainty regarding climate change, it is difficult to accurately predict the extent of the impact. Therefore, only a general assessment of the relationships between wetlands and climate change can be given. Details of impacts must be considered on a case by case basis (Bergkamp & Orlando, 1999).

The Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment (2007) predicts an intensification of the global hydrological cycle. This may equate to major impacts on regional water resources (IPCC, 2007). The influence of climate change on wetlands includes changes in precipitation, evaporation, transpiration, runoff, groundwater recharge and flow (Bergkamp & Orlando, 1999). Changes such as the re-distribution and change of intensity of precipitation may lead to shifts in the geographical distribution of wetlands (Bergkamp & Orlando, 1999; IPCC, 2007). Wetlands most vulnerable are those in arid and semi-arid regions, as well as those in lowland areas that are reliant on winter rainfall and spring snow melt. Climate change impacts predicted by the IPCC for freshwater systems were made using observed and predicted increases of temperature, sea level and precipitation (IPCC, 2007). They are categorised as having ‘very high confidence’, which has ‘at least a 9 out of 10’ chance of happening (IPCC, 2008).

The IPCC prediction for sea level rise has high uncertainty attached because of a limited understanding of some of the important mechanisms that drive it. However, the projected average global rise in sea level is between 0.18m to 0.59m by 2090 (as compared to 1990) (Mullan, et al., 2008). New Zealand is thought to be experiencing an average rate of rise, so this figure holds for the predicted rise on the Kapiti Coast. This prediction does not include the impact of changes in global ice sheet flow which, if they occur at a linear rate, will add another 0.1 to 0.2m (Mullan, et al., 2008). The IPCC notes that even larger sea-level rises cannot be excluded, but no consensus has been possible to date because of limited understanding of the processes involved (IPCC, 2007).

Potential impacts of rising sea levels on coastal wetlands include increased coastal flooding, loss of habitats and increase in salinity in coastal lowlands and aquifers (Bergkamp & Orlando, 1999). Changes in sediment transport pathways (nutrient flow) and coastal erosion will also occur. This will result in changes to species composition and distribution, as well as wetland productivity and function (Warren & Niering, 1993). Coastal wetland flora and fauna can generally respond to small changes in water level, providing there are surrounding areas of available land for gradual migration (Bergkamp & Orlando, 1999). If, however, these migration pathways are obstructed by anthropogenic barriers such as reclaimed land, drained pasture, levees and roads, the wetland will be under increased threat for survival as its ability to adapt is limited (Kursler, et al., 1999).

The IPCC fourth assessment used 12 different models and six different emissions scenarios to predict climate change for the periods 1990 to 2040, and 1990 to 2090 (IPCC, 2007; Mullan, et al., 2008). The range of estimates for climate change among (and within) these different scenarios is vast. Averaging over all 12 IPCC models and all six illustrative emissions scenarios gives a New Zealand-average warming of 0.2–2.0°C by 2040 and 0.7–5.1°C by 2090 (Mullan, et al., 2008). In the A1B scenario[6], the projected warming is 0.3–1.4°C by 2040 and 1.1–3.4°C by 2090, with a 12-model average (or 'best estimate') of 0.9°C and 2.1°C for 2040 and 2090, respectively. For comparison, IPCC's average global estimate is 2.8°C by 2090 under the A1B scenario, with a likely range of 1.7–4.4°C (Mullan, et al., 2008). The projected New Zealand temperature changes are in all cases smaller than the globally averaged changes. For New Zealand, the IPCC Fourth Assessment predicts a rise in average temperature and average precipitation; a significant increase in frequency and intensity of storm surge events; and an increase in mean sea level (Mullan, et al., 2007). A report for local authorities by Mullan et al. (2007) downscaled climate change projections from New

[6] The A1B scenario is one of 6 groups of climate change scenarios. It is characterised by rapid economic growth, population reaching 9 billion in 2050, rapid spread of new and efficient technologies, a convergent world where income and way of life converge between regions, extensive social and cultural interactions worldwide, and a balanced emphasis on all energy sources. It is a 'middle of the road' climate change scenario. The IPCC has not indicated if one scenario is more likely than any other (Mullan, et al., 2007).

Zealand to the Kapiti Coast. Three scenarios were used[7] by Mullan et al to calculate average temperature increase for the Kapiti region. The predictions suggest a rise of 0.6 to 5.1°C (with a mean rise of 2.1°C) by 2090. The seasonal breakdown is shown in table 4.3.1 below.

Estimates of changes in precipitation across New Zealand to 2090 also vary widely. An increase in westerly quarter winds is expected to bring a average change in mean national rainfall of between -7 to +14% (Mullan, et al., 2008), though this figure varies considerably from region to region. Extreme rainfall events are predicted to become more frequent and the intensity of the extreme rainfall events will likely increase. This will increase runoff, surface ponding, and will likely impact on groundwater (IPCC, 2008). The Kapiti Coast region is expected to be on par with the national average of between -7 to +14% (Mullan, et al., 2007). The seasonal breakdown is shown in table 4.3.1 below. Summer months are predicted to be slightly drier on average whilst winter months will be slightly wetter. Given the same changes to precipitation intensity and duration noted above, surface flooding would be more likely and there may be less water percolating down to recharge groundwater. This could put stress on groundwater fed wetlands.

Table 4.3.1: Average projected change in temperature (in °C since 1990) and precipitation (in % since 1990) for Paraparaumu by 2090. Lower and upper limits are shown in brackets. Values were produced using an average over the 12 IPCC models and six emissions scenarios. (Mullan, et al., 2007)

Location	Summer	Autumn	Winter	Spring	Annual
Change in temperature (°C)	2.2 (0.8, 5.6)	2.1 (0.6, 5.1)	2.1 (0.6, 5.0)	1.8 (0.3, 4.8)	2.1 (0.6, 5.1)
Change in precipitation (%)	-1 (-38, 16)	2 (-12, 14)	9 (0, 26)	2 (-15 to 26)	3 (-7 to 14)

Predictions of future climate change are associated with considerable uncertainty. This makes down-scaling the predictions for small scale features such as wetlands difficult. However with the information we have available it is most likely that the Kapiti Coast will experience some warming and an increase in precipitation. Any change in the hydrological cycle is likely to affect ecosystems (such as wetlands) that rely on it. Changes in runoff resulting from a predicted increase in heavy rainfall are likely to affect the amount of groundwater recharge. This may be countered by a predicted increase in precipitation, but the region may suffer seasonal extremes that threaten ephemeral wetlands.

[7] Mullan et al used the A1B (mid range) scenario; the B1 (lowest emissions) scenario; and the A1F1 (highest emissions) scenario.

V Results 2: Eco-hydrology of Te Hapua Wetland Complex

5.1 Introduction

This chapter reports the results of field work carried out to provide information deemed important when considering the key questions and objectives of this study.

Section 5.2 describes and interprets data collected from three wetland monitoring sites installed at Te Hapua by Wellington Regional Council in April 2009. The relative height of groundwater and pond water was assessed and hydrologic response to rainfall is compared at different times of the year. GIS was used to analyse surface flow accumulation and calculate the watershed for wetland areas. A water balance approach then attempts to compare the hydrology of the three sites and pump testing field work looks at the potential for aquifer leakage.

Section 5.3 classifies 21 individual wetlands within the complex according to measured water quality and water regime observations. These results are compared to local soil and elevation maps. There is also a comparative analysis of water quality measures in wetlands, bores and rain water to look for the most likely source of wetland surface water.

5.2 Te Hapua Wetland Monitoring Sites

This section summarises the water level trends for wetland ponds and nearby shallow bores at the three wetland monitoring sites – Jill and Joy's, Shoveler and Pateke (see figure 5.2.1). Water levels have been analysed relative to each other looking at general trends, seasonal trends, and response to specific significant rainfall events. Wetland levels were also compared to deeper bores around the wetland – R25/5262, R26/5117 and R25/5171 (figure 5.2.1).

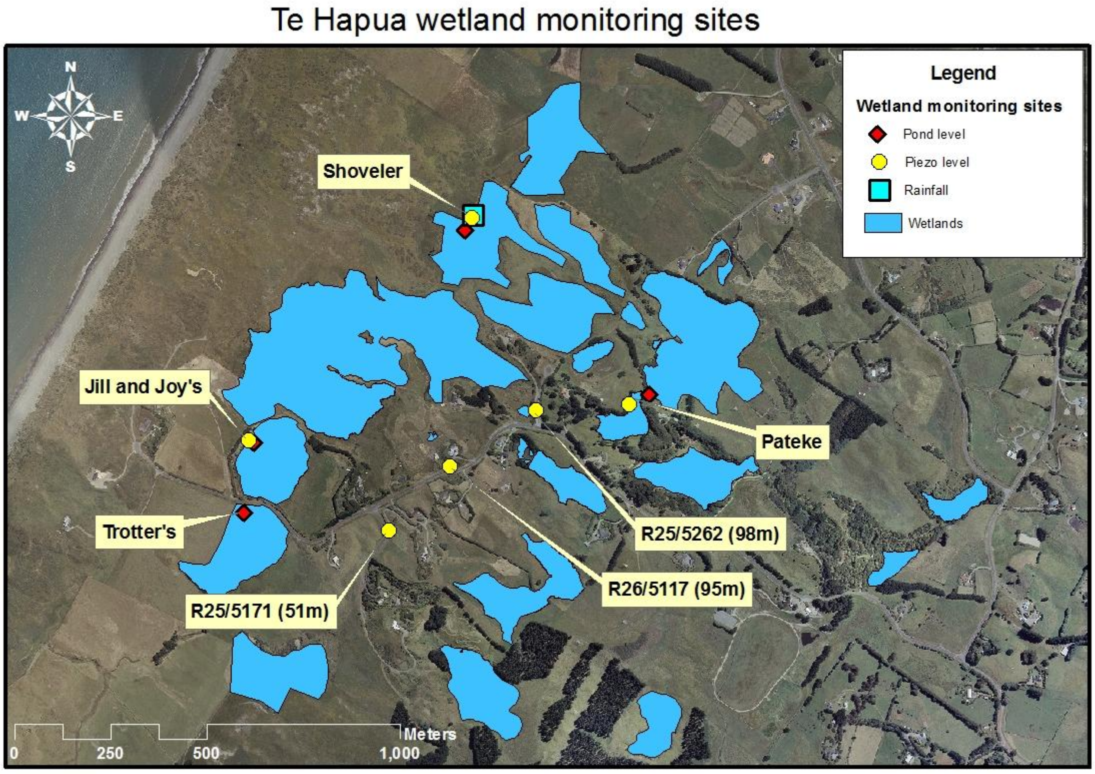


Figure 5.2.1: Locations of the three primary Te Hapua wetland monitoring sites (Shoveler, Pateke, Jill and Joy's). Trotters is a fourth pond stage site but was not used for this study. The three deep bores (R25/5171, R25/5262 and R26/5117) were used in conjunction with the main monitoring site data.

5.2.1 Overview of the sites: Jill and Joy's, Shoveler, and Pateke.

Water level and rainfall data were recorded every 15 minutes at wetland pond and shallow bore sites between April 2009 and March 2010. Table 5.2.1 summarises observations inferred from figures 5.2.2, 5.2.3, 5.2.4, and 5.2.17. Refer to Chapter III, section 3.5 for further details on the placement of the three wetland monitoring sites.

Table 5.2.1: Relative wetland response to rainfall events.

	Jill and Joy (Figure 5.2.2)	**Shoveler** (Figure 5.2.3)	**Pateke** (Figure 5.2.4)
Recharge Wetland (Pond > groundwater) or **Discharge Wetland** (Groundwater > pond) (For definitions see chapter II, section 2.5.6)	Pond 35mm to 150mm higher than groundwater. Recharge Wetland	Pond usually up to 120mm higher than groundwater. The exception was after significant rain when groundwater was up to 20mm > pond for 12 to 18 hours. This happened twice during the year. Recharge Wetland	Groundwater 5mm to 90mm higher than pond. Discharge Wetland
Immediate response to rainfall	Groundwater faster to rise and fall than pond	Groundwater faster to rise and fall than pond	Similar timing of groundwater and pond responses
Extended response to rainfall: 2009 dry season	Pond takes approximately 2 days to peak and stays high for another 2-3 days. Groundwater takes approximately 1 day to peak, then immediately declines.	Pond takes approximately 3 days to peak and stays high for another 2 days. Groundwater takes approximately 1 day to peak, then immediately declines.	Pond takes approximately 1 to 3 days to peak and stays high for another 1 to 2 days. Groundwater takes approximately 1 day to peak, then immediately declines.
Extended response to Rainfall: 2009 wet season	Pond water appears to drain faster during the wet season and more closely resembles the groundwater hydrograph	Pond water appears to drain much faster during the wet season than it does in the dry season	Pond water appears to drain much faster during the wet season than it does in the dry season
Seasonal influence: General levels	Both pond and groundwater levels are highest from September to January	Both pond and groundwater levels are highest from June to January	Both pond and groundwater levels are highest from June to January
Seasonal influence: Pond level relative to groundwater level (see figures 5.2.2 to 5.2.4)	Levels don't look significantly different in the wet season compared to the dry season	During the wet season groundwater levels closely resemble pond levels. During the dry season groundwater is low relative to pond water level.	During the wet season groundwater levels are generally much higher than pond levels. During the dry season groundwater is still higher than pond water level, but by a lot less.

Pond levels are generally higher than groundwater levels at the Jill and Joy and Shoveler sites indicating they are 'recharge wetlands'. This type of wetland usually loses water to groundwater given the difference in hydraulic head. The hydrology is generally more influenced by surface runoff (via through-flow) and precipitation than groundwater inflow. Pateke wetland is the opposite; groundwater is generally higher - a 'recharge wetland'. These wetlands are usually found in topographical depressions and the hydrology may be more influenced by groundwater inflow than surface water.

The Pateke site is more elevated than the other sites and is also closer to relatively high dune systems (see figure 5.2.9). Groundwater mounded beneath dune areas east of the Pateke site probably has the effect of raising the water table, as discussed in chapter II. There are two springs[8] located near the Pateke wetland site (see figure 5.3.1), so groundwater appears to be emergent in the area.

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[8] Note that one of the springs was learned of via anecdotal evidence only (from the current land owner, Mr Dale), and there is a difference of opinion as to its existence (from Mr Jensen).

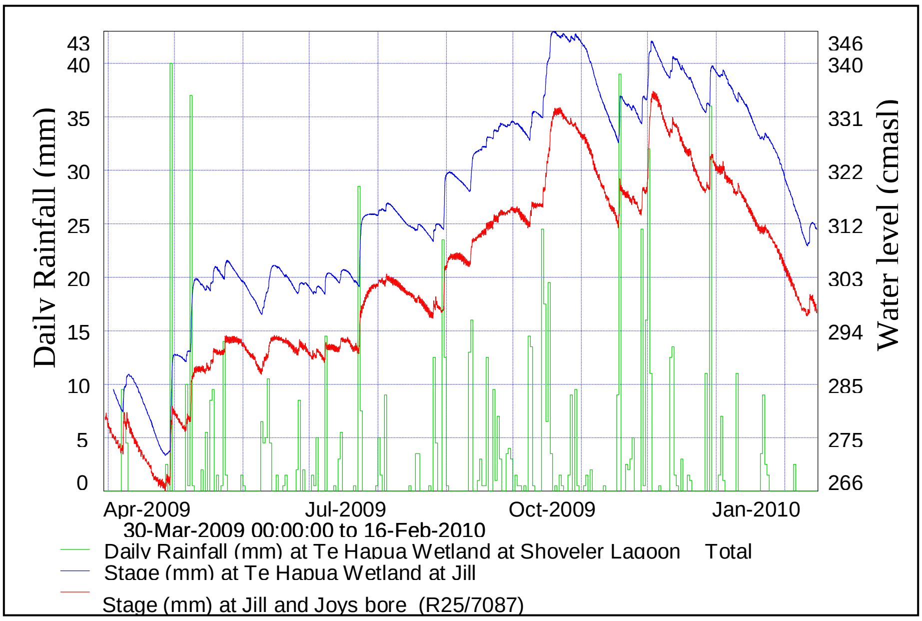


Figure 5.2.2: Wetland pond (blue) and shallow bore (red) levels at the Jill and Joy site showing response to local rainfall (green).

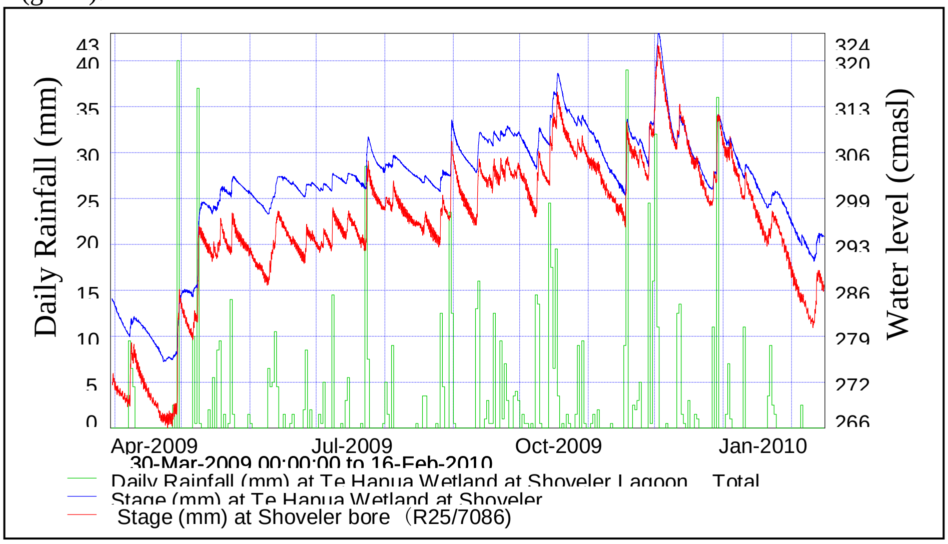


Figure 5.2.3: Wetland pond (blue) and shallow bore (red) levels at the Shoveler site showing response to local rainfall (green).

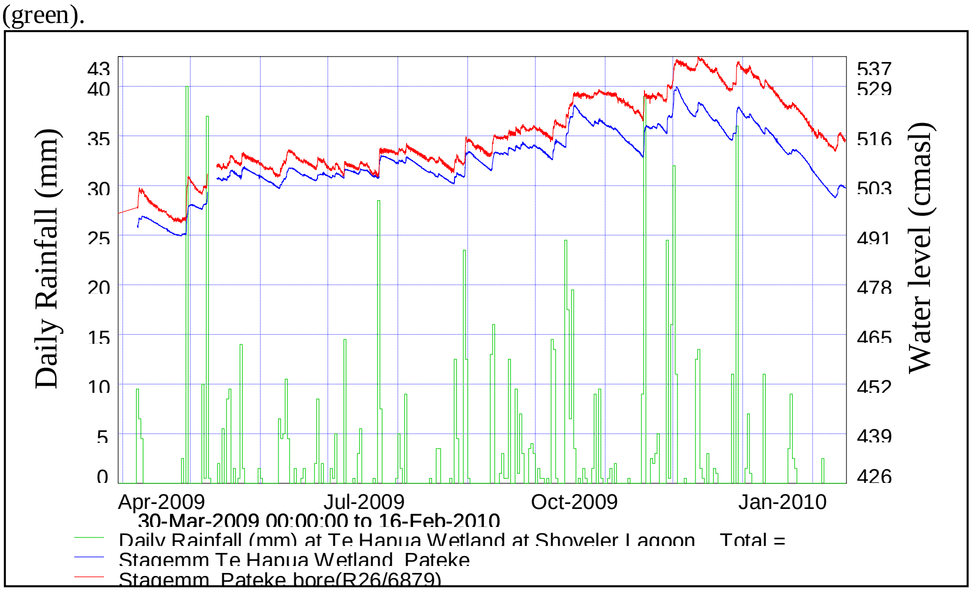


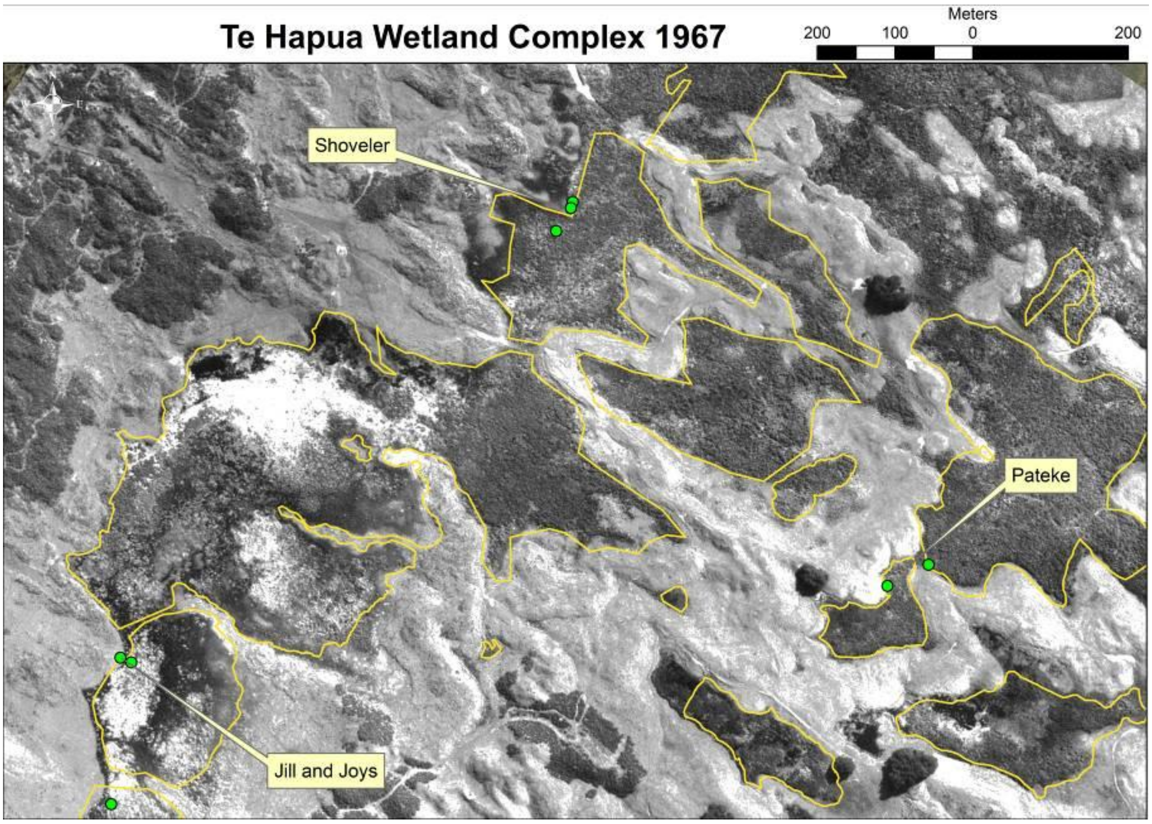
Figure 5.2.4: Wetland pond (blue) and shallow bore (red) levels at the Pateke site showing response to local rainfall (green).

Anecdotal description of the hydrology

Comparison of historical aerial photos (chapter III) together with discussions with land owner and long term visitor to the area Ian Jensen revealed that the hydrology of many individual wetlands around the Te Hapua complex (including all three of the monitored sites) has been modified at some stage with the installation of culverts, drains or dams. For the past 50 years Mr Jensen has been visiting the area given his interest in water fowl hunting and has paid particular attention to water levels in the wetland over this period. More recently, he has had parts of his land surveyed in preparation for plans for subdivision and wetland enhancement in adjacent areas. This work included surveying the elevations of some of the culverts and drainage points in the area. During a conversation in November 2009 he described his observations and local knowledge. According to Mr Jensen, drains were installed in the 1960s and 1980s that saw wetland water levels remain low or below ground for much of the year, thus allowing farmers to graze the entire region. *"There was one summer in the 1960s when the peat was so dry I was able to stand in cracks as deep as my waist"*. Mr Jensen described some summers where all of the wetlands were dry - except one, the Stevenson / Sanft fen on the eastern side of the complex. His observations of wetland pond fluctuation are in line with those evident from the 2009 wetland monitoring data, where western wetlands fluctuate more than wetlands in the east. The conversation with Mr Jensen, together with historical aerial photos from 1948, 1967, 1977 and 1993 (shown in chapter III), identified a number of wetlands that have been dammed at their natural point of outflow. Figure 5.2.5 displays the positions of modifications relevant to the three monitoring sites. Areas of open water have appeared gradually in some wetlands on historical aerial photographs, probably due to excavation within the wetlands to encourage bird life and to provide a water source for stock.

Earth has been filled in around the outlet of some wetlands to create dams – these are marked dams A, B, C and D. Dams A and B were created to aid water retention in adjacent wetlands (Shoveler and Pateke respectively). As can be seen in the aerial photos, wetland areas north of dams A and B have been extensively drained since 1967. Dams C and D break up the once continuous wetland through the western edge of the complex. Culverts installed in the dams (culverts C and D) have a big influence on water movement through this part of the wetland, effectively acting as bottlenecks and define critical drainage levels. Flow through culverts A, B, C and D is determined by the water level in the wetland, so varies considerably, hence the level that the culvert is set at is therefore very important. Culvert C for example, according to Mr Jensen, has possibly never had water flowing through it because it is set too high in the dam. Culvert D is set much lower and as a consequence is either partly filled with water or completely below the water surface at all times. Culvert A is usually dry because it is located in what looks like the natural divide and water flows either north or south from here. However if ponds are high and there is a significant rainfall event then water flows northward through the culvert – possibly the consequence of the installation of dams C and D and culvert C being set too high. Flow direction around the wetlands is analysed in detail in section 5.2.2.

At the Pateke site (see figure 5.2.4), shallow groundwater continues to rise over the wet season (from October – December) where as the rise in pond levels over this time is more modest. The difference between shallow groundwater level and pond level is therefore greater during the wet months. Also, during the dry season pond water looks to rise and hold its level for longer. Given this, during the wet season the pond level seems to reach a point above which it drains more rapidly (figures 5.2.2 to 5.2.4). This may be due to the water level in the pond reaching near the top of dam B, around 5250 mm above sea level, above which macro pores in the soil facilitate more rapid drainage. Similarly at the Shoveler site, the pond water reaches close to the top of dam A in October / November, and does not rise much above 3150 mm above sea level (figure 5.2.3). Water regime observations at this site noted a small trickle of surface water flowing over the top of dam A during high water. The hydrology at Jill and Joy's site is slightly different. The difference between groundwater level and pond level remains relatively constant over the year (figure 5.2.2). This may be due to the influence of culvert D. When water level rises beyond the upper limit of the culvert the pond water cannot drain at a rate that is relative to water input, hence that culvert effectively acts as a 'bottleneck'. This is explored more in sections 5.2.3 and 5.2.4. Another drain that was installed by the previous farmer extends from the western edge of the O'Malley / Crafar Jensen wetland, south to the southern edge of the Trotter wetland (shown in figure 5.2.5). According to Mr Jensen, this drain remains at least partly functioning today.



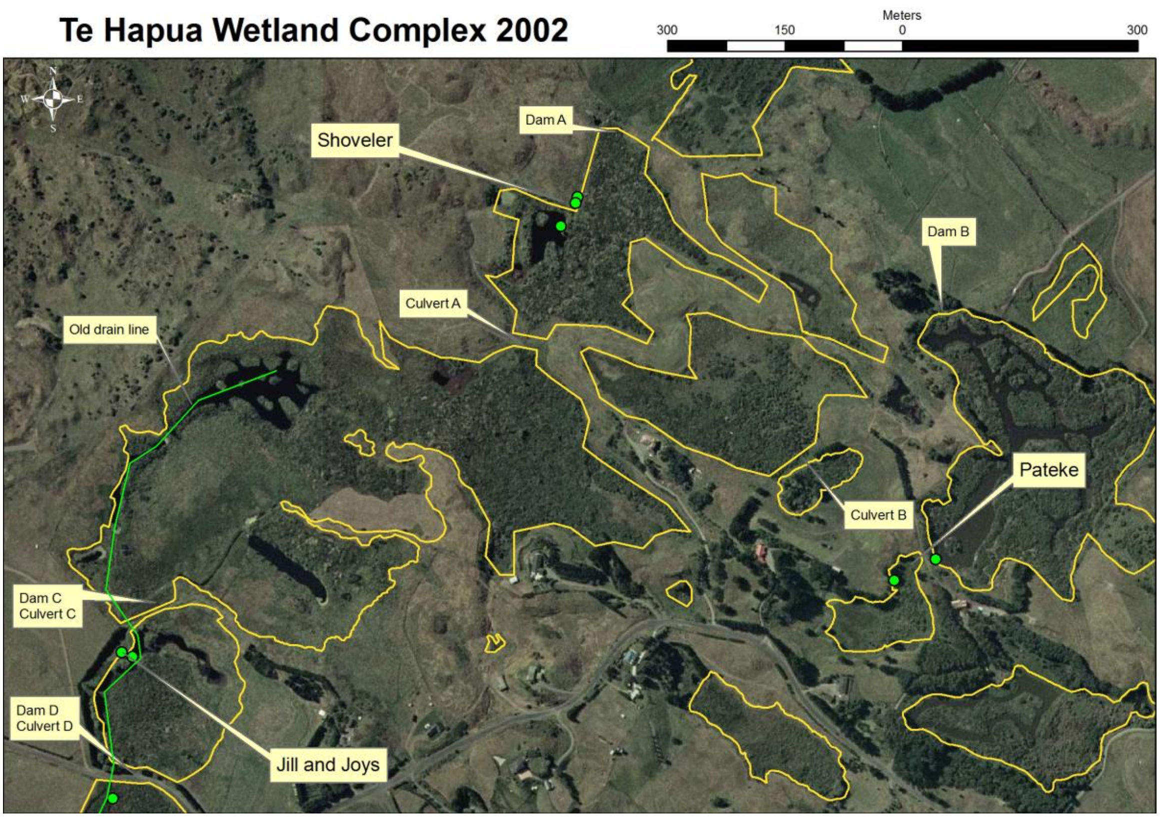


Figure 5.2.5: Te Hapua wetlands in 1967 and 2002. The location of features that may affect the hydrology at the three monitoring sites are shown in the 2002 aerial

5.2.2 GIS Analysis

A digital elevation model (DEM) of the study area was supplied by Wellington Regional Council. The DEM was derived from LiDaR remote sensing technology. LiDaR (Light Detection And Arranging) detects the range of an object (in this case the ground surface) by measuring the time delay between the transmission of a pulse (usually laser) and the return of its reflection from the object. The LiDaR can produce a data set with multiple elevation points per square metre. A GIS is then used to interpolate this data into a DEM.

The ArcGIS hydrology toolset was used to create a flow direction raster, flow accumulation raster, and watershed delineations (see process diagram, appendix 5), using the DEM together with wetland shape files also provided by Wellington Regional Council. Watersheds were calculated for the five main drainage basins within the Te Hapua complex (as defined by the flow accumulation raster); as well as to individual study sites (Jill and Joy's, Shoveler, Pateke and Trotters).

Field investigations revealed that some areas of the GIS output / DEM were not representative of the ground surface. The wetlands are typically situated in flat, low lying areas between dune systems. The western band of wetlands (see 'swamps' figure 5.3.2) are particularly low in elevation and are characterised by very subtle gradients that facilitate surface water movement. The natural shapes of low lying dunes in this area create discrete land bridges, where low narrow dunes separate individual wetlands. The dune crests may be as little as 1m above the level of the wetland, but form the divide either side of which is a separate catchment (see section 5.2.1). One of the problems encountered with the LiDaR was that the occasional presence of a dense 4m high canopy of flax would alter the interpolated ground surface level. The subtle natural controls on surface flow were therefore not realised in parts of the interpolated surface, and hence the direction and extent of drainage was lost. Another problem encountered was the presence of sub surface man-made drainage that is generally impossible to detect when using LiDaR or any other remote-sensed data. As discussed, parts of the wetland have been highly modified with the construction of dams, roads and associated culverts (see figure 5.2.5). Interpolating a surface using LiDaR data in an area where there is significant sub-surface drainage will produce an erroneous flow direction raster, and consequently the flow accumulation and watershed calculations will be incorrect. Finally, there was a problem with some of the delineations of the wetland shape /

boundaries. These areas had previously been incorrectly drawn, apparently due to access issues.

Ground truthing of elevation data was carried out in areas where man made structures or low lying land bridges affect flow surface direction, as well as where the vegetation canopy had given false ground elevation data. These were identified whilst visiting the site with landowner Ian Jensen to visually evaluate the watershed results calculated using the original DEM. Drainage in some areas was defined by the presence of culverts below land bridges, requiring elevation data from the point at which water would start flowing into the culvert (i.e. the bottom of the high end of the culvert pipe). Figure 5.2.6 shows the locations where ground truthing was carried out and the feature that is present at each location.

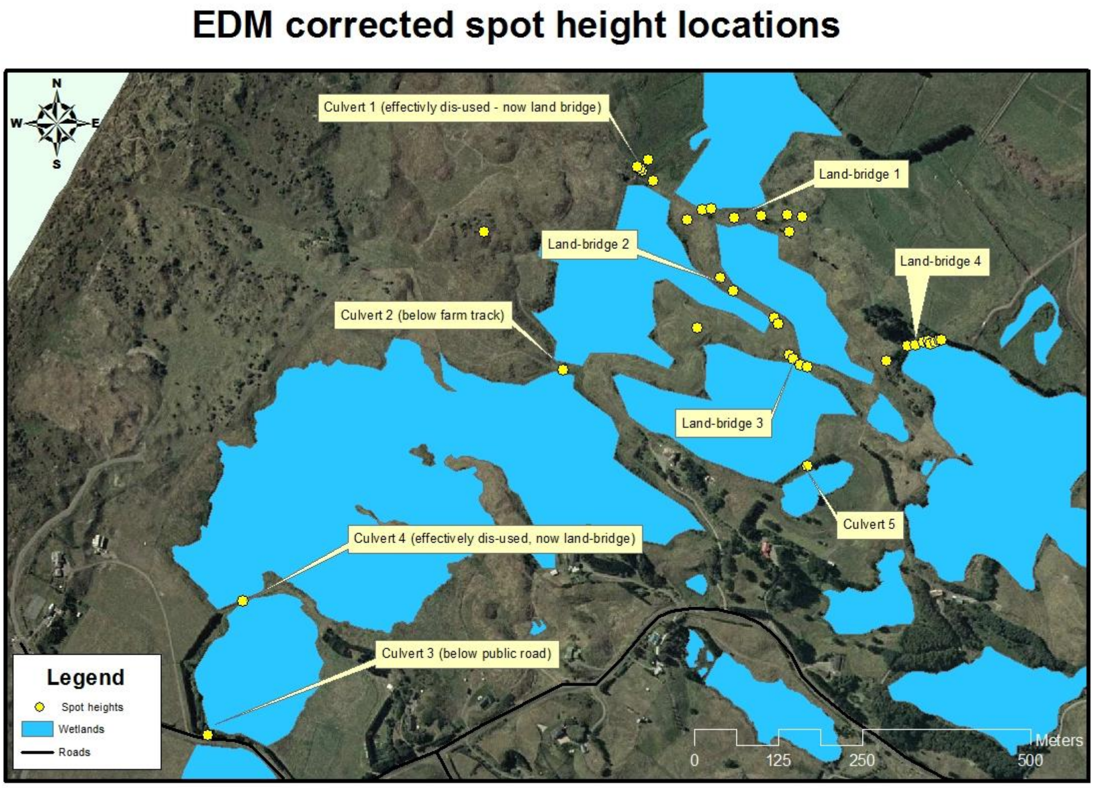


Figure 5.2.6: Locations of ground truth work carried out to correct elevation data around the wetland.

Ground truthing was carried out using a Total Station EDM to collect elevation data, together with differentially corrected GPS data to capture horizontal point data. Differentially corrected vertical GPS data alone could not be relied on for accurate elevation, as it is only capable of 1 to 2m accuracy. The Total Station (Sokkia 03R) was set up with a staff mounted prism reflector and tied into established survey benchmarks around the wetlands. EDM data was processed using Mapsuite plus (version 7.0) software, giving an accuracy of +/- 5mm (Sokkia, 2006). An external GPS antenna was mounted on the prism reflector. The GPS (Trimble GeoXT) recorded horizontal point data in the same locations. 60 points were recorded over a 1 minute interval using carrier phase data. A GPS base station (Trimble Pro XR) was set up at a known trig point for the duration of the survey (2 days). The base data was processed using Trimble Pathfinder Office (version 3.10), giving a post processed accuracy of +/- 200-300mm (Trimble, 2005, 2006).

The EDM and GPS point data was then integrated into an ArcGIS shapefile and from there into a new DEM which was used for the analysis of surface hydrology in ArcGIS as described above. To create a culvert in the DEM, the upstream and downstream ends of the culvert were measured (elevation and location). When merging the data with the existing LiDaR points, it was necessary to create a 'stream' to replace the known culvert locations. The elevation of each end of the culvert was measured during ground truth field work, and then linked in ArcGIS by creating more points in between to create a gradient. One culvert proved problematic because there were canopies of flax and large trees nearby. To overcome this it was necessary to clear a patch of the existing LiDaR points around the area of the culvert – a buffer of approximately 12m. The new culvert points were then the only source of data within the 25m area that the interpolation could use. This created a broad flow pathway in the DEM at the level of the culvert. This new feature is visible in the hill-shade version of the DEM in figure 5.2.11 – just above the Trotter site.

The data was interpolated using both a 1x1m and a 5x5m cell size. The different resolution DEMs gave slightly different results, so to illustrate this issue both results are given. Figures 5.2.7 and 5.2.8 show two areas where different results were achieved by using different resolution DEMs to calculate surface flow. Figure 5.2.7 shows problem area 1, where the cells calculated using the 1x1m DEM do not intersect with the wetland area. The 5x5m DEM cells overlap with the edge of the Jill and Joy wetland shape. This 'edge effect' results in a difference in calculated watershed of approximately 8.1 hectares – the 5x5m interpolation having a watershed almost twice the size of the 1x1m. Looking more closely at the problem area, the flow accumulation line in question (see arrow on the left hand side of figure 5.2.7) passes very close to the wetland, but surface water does not actually enter the pond from this drainage area. The coarser resolution of the 5x5 flow accumulation model overlaps the watershed flow line with the wetland shape. This infers a flow path between the two and hence incorrectly interprets the data.

The 1x1m calculation is therefore the more 'correct' interpretation of the watershed (see figure 5.2.12). 'Edge effect' is a potential source of error in other parts of the wetland too.

As discussed, the wetland shape file supplied by Wellington Regional Council was not 100% accurate. It was therefore necessary to visually ground truth wetland delineations in specific areas and then apply these changes to the wetland shape file. Wetland shape is seasonally different, so for the purpose of calculating watersheds using a DEM, the wetland shapes used for the calculation should probably be delineated using the highest possible water level. However time and resources for this study were limited, so it was not possible to re-evaluate all wetland shapes.

Figure 5.2.8 shows problem area 2, where the drainage direction changes from south bound in the 1x1m DEM, to north bound in the 5x5m DEM (see arrows). Ground truthing at this location revealed that the flow direction is usually toward the south. However, according to land owner Ian Jensen, when the wetland pond level is particularly high and there is a significant rainfall event, surface water flows back up through the culvert in a northward direction. The coarseness of the DEM affects the modelled flow direction in this area due to very slight changes in elevation. For the purposes of this study, the 1x1m cell size interpretation is relevant for the majority of the time. The watershed calculated for individual wetlands (figure 5.2.12) gave a very similar result using both DEMs, with a difference in watershed area of 0.3 hectares. The second problem in this area is the delineation of the wetland shape. The shape does not include a low lying area to the northwest of the wetland (see figure 5.2.8). Though not officially 'wetland' it would almost certainly receive runoff from the watershed northwest of here, marked by the flow accumulation line that runs nearby. This will decrease the calculated watershed area.

DEM data such as that derived from LiDaR is a useful tool for the analysis of surface water flow using the ArcGIS hydrology toolset. However, in an environment such as this it has proven problematic. The existence of culverts and sections of old drainage complicates the hydrology and undermines the value of the GIS interpretation of surface flow and watershed. However with high resolution wetland shape delineation, ground truthing where necessary, some local knowledge, and careful editing of the DEM, a reasonably accurate picture of the watersheds have been created. Figures 5.2.9 to 5.2.12 summarise the results of the analysis.

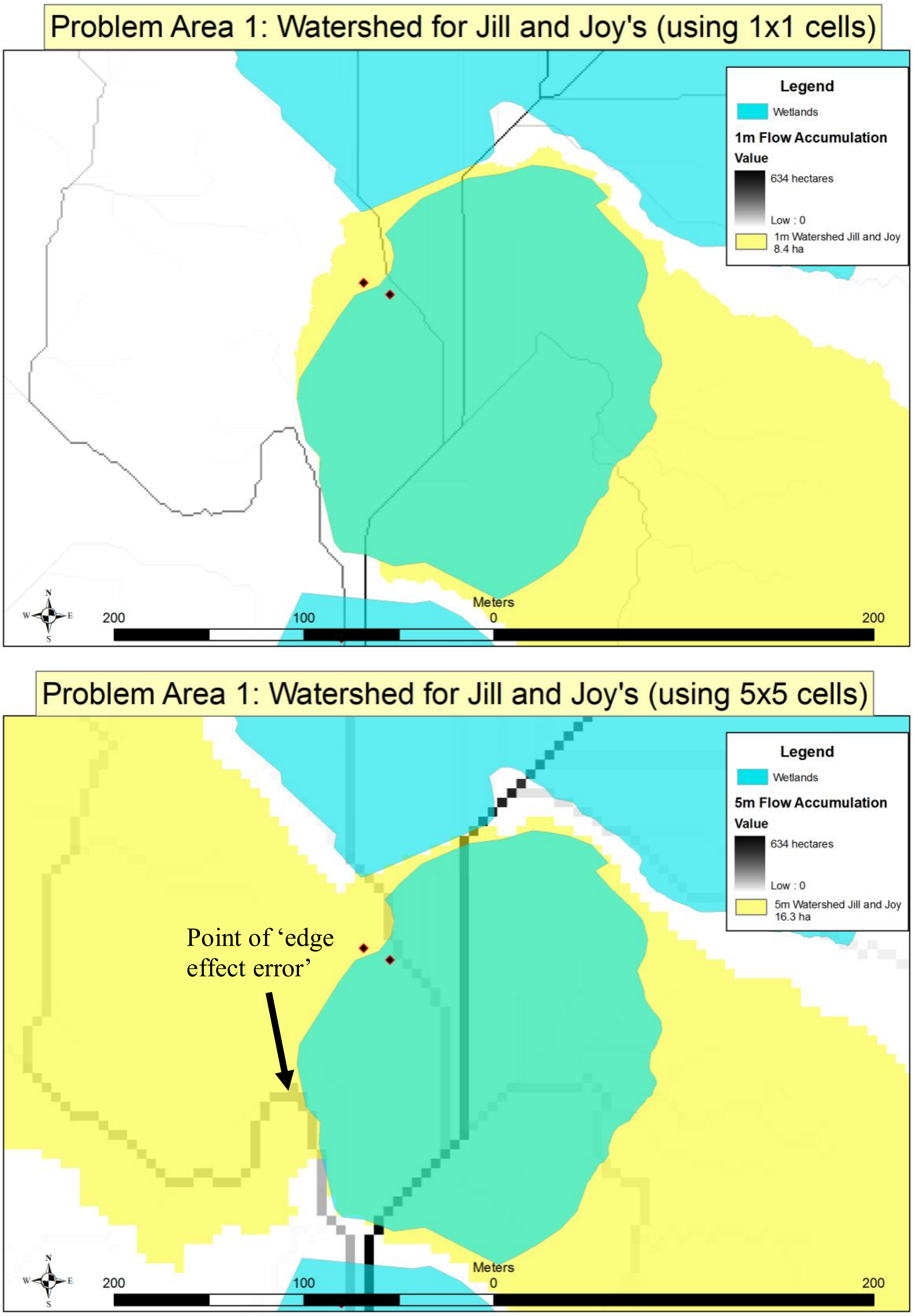
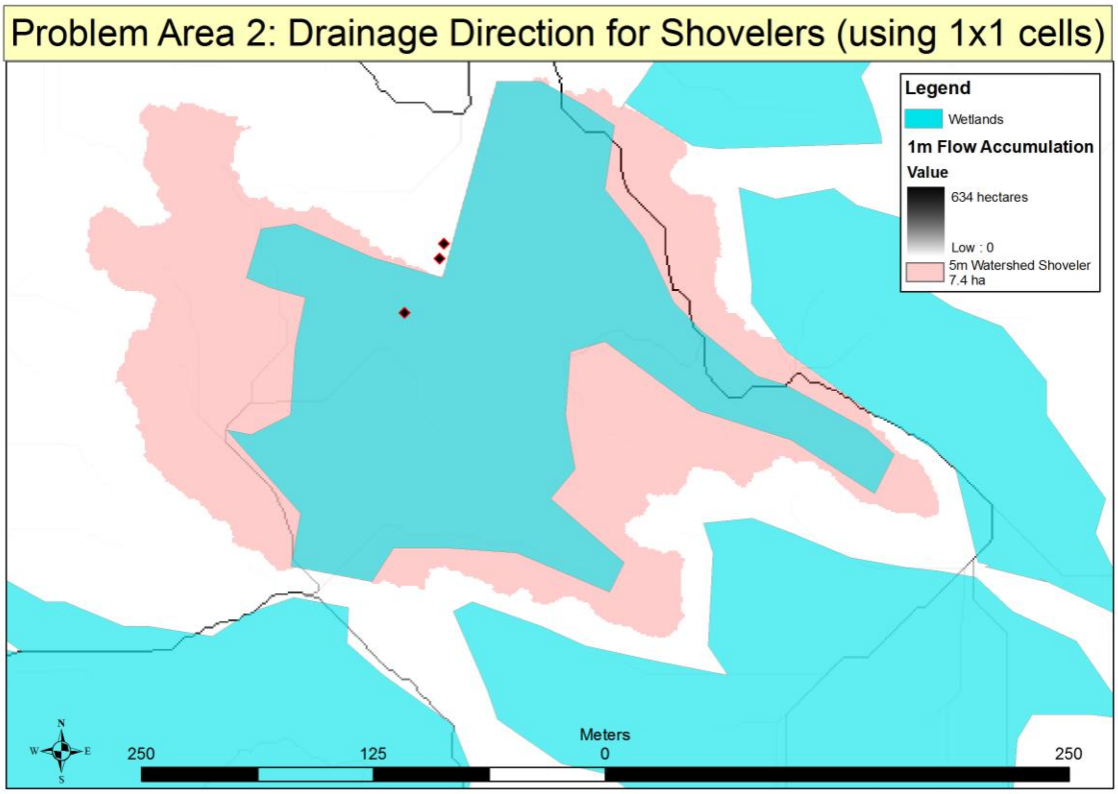


Figure 5.2.7: Problem area 1: Using the 1x1m DEM instead of the 5x5m DEM reduced the size of the watershed by 8.1 hectares because of 'edge effect' caused by the larger 5x5m cell size.



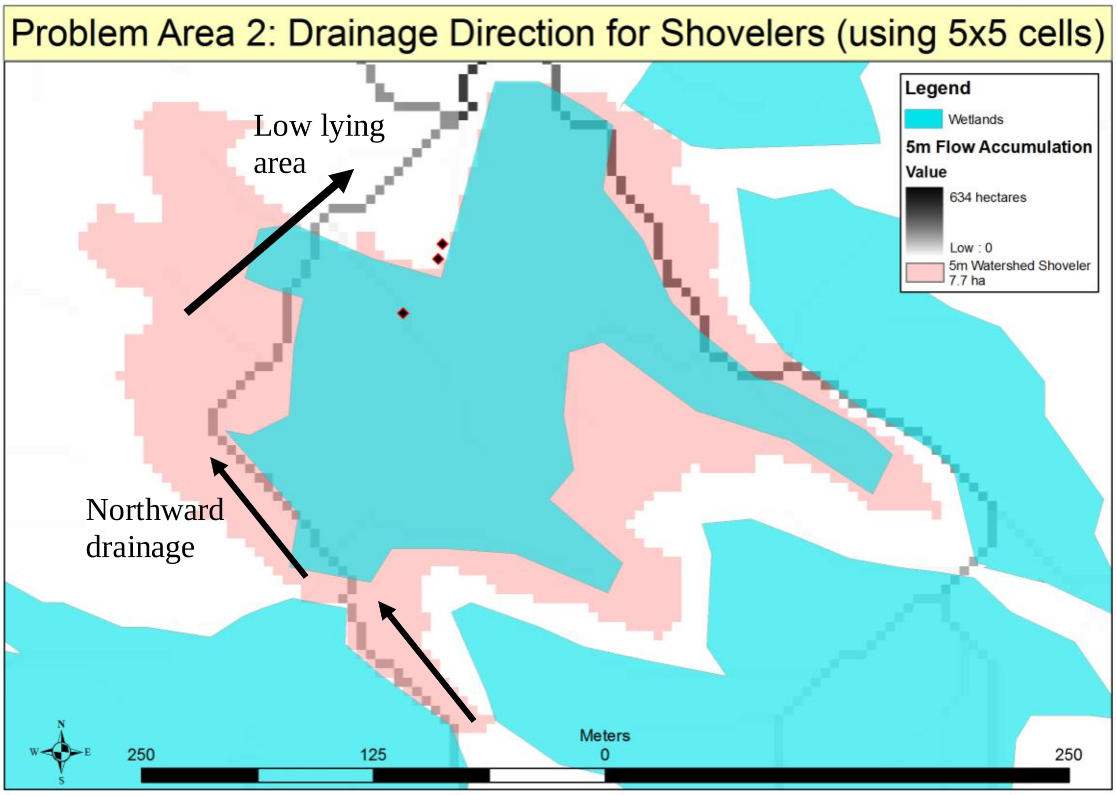


Figure 5.2.8: Problem area 2: Given the small changes in elevation throughout the wetland, using a 1x1m DEM instead of a 5x5m DEM can bring about an entirely different flow direction.

Results: surface drainage / flow accumulation

Figure 5.2.9 shows the corrected wetland shapes and flow accumulation calculated using ground truthed LiDaR data. As discussed, the actual flow of surface water in the wetlands is dependant on the pond level. Flow accumulation calculates the runoff area that flows through each cell of the DEM. It does not consider loss to groundwater, interception or evapotranspiration. It is therefore important to note that the flow accumulation lines that have lower values (i.e. are lighter in colour on figure 5.2.9) serve only as an indication of drainage direction within the contributing area, not actual surface flow. By the time surface water makes it to the areas with higher flow accumulation value (i.e. the darker lines) there is a stream (or excavated drain) that looks to be more or less permanent – for example the line south of the Trotter site and north of the Shoveler site. Land bridges separate all of the individual wetlands shown on the map. Some are linked with culverts but many of the culverts do not allow flow until the water level is sufficiently high. Given this, it seems safe to assume that water runoff moving around this part of the wetland complex is mostly via through-flow.

Watershed analysis

Figures 5.2.10 to 5.2.12 below show the calculated watersheds at various scales of interest. These figures include watershed surfaces interpolated at 1x1m and 5x5m, to illustrate the difference in watershed area and shape depending on the cell size. Figure 5.2.10 is a broad look at all of the wetland areas and the points where surface water would flow. There are five main watersheds within the wetland complex. Figure 5.2.11 focuses on the monitored wetlands only, and considers the entire watershed 'uphill' from each site. This encompasses other wetlands nearby and their associated watersheds that could potentially contribute to the monitored wetland. Figure 5.2.12 looks at the watershed immediately surrounding the monitored wetlands. This is the primary source of surface recharge for each wetland given local rainfall.

Given the edge effect error discussed earlier and assuming that higher resolution data will be more accurate, the 1x1m resolution DEM provides the most accurate picture of watersheds for the wetlands. The wetland shapes provided by Wellington Regional Council are not accurate in some areas, so the watershed calculations will not be exact. Without a detailed survey of all wetland areas this is an inevitable source of inaccuracy.

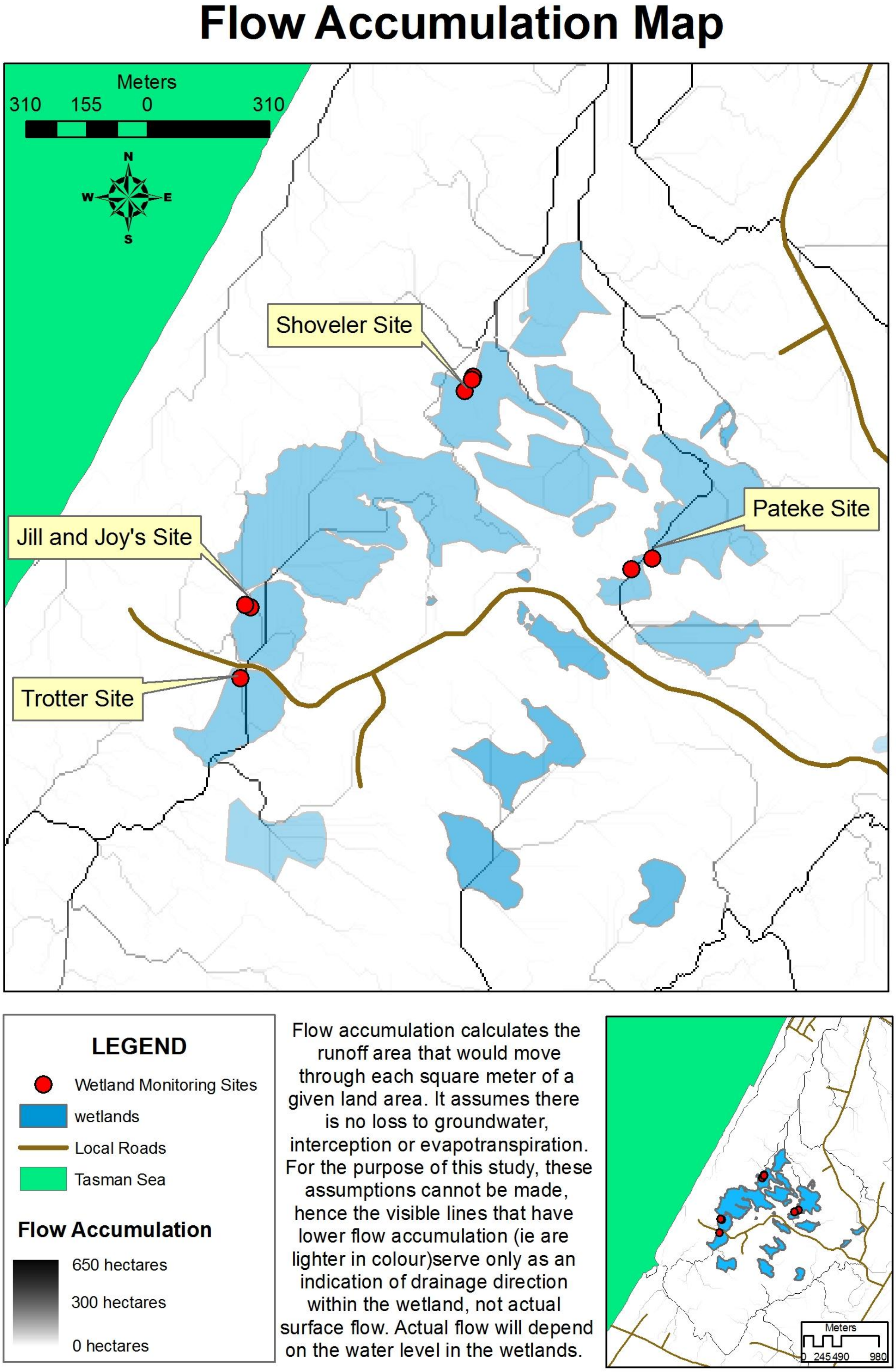
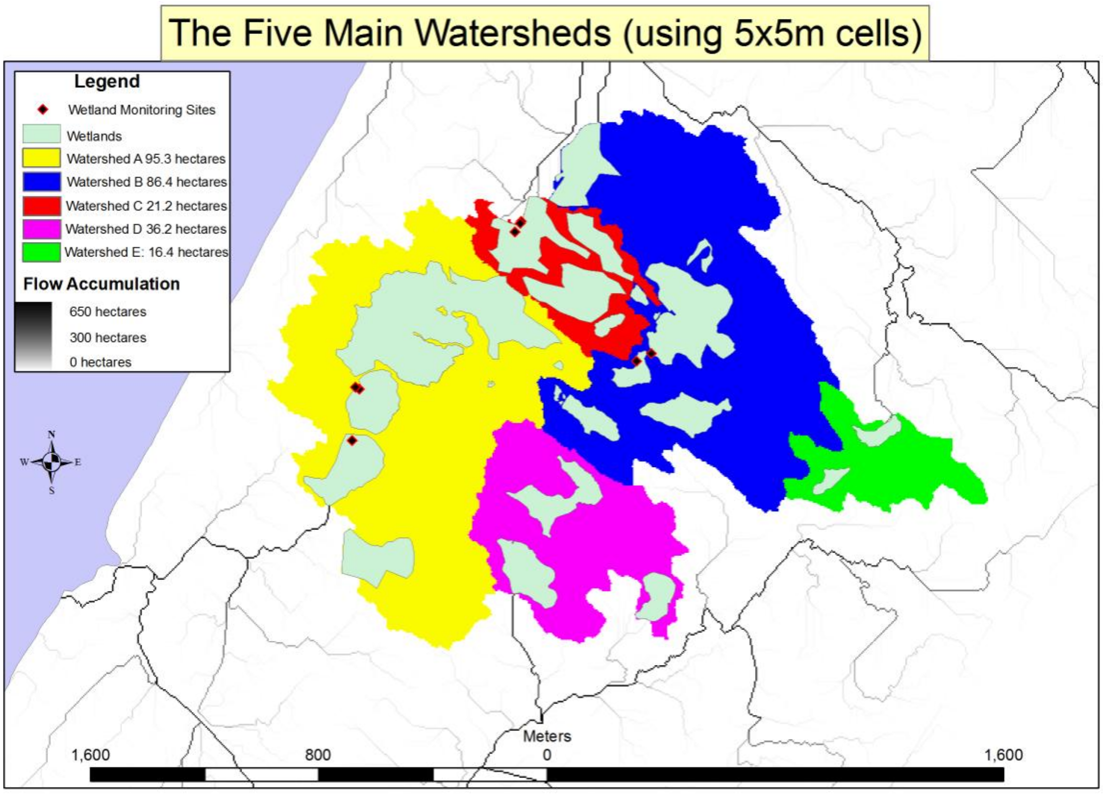


Figure 5.2.9: Flow accumulation and direction in the Te Hapua wetland complex. The 5x5m DEM was used for this map because it is very similar to the 1x1m DEM and much easier to see the drainage patterns. The flow accumulation index shown in the legend displays the approximate number of hectares that contributes to a given flow accumulation line.

Summary

Wetland areas were mapped together with LiDaR elevation data across the study site. Flow accumulation was calculated and watershed was mapped for individual wetlands. Wetland areas calculated using a shape file supplied by Wellington Regional Council (WRC) gave approximate sizes of 3.1ha, 4ha and 7.3ha for Jill and Joy's, Shoveler, and Pateke wetland respectively. The immediate watershed calculated for each wetland was 8.4ha, 7.4ha, and 17.8ha respectively. There are five main drainage basins in the Te Hapua complex, two of which have seasonally significant surface outflows.

There were problems with the data used for the GIS analysis. The LiDaR data gave false elevation readings in some areas where dense vegetation covered the land surface. Also, the LiDaR data could not pick up on subsurface drainage in the area. This affected the DEM and subsequent calculations of flow direction and accumulation. Ground truthing and manipulation of a new DEM to show culverts as surface depressions eliminated these problems. Further problems were encountered because the WRC wetland shape file was not accurate in some areas. This resulted in errors in the watershed calculation and could not be completely remedied without a full survey of the wetlands. Due to time constraints this was not possible but an estimate based on field observations was sufficient to fix most of the problem areas.



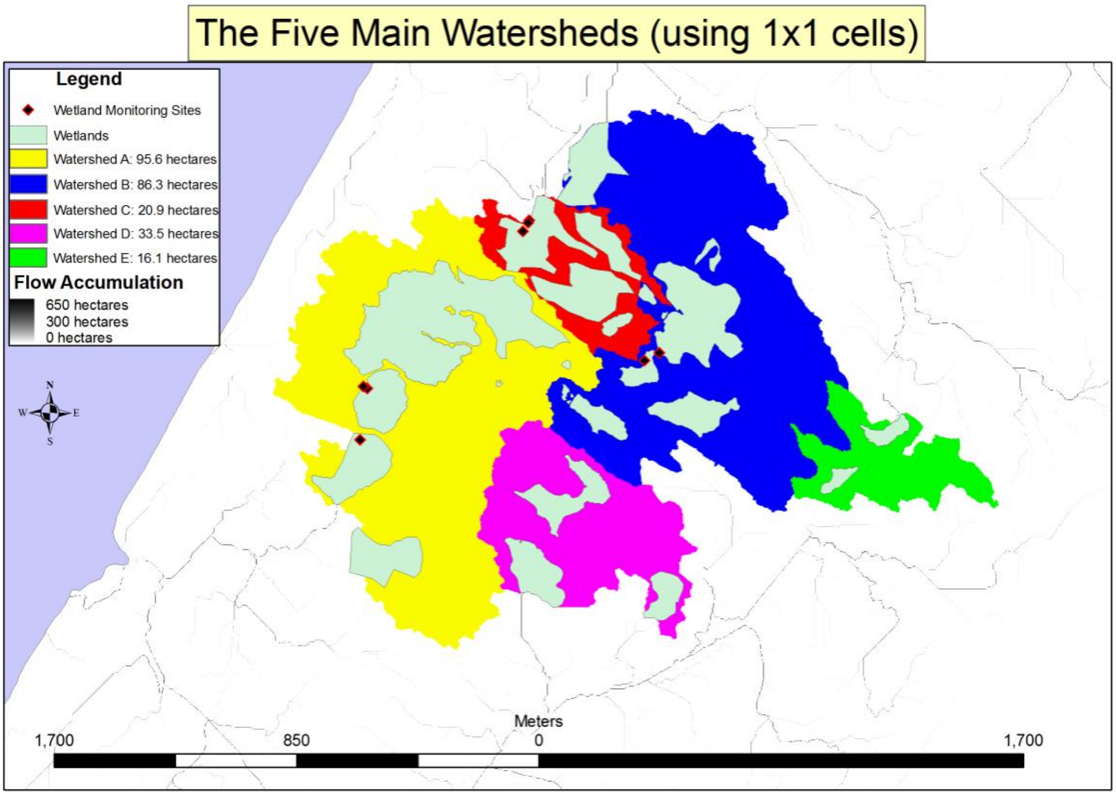
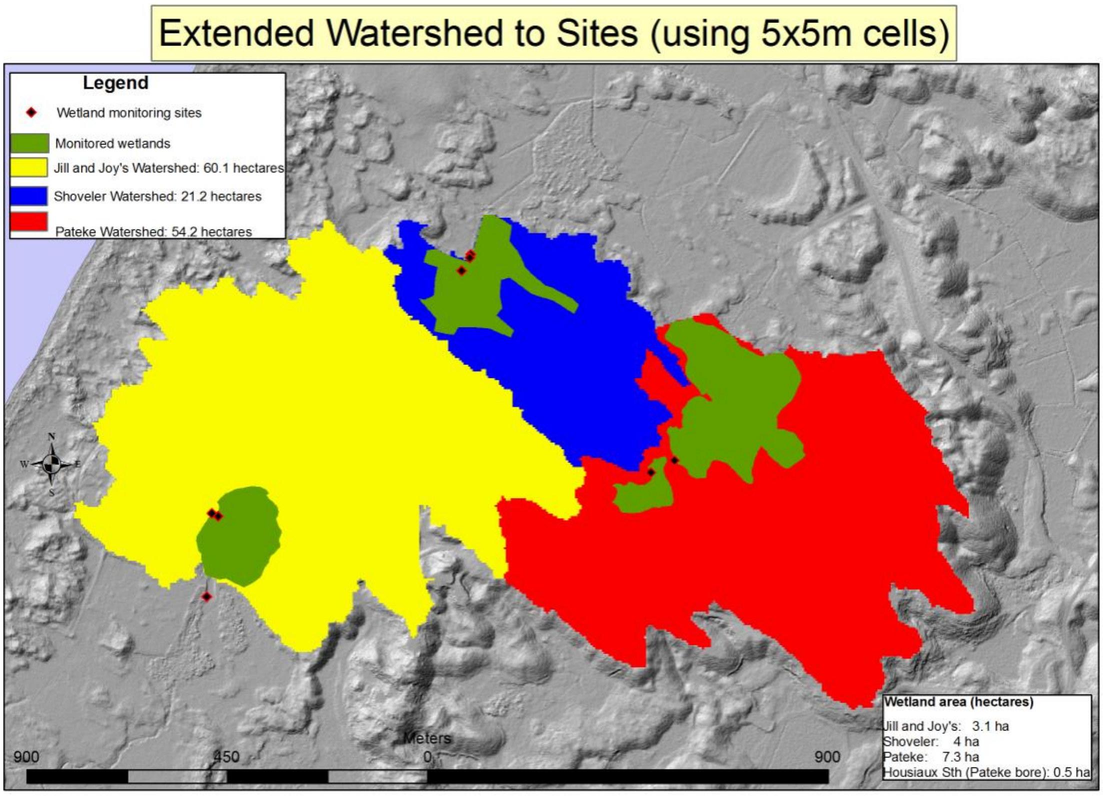


Figure 5.2.10: The five main drainage basins of Te Hapua



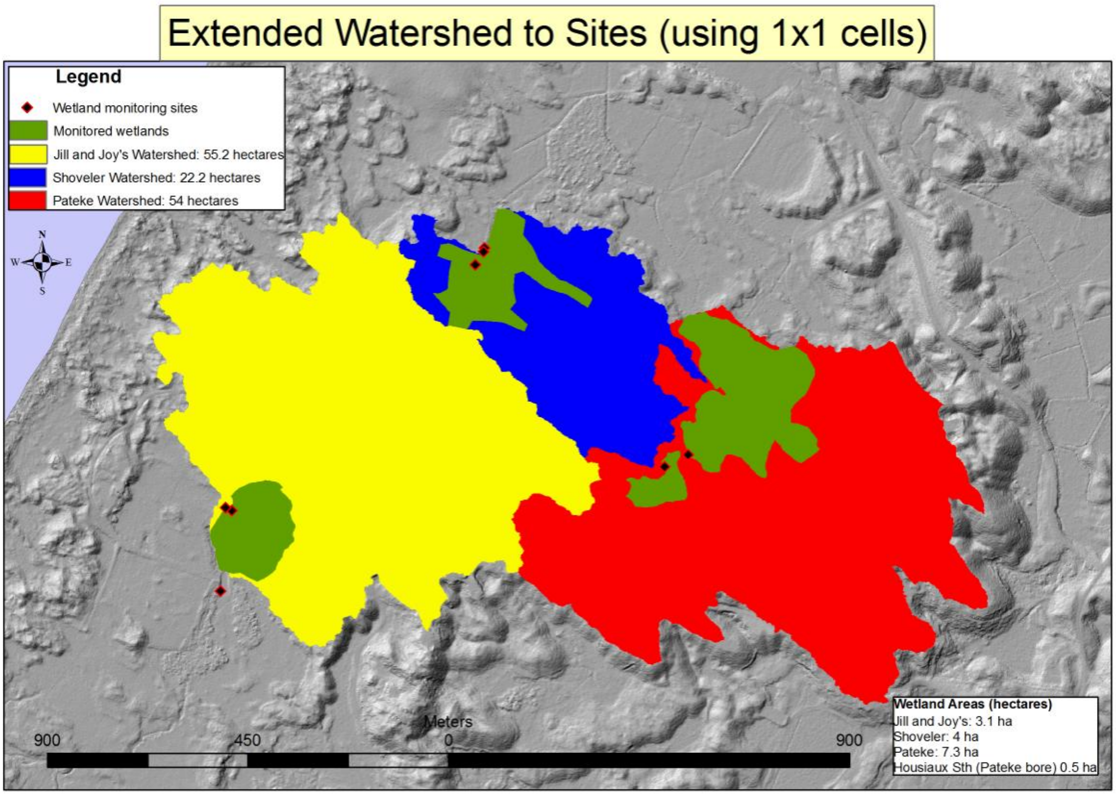


Figure 5.2.11: Full drainage to the three monitoring sites at Te Hapua. This includes all of the wetlands in the complex (and their catchments) that ultimately drain through the monitored wetlands.

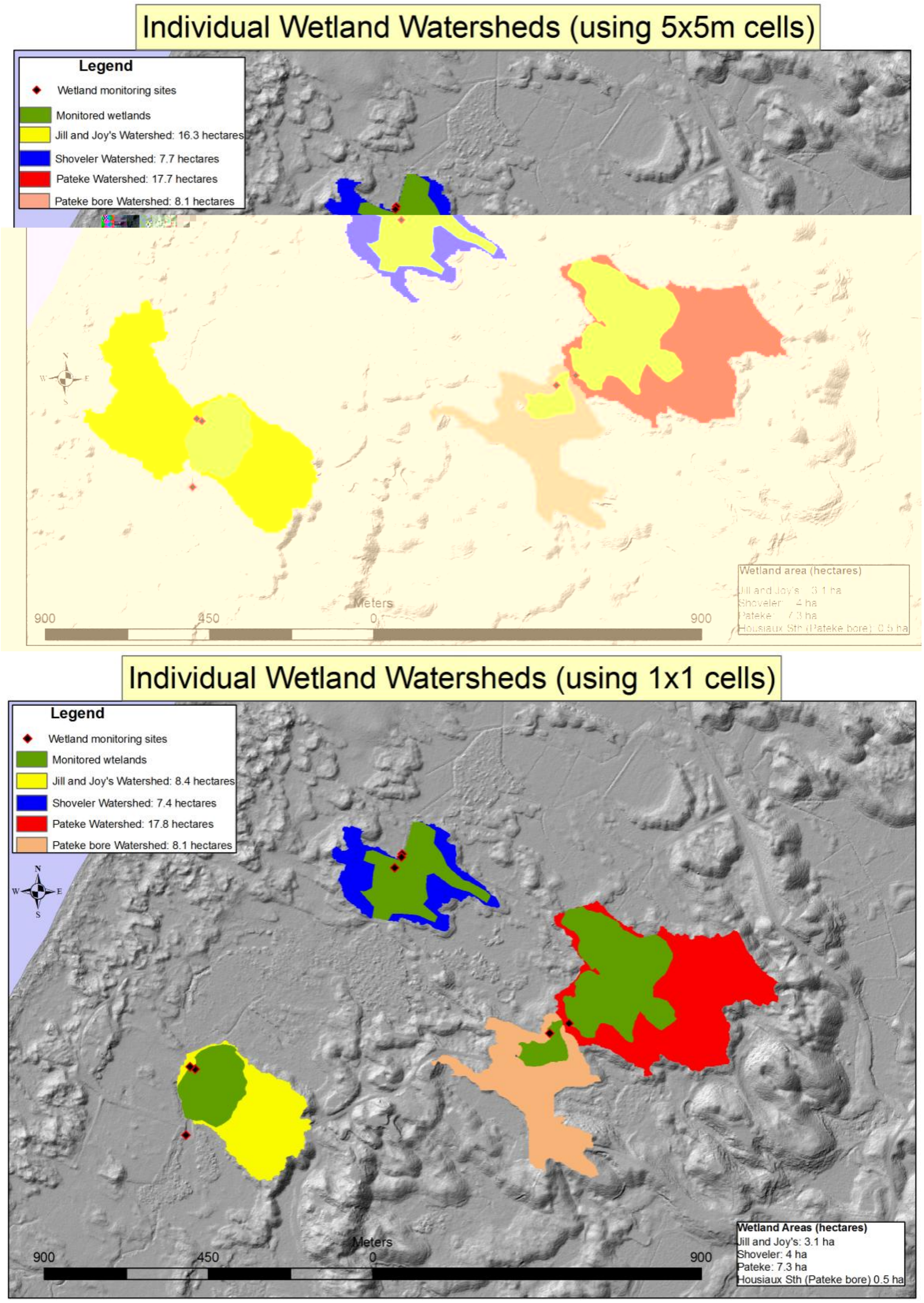


Figure 5.2.12: Drainage of the immediate catchment surrounding monitored wetlands in the Te Hapua complex.

5.2.3 Water Balance: Net Flow Calculations

As discussed in chapter II section 2.5, a water balance can be calculated for a given wetland by quantifying the various inputs and outputs (equation 2.2).

Equation 2.2: ***Wetland water balance***

$(P + Q_{in} + G_{in}) – (E + Q_{out} + G_{out}) = \Delta S$

Where: ΔS = change in stored water within the wetland; P = precipitation; Q_{in} = surface water inflows; G_{in} = groundwater inflows; E = evapotranspiration; Q_{out} = surface water outflows; G_{out} = groundwater outflows.

(Campbell & Jackson, 2004)

Precipitation (P) was measured by Wellington Regional Council and evaporation (E) was calculated by NIWA over the course of the study. Change in storage (ΔS) can be calculated from wetland water level data. Surface water input (Q_{in}) is negligible in the three monitored wetlands and surface water output (Q_{out}) proved too difficult to measure due to slow / nil velocities and eutrophic weed growth. Without these surface water quantities, inferring groundwater movement to complete the water balance becomes difficult. Instead it was decided to look at the data in terms of net wetland inflow and outflow. This approach still allows us to build a picture of spatial variability between the three sites and enables comparison between the ponds and nearby shallow groundwater to help define their relationship. The other issue with using traditional hydrology (i.e. Darcy’s Law) to infer groundwater movement in this environment is that water movement though peat soil is often considered unpredictable and hence may be an inappropriate application. As discussed in chapter II section 2.5.7, pores are often blocked by gas bubbles that form as a result of microbial activity in the anaerobic environment (Baird, 1997; Campbell & Jackson, 2004). This can block water flow in an unpredictable way. Peat soils are also different from most other soils in that pores decrease in size and permeability with depth due to being more decayed and compacted in deeper layers (Campbell & Jackson, 2004).

Net flow was calculated for the three Te Hapua wetland monitoring sites; Jill and Joys, Shoveler and Pateke. Calculating the net flow for each wetland gives an idea of the relative influxes and out-fluxes whilst taking into account local rainfall and evaporation. Equation 5.1 below was used to calculate the net flow (in/out) of the wetland at each of the three monitored sites. Net Flow (Figure 5.2.13), Cumulative Net Flow (figure 5.2.14) and Relative Water Level (Figure 5.2.15) can be used to compare the hydrology of the three sites. Rainfall was measured on-site at the Shoveler wetland. Open water evaporation data for the same period was downloaded from the NIWA climate database.

Equation 5.1: ***Net Flow of water (in/out)***

Drainage (t) = Pond level (t) – Pond level (t+1) + Rainfall (t) – Evaporation (t)

Note: All units are in mm

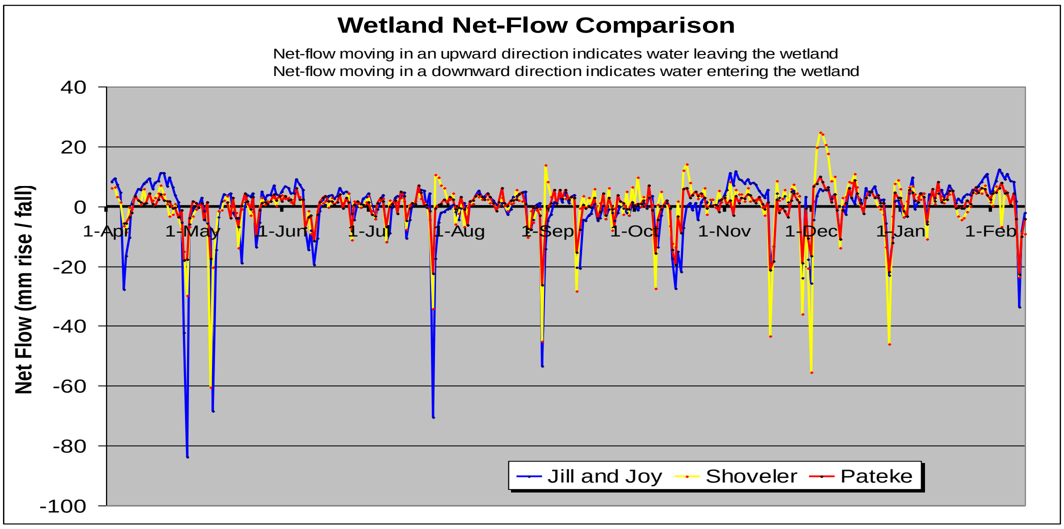


Figure 5.2.13: Net-Flow fluctuation for the three sites between April and November 2009. Note the direction of net flow movement indicates if water is entering or leaving the wetland. Around May 1st, for example, there was a significant rainfall event, so a large downward net-flow followed as water entered the wetland. This water quickly left the wetland area (upward net-flow). Rainfall events are therefore typically seen in the wetland net-flow graph as downward spikes.

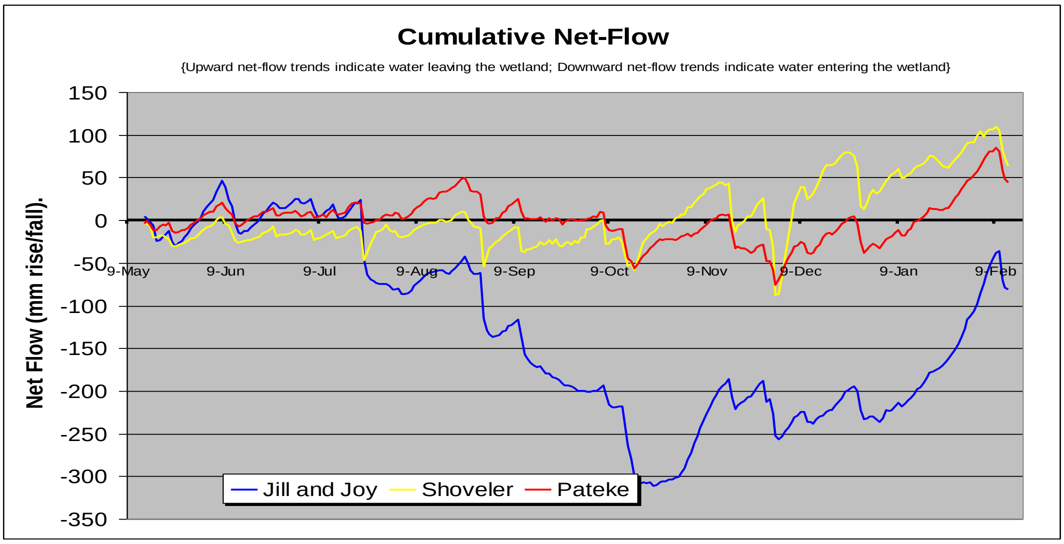


Figure 5.2.14: The cumulative net-flow for the three sites between April and November 2009. Note that a gap in data at the Pateke site in May skewed the Pateke data, so all data was started after the gap in May.

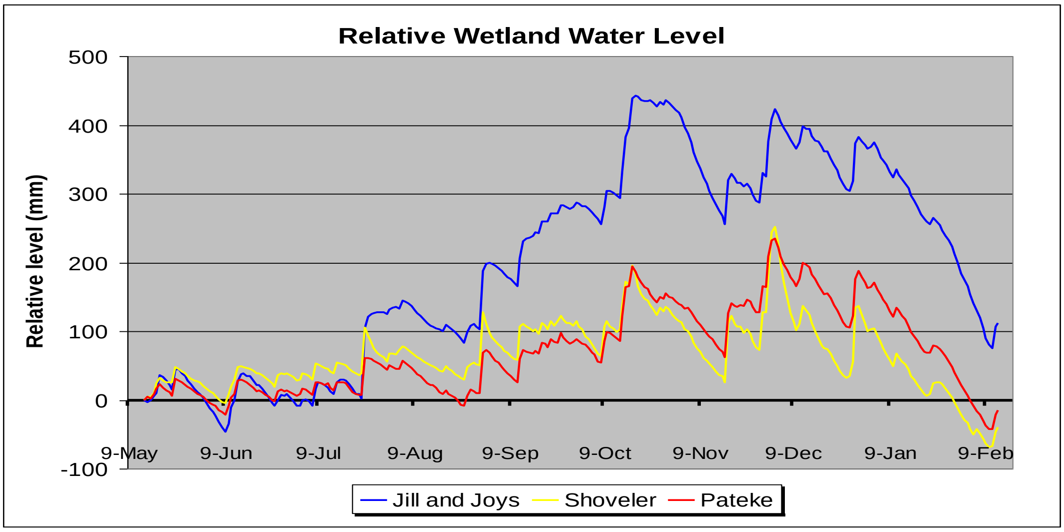


Figure 5.2.15: The relative water level for the three sites between April and November 2009. Note that a gap in data at the Pateke site in May skewed the Pateke data, so all data was started after the gap in May.

These graphs show two interesting trends:

During the 'dry season' (April to August 2009), Jill and Joy's pond level rises and falls much more than the other sites (Figure 5.2.13). From about September (when relative water levels are higher), water level at Jill and Joy's tends to maintain a relatively steady height, rather than rise and fall (Figure 5.2.13). The other sites continue to rise and fall as they did during the earlier period. Cumulative net-flow and relative water level at Jill and Joys are much higher than the other sites over this 2009 'wet season'. This indicates that, compared to the other sites, more water is entering (and leaving) Jill and Joy's pond in the earlier months, and less is leaving in the later months. In other words there is more storage occurring at Jill and Joy's wetland over winter months. A possible explanation for this is that water reaches the top of culvert D sometime in mid-September. Water can no longer drain effectively so water accumulates. Meanwhile at Pateke and Shoveler lagoon, where the main water influx / out-flux is via through-flow, water is still able to drain (or seep) at a 'usual' rate.

Wetland pond level at the Pateke site fluctuated the least (figure 5.2.13 and 5.2.14). There are two possible explanations for this. One is that Pateke, being a recharge wetland, has a buffered hydrological response following rainfall. A recharge wetland is most influenced by groundwater inflow and hence water level fluctuations are more buffered than in surface water dominated wetlands. Another possible reason for there being less fluctuation at Pateke is that the wetland size and shape is such that incoming water results in an increase of area rather than level. It is therefore necessary to calculate the change in volume to determine the change in storage, rather than water level. This is covered in detail in section 5.2.4 for each site during five individual rainfall events.

Factors that may be important when considering possible reasons for the differences in net flow between the different sites include:

- The size of the wetland relative to its watershed, and corresponding increase in water volume as opposed to wetland water level.
- The presence of culverts and dams that drain at different rates depending on the height that the culverts / dams are set.

Table 5.2.2 summarises the % area each wetland covers in its catchment. The areas used were calculated using ArcGIS (see section 5.2.2 for details on methodology and full results). Two watershed definitions were considered; one that looks at watershed immediately surrounding the wetland (immediate catchment); and one that encompasses watershed from the wider flow accumulation (extended watershed), as calculated in the GIS analysis described in section 5.2.2. This includes other wetland areas and their immediate catchments that will ultimately drain into the monitored wetland.

Table 5.2.2: Catchment size and dominant drainage at the three sites (calculated using GIS watershed analysis described in section 5.2.2).

Wetland Name	Pond area (hectares)	Immediate catchment size (hectares)	Extended catchment size (hectares)	% Pond to Immediate catchment	% Pond to extended catchment
Jill and Joys	3.1	8.4	55.2	37%	6%
Shoveler	4	7.4	22.2	54%	18%
Pateke	7.3	17.8	54	41%	14%

Comparing the three sites, Jill and Joy's wetland has the smallest pond size relative to both catchment definitions. Having a small pond and large catchment could partly explain why the pond at Jill and Joy's fluctuates more during the dry season than at the other sites.

5.2.4 Relative water level during significant rainfall events

Wetland response to five individual rainfall events were compared using rainfall data collected at the Shoveler site. Events analysed occurred on April 29th, July 24th, October 14th, November 18th, and December 1st (shown as arrows on figure 5.2.16) and the response of shallow groundwater and wetland pond level was compared for all three sites (figure 5.2.17).

Equation 5.2 was used to calculate the volume of rainfall for each of the five events using both the wetland pond area and the wetland pond catchment, as defined from Wellington Regional Council's wetland shape file and the ArcGIS methods described in section 5.2.2. Table 5.2.3 and figure 5.2.17 summarise the results. Equation 5.3 was used to calculate the maximum change in volume observed in each wetland during each event.

A problem with this analysis is that it calculates the change in volumes using the Wellington Regional Council wetland shapes. As discussed already, these shapes are not 100% accurate. Also, the wetted area of each wetland will change depending on the pond level, so calculations that use the same wetland area for events in the dry season and wet season may not be accurate. It does however give an indication of the pond's volumetric response to rainfall and the approximate proportion of rainfall that ends up stored in the wetland.

Equation 5.2: ***Rainfall volume for a given rainfall event***

Volume (m^3) = (rainfall (mm)/1000) x pond (or) catchment area (m^2)

Equation 5.3: ***Volumetric increase in pond level for a given rainfall event***

Volume (m^3) = change in water level (m) x pond area (m^2)

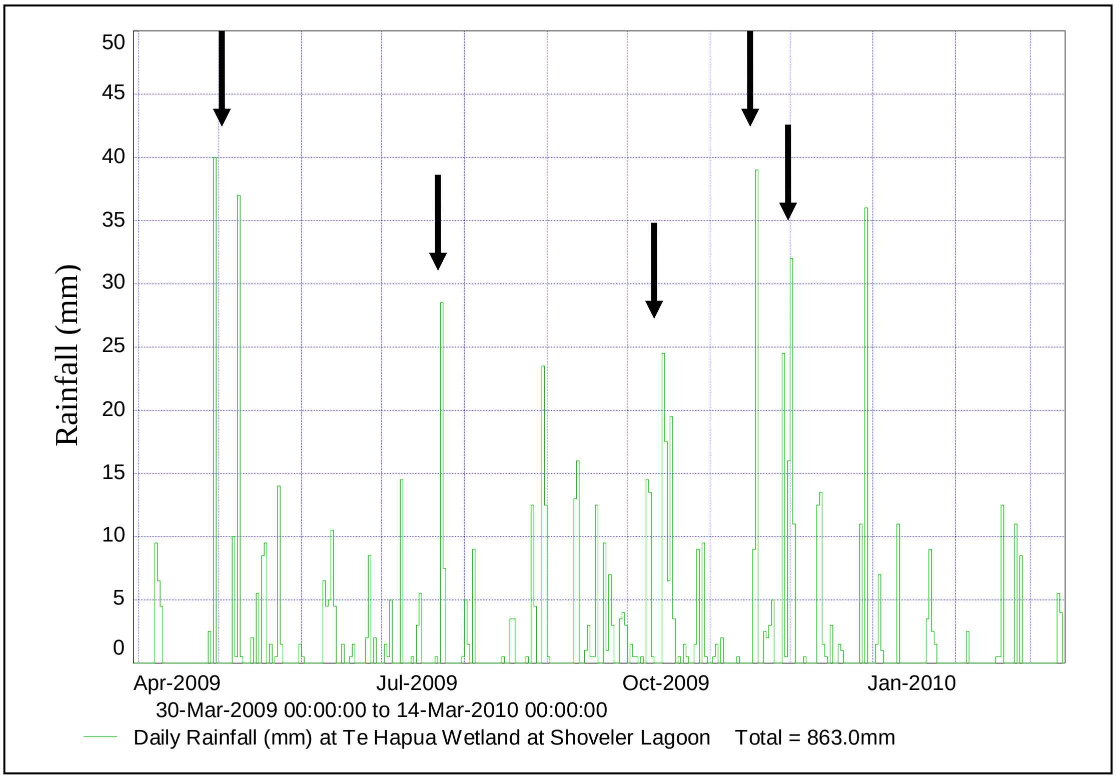


Figure 5.2.16: Daily rainfall at Te Hapua wetland. Arrows indicate events used for the analysis.

Table 5.2.3: Summary of rainfall volume and change in pond volume for the five rainfall events.

Wetland Name		Rainfall Volume (m^3)				
		April	**July**	**October**	**November**	**December**
Jill and Joy's	Pond Area (3.1 ha)	1317	1116	2294	1627	1829
	Catchment Area (8.4ha)	3570	3024	6216	4410	4956
	Change in pond volume (m^3)	5301	3689	4619	2356	2976
Shoveler	Pond Area (4 ha)	1700	1440	2960	2100	2360
	Catchment Area (7.4ha)	3145	2664	5476	3885	4366
	Change in pond volume (m^3)	4040	2720	4160	4320	5200
Pateke (wetland site only)	Pond Area (7.3 ha)	3102	2628	5402	3832	4307
	Catchment Area (17.8 ha)	7565	6408	13172	9345	10502
	Change in pond volume (m^3)	5913	3577	8030	5767	5548

An 'expected' result from this analysis would be a progressive increase in water volume across the three measures: such that the smallest volume is calculated using rainfall over the pond area; and the largest is calculated using rainfall over the catchment area. In theory, the change in pond volume should be somewhere in between. Some of the rainfall that has fallen on the catchment will be lost to either evapotranspiration or groundwater recharge before it reaches the pond. The volume of catchment rainfall that is greater than the volumetric pond increase is the approximate amount of rainfall that has been lost.

The results in table 5.2.3 and figure 5.2.17 show that this 'expected' result did not always occur. This indicates that some of the assumptions made are not accurate at the given place and time. Pond volume at the Shoveler site increased more than the volume of rainfall on the catchment during 4 of the 5 rainfall events. There are two possible explanations. One is that the calculated catchment area for the Shoveler pond is smaller than the actual catchment area. This is probably true given the problems encountered with the GIS analysis – namely the inaccurate wetlands shapes not intersecting with the flow accumulation lines when calculating watershed. The area marked 'Low Lying Area' in figure 5.2.8 is an area that probably receives surface runoff (and shallow groundwater inflow) from dunes to the west. Since the wetland shape did not intersect with the flow accumulation line during the analysis, and the topography in this area is relatively featureless, that part of the catchment was not included. This error highlights the limitations of using LiDaR data and GIS to delineate watershed in low lying wetlands. The other possible explanation for the volume results at the Shoveler site is that the wetland is groundwater fed as well as rainfall, though this seems unlikely given multiple confining layers below.

During the April and July events, Jill and Joy's wetland volume increased by more than the volume of rainfall that fell over the immediate catchment. Later in the year, when relative water levels were higher, the pond volume increase was between that of the wetland and the catchment rainfall volumes. Also during these two events, Jill and Joy's wetland rose a lot more relative to the other wetland pond sites when compared to the response later in the year. The reason for this is unclear. There is an old drain that runs down this part of the wetland along the western edge (see figure 5.2.5). This drain used to join Jill and Joy's wetland to wetlands north and south along this western edge of the complex. Dam C (figure 5.2.5) now separates Jill and Joy's wetland from northern areas (and Culvert C is defunct), so there should not be any surface inflow from outside the immediate catchment. It is possible that there are macro pores in the dam wall that allow water movement.

Pateke had the lowest or second lowest stage response in every event. However once the wetland area was used to calculate the volume of response, it consistently had the greatest response, probably because of its much larger catchment area. The wetland volume increase was between the calculated wetland rainfall and catchment rainfall volumes throughout the five separate events.

During the July event the bore water level at Jill and Joy's rose gradually over 6 or 7 days whilst wetland pond level held high. This was inconsistent with the other wetland sites and when plotted against deeper bores in the region, it looks to be consistent with a rise in deeper groundwater. The 98m Te Hapua bore, the 60m Te Horo bore and the 192m Te Horo bore all showed a similarly timed rise in groundwater level. However this only happened once, so is inconclusive and needs further investigation.

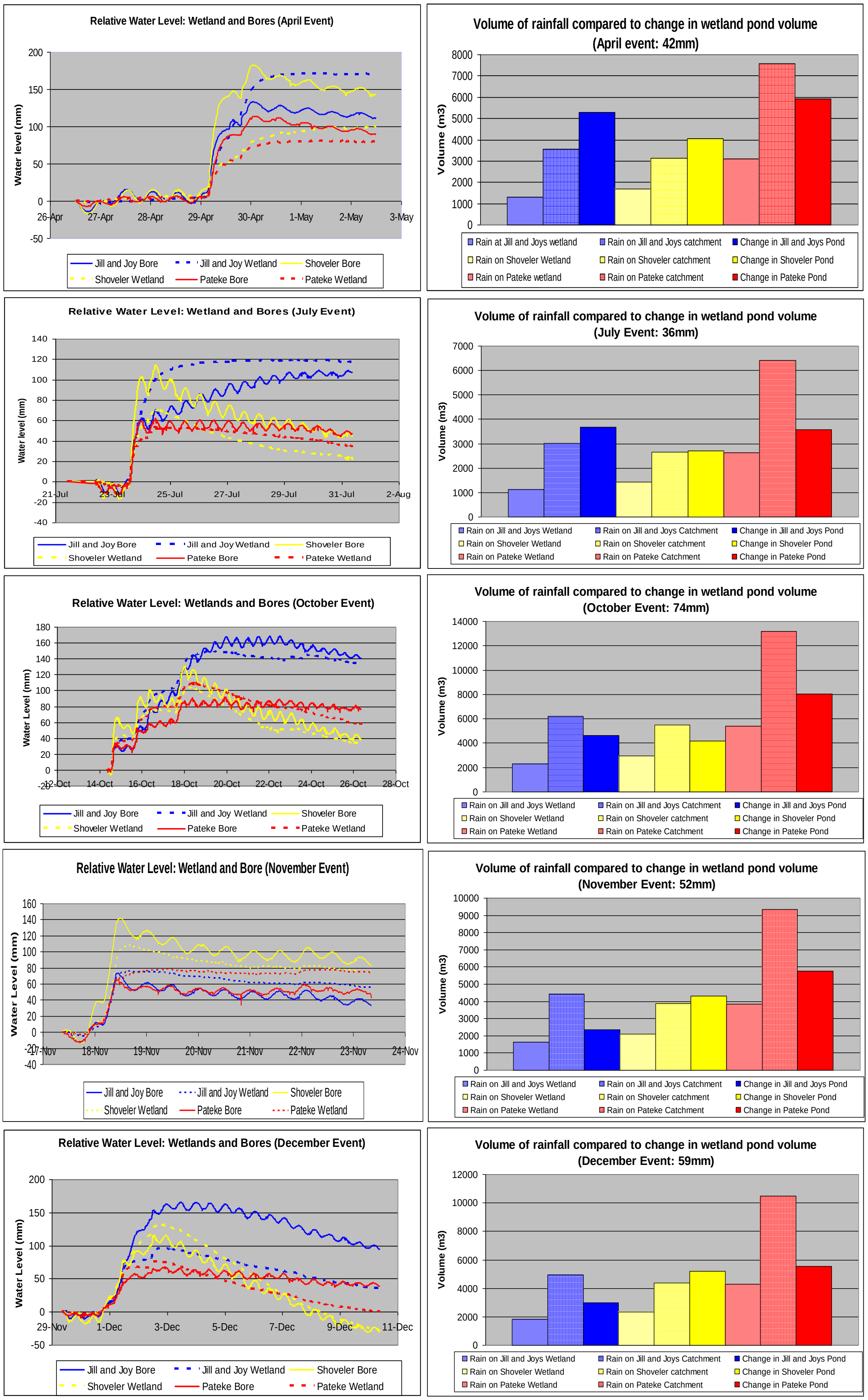


Figure 5.2.17: Wetland pond and shallow bore level at the three sites during five separate rainfall events in 2009 (left); and (right) the calculated volume of rain that fell on each wetland; the immediate catchment surrounding the wetland; and the change in volume of each wetland pond.

5.2.5 Abstraction induced drawdown in Te Hapua wells

Pump tests and analysis of existing data was carried out to look for evidence of leakage between aquifers. Figure 5.2.18 shows the bores used for the analysis.

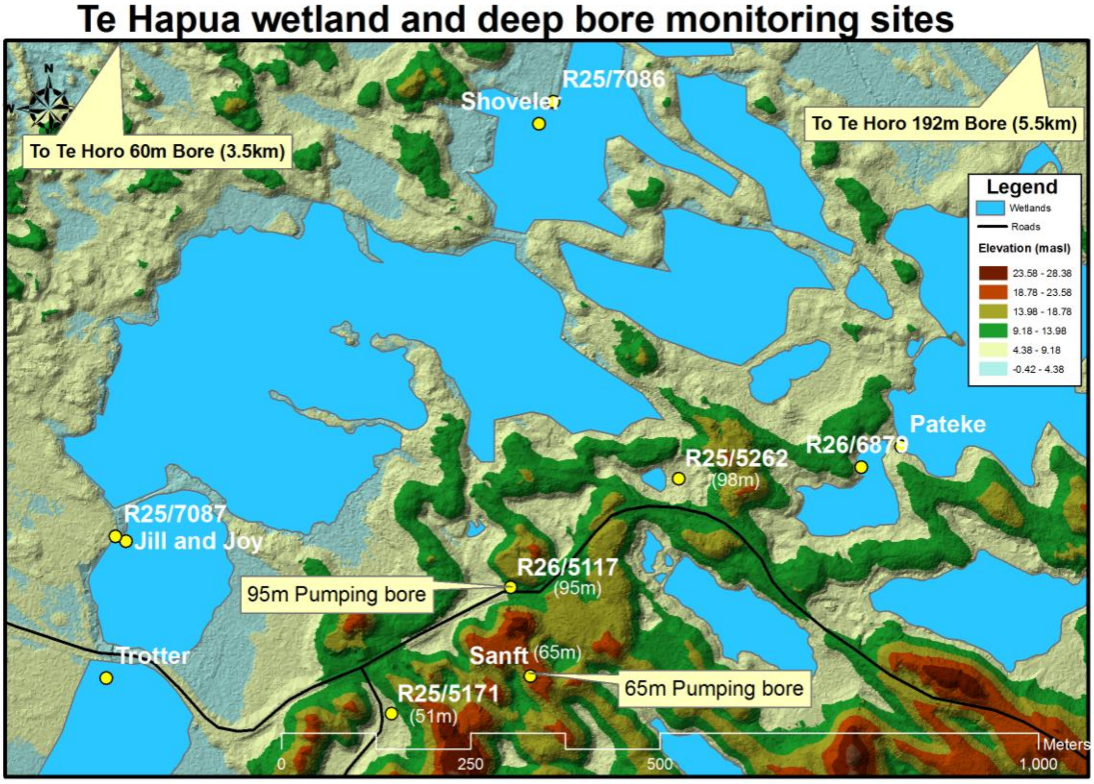


Figure 5.2.18: Wetland monitoring sites.

R25/5262 is an unused bore penetrating the second deepest confined aquifer to 98m. Another bore, R26/5117, sits at a very similar depth (95m), 260m southwest of R25/5262. This bore is periodically pumped during the dry season. Figure 5.2.19 is a hydrograph showing water levels in the unused 98m bore (R25/5262 - blue) during April 2009. Pumping at nearby R26/5117 lowered the water level in R25/5262 by 200-300mm. It took 5 to 7 days for groundwater level to return to the pre-pump level. Also plotted are the water levels at some of the Te Hapua monitoring sites, where water levels in the shallow bores and wetlands did not appear to drop any faster than they were before the pumping started.

To investigate this further, a low stress pump test was carried out in two of the deeper Te Hapua wells to see if it induced drawdown in other wells and monitoring sites around the wetland. Due to time and equipment constraints a comprehensive pump test was not possible, so the test is not a full pumping test from which the hydraulic characteristics and leakage of the aquifers can be calculated.

Two bores were pumped to look for drawdown in nearby bores and wetlands. Testing was done following periods that had little or no significant rainfall for the previous 7 days, and landowners in the immediate vicinity were asked to refrain from unnecessary bore use for the duration of the tests. The Sanft bore (65m) was pumped for 14 hours straight for 1 night at approximately 40 litres per minute. This induced a drawdown in the nearby 51m bore (R25/5152), but nowhere else. Figure 5.2.20 shows the drawdown which occurred on the night of March 5th 2010. These bores are 190m apart and located, according to figure 4.2.21, at around the same depth within the same aquifer.

The Crafar bore (95m) was pumped for 14 hours straight for 6 consecutive nights at approximately 90 litres per minute. This induced a series of steep drops in the hydrograph of the 92m bore (R25/5262), but not in any of the other monitored bores and wetlands. Figure 5.2.21 shows the drawdown in R25/5262, as well as the hydrograph for other bores and wetland monitoring stations nearby. These two deep bores are 265m apart and are located, according to figure 4.2.21, at a similar depth in the same aquifer. Figure 5.2.21 shows a fairly constant downward trend in the hydrographs from shallow bores and wetlands before and during the pump test. Note however the sudden upward trend of all the shallow bores and wetlands, coinciding with the cessation of the last overnight pump. There was no local rainfall at the time, but there was rainfall further inland at the 'Mangone at Transmission Lines' site (see figure 5.2.24 for location of rain gauges). Further investigation revealed that groundwater in the 60m Te Horo bore (R25/0003), which is 3.5km north, was also rising at this time (Figure 5.2.22). No rise was evident in the 192m Te Horo 'Centerpoint' bore (S25/5208). Given this, it does not look like the rise in wetland and shallow bore levels at this time is related to the pump test in the 95m bore. There are two possible explanations. One is that rainfall higher in the catchment has increased the pressure head in each of the aquifers, causing water levels in bores lower down to rise. This seems likely given the rainfall at the Mangone at Transmission Lines' rain gauge. The other is that the shallow unconfined aquifer water has risen due to upward leakage from the deeper confined aquifers. Since there are no rain gauges higher in the catchment, the data do not exist to prove / disprove either of these theories.

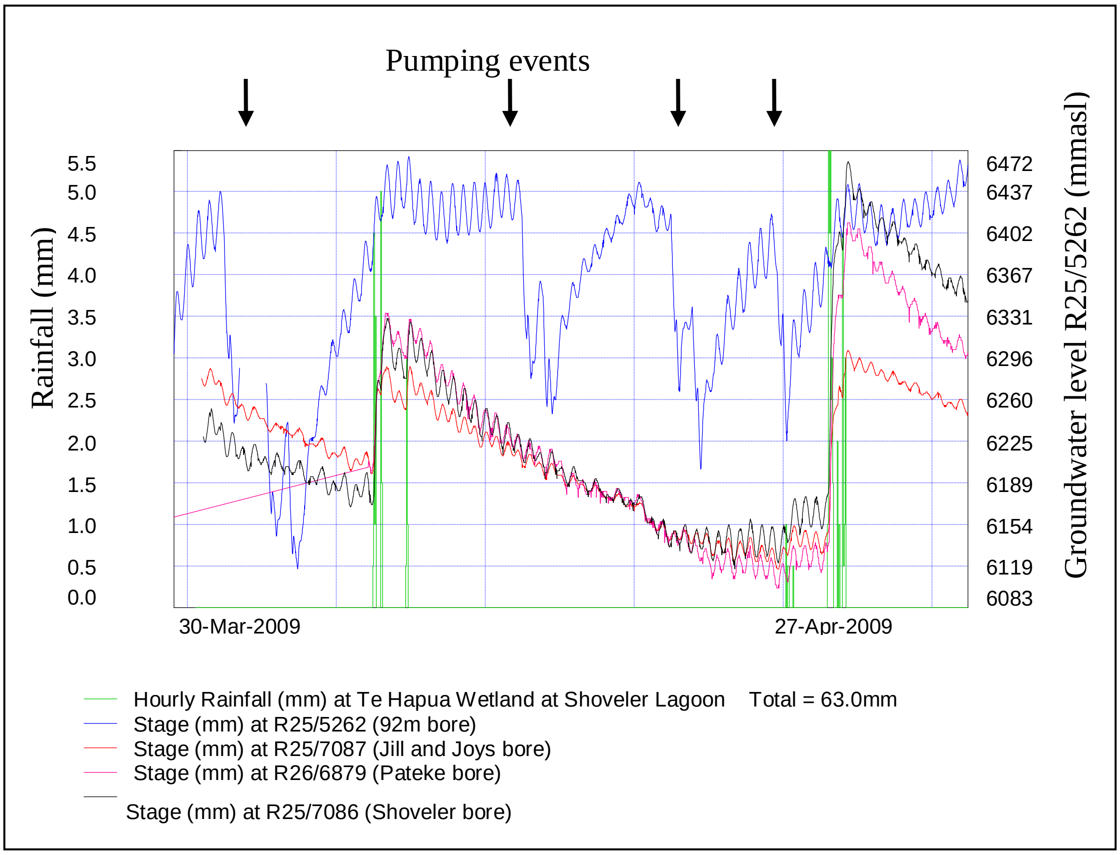


Figure 5.2.19: Water level in the unused 98m Te Hapua bore (blue) during pumping from nearby R25/5262. Water levels in the three shallow bores did not drop any faster than they were dropping before pumping started.

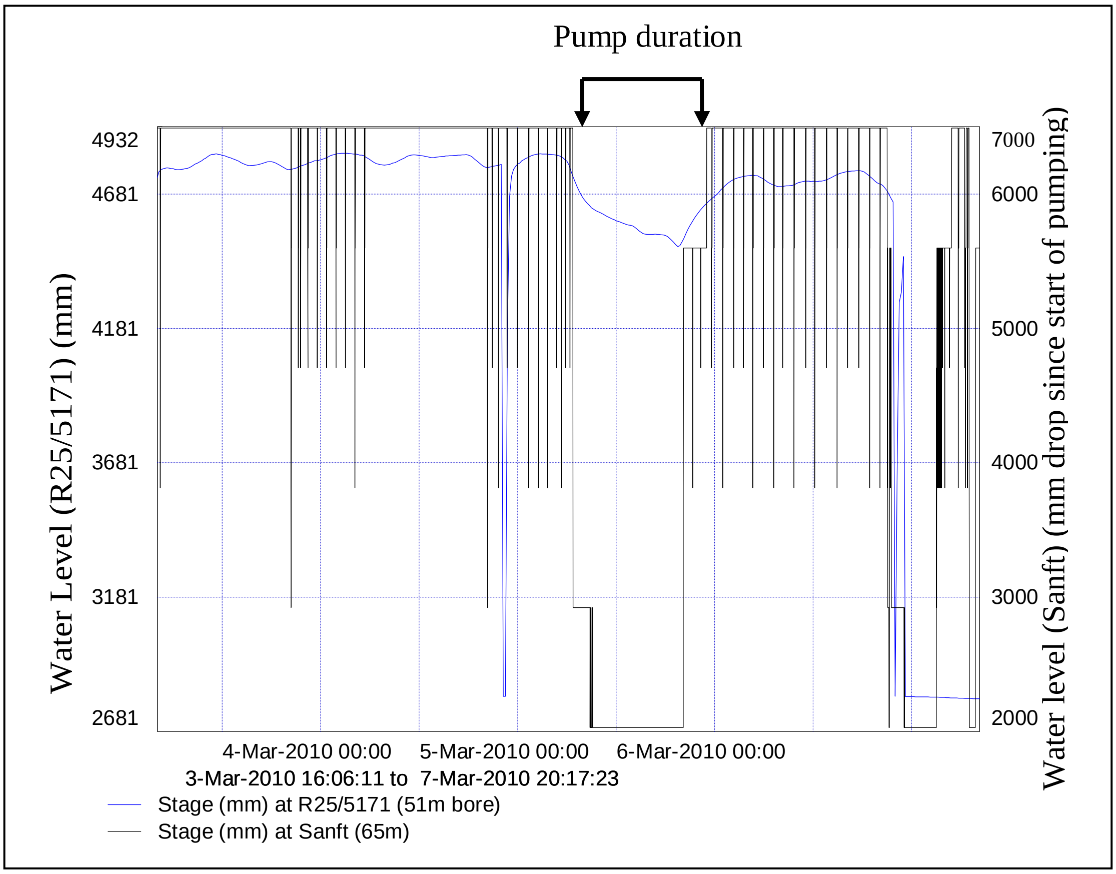


Figure 5.2.20: Drawdown in the 51m bore (blue) following overnight pumping in the 65m bore (black).

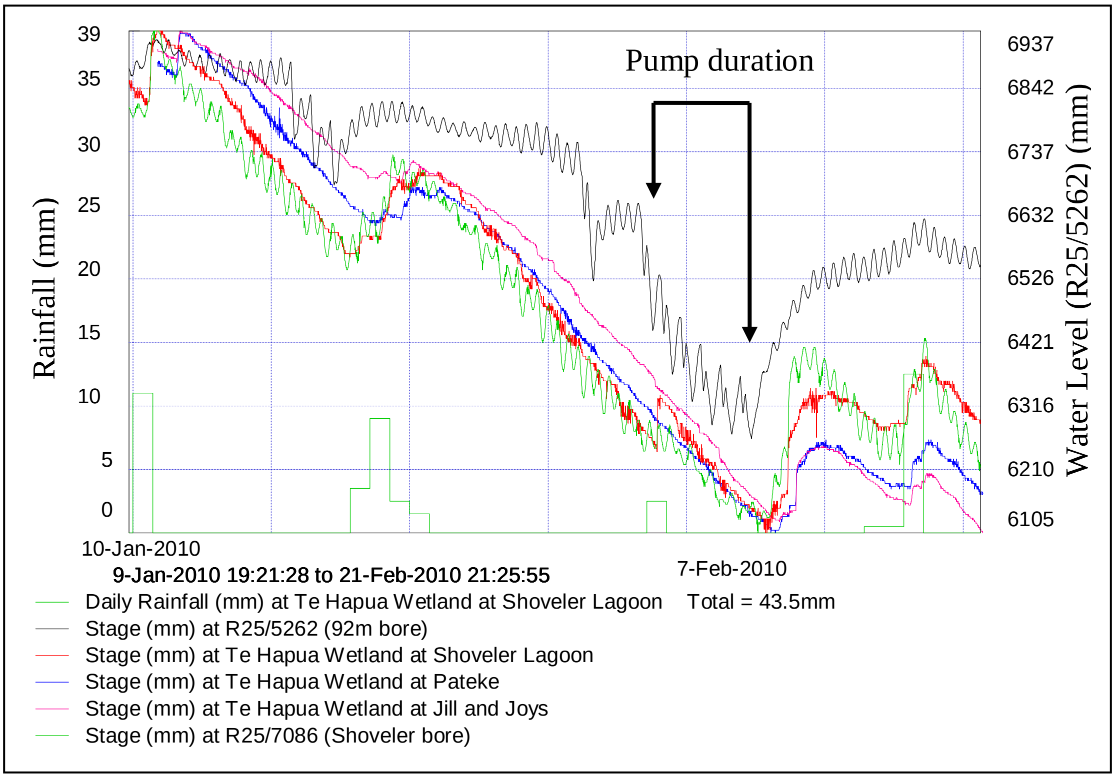


Figure 5.2.21: The hydrograph of various nearby bores and wetlands during 6 consecutive nights of pumping at the 92m bore (R26/5117 – no water level monitoring equipment is located in this bore).

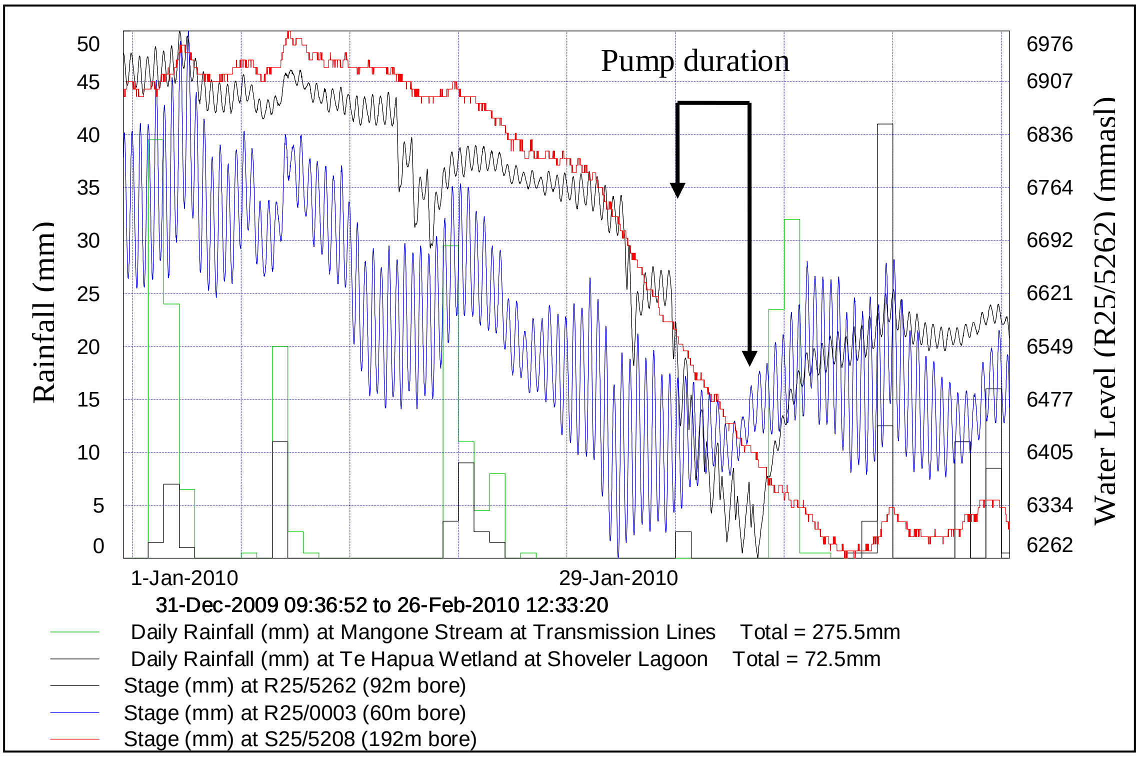


Figure 5.2.22: The rise at the end of the pumping period (showing in the hydrograph for R25/5262) coincides with a rise in groundwater level in a 60m bore 3.5km away (R25/0003), hence the rises are probably not related to the pumping.

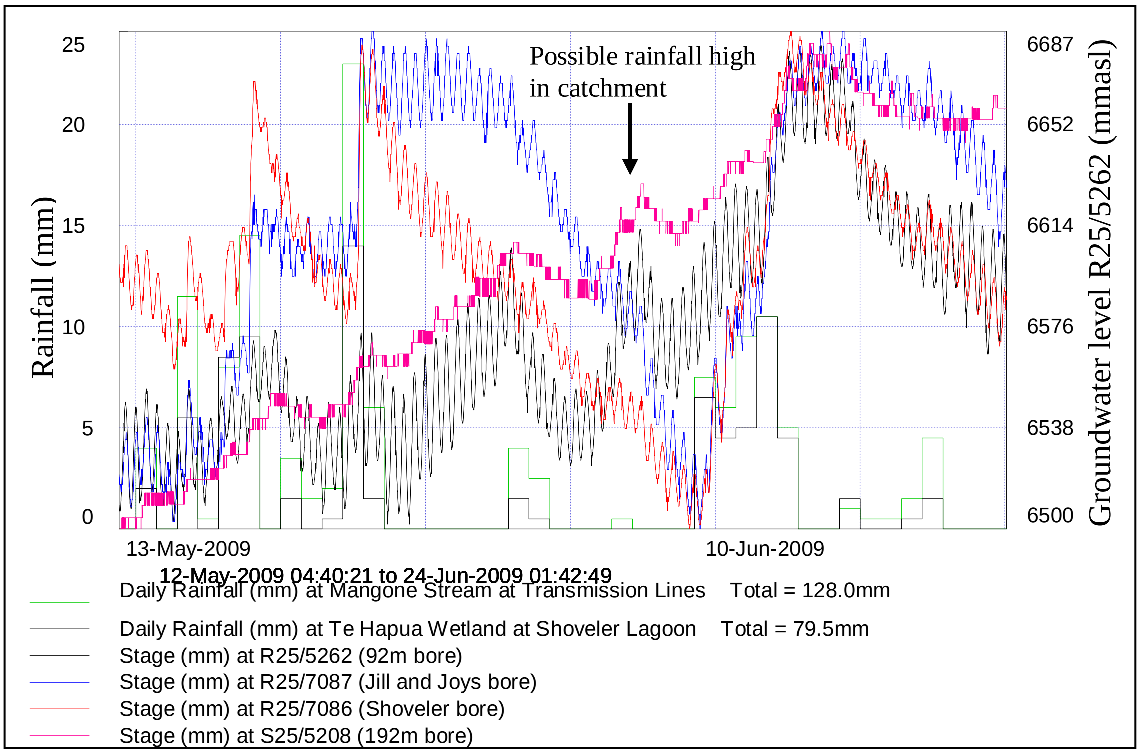


Figure 5.2.23: Fluctuations in groundwater level in the 98m bore (black) usually follow the rise and fall of the shallow bores (red and blue) - except in late May / early June where 3 rises follow fluctuations resembling the 192m Te Horo deep bore (pink).

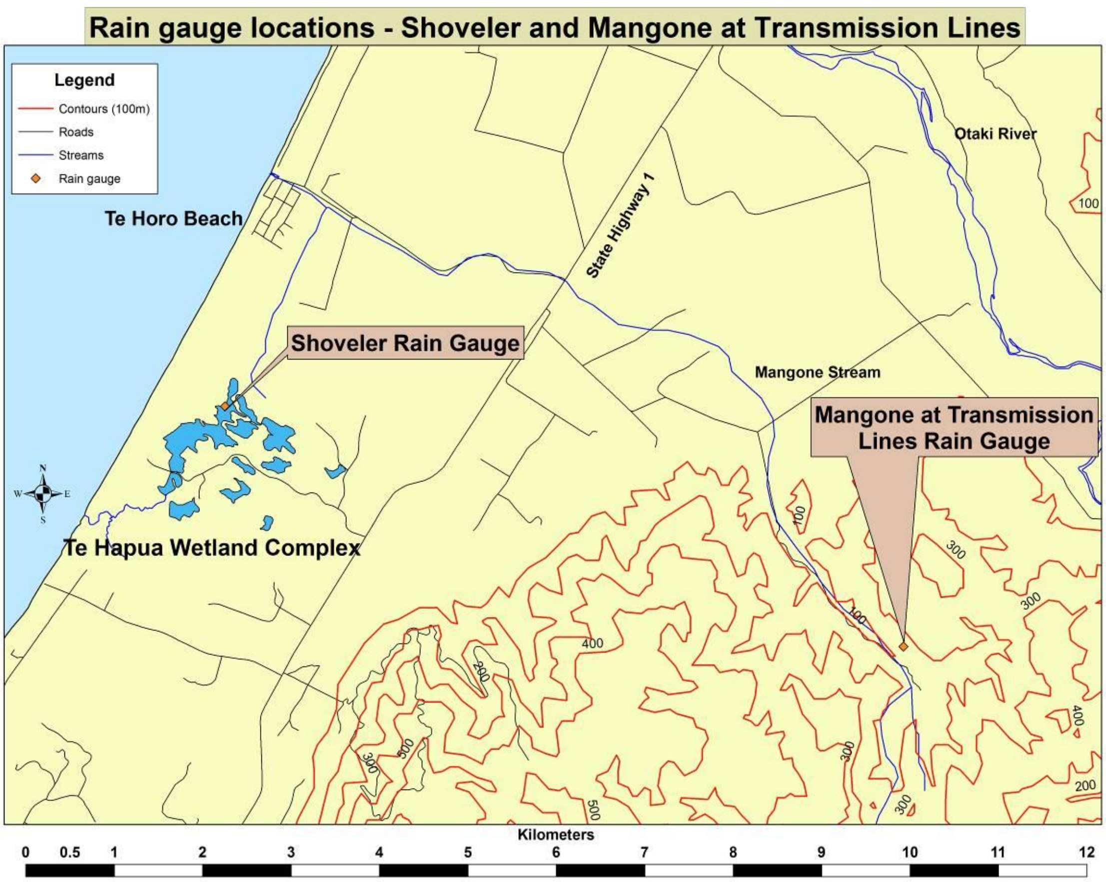


Figure 5.2.24: The location of rain gauges used for analysis of groundwater response to rainfall. The Mangone at Transmission Lines site is 9km from the coast.

Fluctuations of groundwater level in the 98m Te Hapua bore seem to follow the trend in various other aquifers and various times. During the 2009 wet season, water level usually resembles the rise and fall of the shallow bores nearby. However there are times when the deep bore rises steadily whilst the shallow bores are in decline (May 25th to June 15th, figure 5.2.23). This does not correlate with immediate rainfall at any of the 5 rainfall sites monitored. Whilst the rises do not follow fluctuations in the shallow aquifer they do coincide with rises in groundwater in the 192m bore in Te Horo (also shown in figure 5.2.23). The same fluctuations were visible in the 60m bore at Te Horo beach (R25/0003). There are two possible explanations for this. One is upward leakage from the third confined aquifer through to the second confined aquifer. There is no data available to see if the same fluctuations were present in the first confined aquifer (35m-60m). The other possible explanation is rainfall higher in the Tararua feeding the deeper aquifer's recharge zone. There is a small amount of rainfall at the 'Mangone at Transmission Lines' rain gauge site, which is closer to the mountains than the Te Hapua rain gauge, so receives more rain (figure 5.2.24). This could indicate heavier rainfall in higher areas which would cause a surge in deep aquifer pressure heads on the coastal plain.

5.2.6 Summary

Both Jill and Joy’s and Shoveler wetlands are ‘recharge wetlands’, where pond water is usually higher than shallow groundwater. Their hydrology is likely to be more influenced by local rainfall and surface runoff than by shallow groundwater. Pateke wetland is a ‘discharge wetland’, where shallow groundwater is usually higher than pond water. Pateke’s hydrology is more influenced by shallow groundwater than surface runoff. High dunes surround the site which means the water table will be higher relative to the pond. A spring close to Pateke wetland indicates that groundwater is emergent in the area. All of the wetlands drain faster in the wet season. Jill and Joy’s wetland has more seasonal storage relative to the other wetlands, as the pond level peaks later in the year. Shallow groundwater is seasonally higher relative to pond water in the Shoveler and Pateke wetlands, reflecting the faster pond drainage during the wet season. This possibly indicates variations in conductivity of soils surrounding the wetlands and / or pond overflow.

The hydrology of many of the wetlands within the complex has been highly modified over the past 60 years. Drains, dams and culverts have been built in parts of the wetland for a number of reasons, though historically to allow farmers to graze the entire region. Dams have been built by more recent landowners in an attempt to retain wetland water and counter the effect of old drains. The western side of the complex was at one stage a single continuous lowland wetland - at least during the wet season. The area is now a series of smaller individual wetlands where the hydrology is determined, to a large extent, by culverts set in small dams at critical levels. Some of the old drains remain and may affect the water level in some of the western wetlands during times of low water. Historical drainage of wetlands on land adjacent to what is currently known as the Te Hapua complex is also thought to have lowered the water table in the area – especially on the north-western edge of the complex.

The approximate area of each monitored wetland was calculated using a shape file supplied by Wellington Regional Council. This gave approximate sizes of 3.1ha, 4ha and 7.3ha for Jill and Joy’s, Shoveler, and Pateke wetland respectively. The immediate watershed calculated for each wetland was 8.4ha, 7.4ha, and 17.8ha respectively. There are five main drainage basins in the Te Hapua complex, two of which have seasonably significant surface outflows.

Analysis and comparison of the water balance for each wetland showed that Jill and Joy's wetland fluctuates more than the other wetlands during the dry season. There are two possible explanations for this. One is the influence of an old drain that was cut through this part of the wetland in the 1980's. According to local long term resident Ian Jensen the drain may still be functioning today. The fact that the larger water level fluctuations only occur in the dry season may be evidence that this drain functions effectively when pond level is low, but when levels are high the drain is submerged and no longer has an effective gradient. The other possible explanation is that, compared to the other sites, Jill and Joy's wetland has a large catchment relative to the wetland pond size (though this would not explain the seasonal difference).

Another observation regarding Jill and Joy's wetland is that there is more storage during the wet season (compared to the dry season), relative to the other sites. This is likely due to the elevation of the culvert set at the southern end of the wetland. This culvert is the only surface water exit for this wetland (and catchment area), so when the water reaches the top of the culvert it acts as a bottleneck and can no longer drain effectively in response to inflow. If the rate of inflow is greater than the maximum outflow at the submerged culvert, then water accumulates in the wetland as storage.

Pond level at the Pateke wetland fluctuated least of the three sites. There are two possible explanations for this. One is that the wetland, being a 'recharge wetland', has pond levels that more closely follow shallow groundwater levels and are buffered somewhat from local rainfall. The higher dunes that surround the area can mound more water beneath them than the low dunes near the other sites and hence the fluctuation in pond level is less pronounced. The other possible explanation is that the immediate catchment area is large and water may 'spread' across low lying land that surrounds the wetland, rather than enter the wetland itself. It is also possible that the damming of the constructed wetland adjacent to Pateke has affected the water levels in the Pateke wetland.

Calculations of wetland volume in response to rainfall revealed that Jill and Joys wetland responds differently to rainfall at different times of the year. An old drain in this part of the wetland may have an influence on Jill and Joy's pond level at times of low water, moving relatively large volumes of water from an extended catchment area into the wetland. When the pond is higher the drain is submerged and no longer functions. The volume analysis also indicates that the calculated catchment area for the Shoveler wetland is too small and that there may be occasional inflow from shallow groundwater to the Shoveler and Jill and Joy wetland areas (though this is inconclusive as the data are very limited).

Another possible explanation for spatial variations in water level response to rainfall includes the influence of local scale variation in heavy rainfall. This phenomenon was not measured in this study, but noted anecdotally by local residents to be the case, especially during autumn months. For example, during the April and July events a heavy downpour may have fallen onto the Jill and Joy site, but to a lesser extent on the other two sites.

Also worth mentioning is surface water movement observed during very high wetland water levels following extreme rainfall in 2007. According to Mr Jensen, surface water was running westward from the western wetlands before filtrating down into base of the dunes. This shows that water movement may not always be in a consistent direction, and is influenced by wetland pond level.

As seen in section 4.2.2, there is a difference in pressure head between the first and second confined aquifers. This creates a pressure gradient that could, providing the confining layer is to some extent permeable, allow upward leakage. Whilst it is possible, the limited historical data provides no evidence of upward leakage in any of the aquifers below Te Hapua wetland. The only monitored well that penetrates the first confined aquifer (R25/5171) has a faulty pump so groundwater level data are meaningless unless the pump is switched off. Whilst we know that the pressure head in the second confined aquifer is generally higher than the first confined aquifer, we don't know if this condition ever reverses, so that there is potential for downward leakage. Downward leakage is the condition that presents a threat to the shallow unconfined aquifer (and wetland pond water) given a large scale abstraction nearby. Installing a data logger in an unused well that penetrates the first confined aquifer would be the first step in finding the answer to this.

The small scale pumping test carried out as part of this study induced drawdown in nearby wells that share the same aquifer, but failed to drawdown water from bores in other aquifers, hence no leakage occurred. A full and extensive series of pump tests in the deep bores could be carried out to test for upward / downward leakage.

5.3 Wetland Classification

5.3.1 Wetland Classification

Twenty one individual wetlands were surveyed to gather information necessary to define their wetland class as bog, fen, swamp, marsh, or seepage - as defined by Clarkson et al (2003) and Johnson and Gerbeaux (2004). Conductivity and pH were measured to assess wetland water quality, whilst the water regime was assessed by noting the presence or absence of surface water inflow / outflow. pH, conductivity and temperature were also measured in six bores of various depth around the wetland to see how similar they are to nearby wetland pond water. All surveying took place on the 14th, 15th, and 16th of December 2009.

Water regime survey methods

The three Wellington Regional Council wetland monitoring sites provide detailed data to describe the water regime at these locations. Each council site includes a wetland pond stage recorder alongside a shallow bore. Both have high resolution data loggers that record water level every 15 minutes. These data can be used to assess hydrological parameters such as net water inflow / outflow, seasonal hydro-period, rainfall response, high water frequency / duration, and groundwater input (Clarkson, et al., 2003).

Given the topographically varied nature of Te Hapua and numerous wetland areas to assess, this study attempted to classify the entire complex. It was not possible to install monitoring equipment at all 21 major wetland areas within the complex, so a visual assessment was undertaken.

The 21 individual wetlands were circumnavigated by foot to survey for evidence of water inflow / outflow, the approximate rate of flow, and hydrological disturbances such as drains or dams. Anecdotal evidence was also gathered where available to describe and approximate seasonal hydro-period. These are considered important indicators when assessing wetland condition (Clarkson, et al., 2003).

Water quality survey methods

To assess wetland nutrient status, water from the 21 wetland areas and 6 shallow bores were sampled for pH, temperature and conductivity. Dissolved oxygen was also going to be tested but equipment failure meant that this was not possible. However, this was not deemed an essential part of the assessment as Clarkson (2003) gives pH and conductivity as the necessary parameters that indicate wetland nutrient status.

pH is an indicator of nutrient availability (among other wetland qualities), and is often used in field studies to assess wetland condition (Clarkson, et al., 2003; Johnson & Gerbeaux, 2004b). Conductivity measurements can also be used to assess nutrient status as it indicates the water's concentration of soluble ions, which includes nutrients important to plants (Johnson & Gerbeaux, 2004b). One concern of using conductivity is that ions measured also include salts which may be present in coastal environments such as Te Hapua.

Other techniques used in New Zealand to assess wetland nutrient status include estimations given the landform setting, plant vigour and presence / absence of particular species of plant. Direct measurement of the two most important nutrients for plant growth, total P and total N, has also been used (Johnson & Gerbeaux, 2004b). However these techniques were deemed outside the scope of this study.

Wetland water samples were obtained from wetland areas using a sampling bucket attached to a long pole that could reach inner wetland pond areas. Water immediately below the surface was used. pH and temperature were measured using an Ecosense pH100 portable probe. The accuracy for this probe is +/- 0.1% for pH; +/- 0.5degC, with a resolution of 0.01pH; 0.1degC (YSI, 2008). Conductivity was measured using a CON 410 portable probe. The accuracy for this probe was +/- 1%, with a resolution of 0.05% full scale (Eutech, 2004) .

Bore water samples were taken using an on-site pump where facilities were available. To ensure the sample was representative of the groundwater, the well was 'flushed' with three times the volume of the bore casing (Osbourne, 2006; Schwartz & Zhang, 2003). This was achieved by calculating the volume given the bore diameter and depth to base. Water was flushed into a 12 litre bucket to measure volume removed.

To sample, once purged the pump was left running into the bucket which provided a pool of running water into which the pH and conductivity probes were placed. Running water was used to minimise contact with the atmosphere and hence provide as representative sample as possible (Osbourne, 2006; Tesoriero, et al., 2004).

Table 5.3.1 summarises the results from the wetland classification survey of water quality and water regime and figure 5.3.1 displays the locations and names of all the wetlands and bores surveyed, as well as the outcome by way of definition of wetland class.

According to the wetland class definitions set out by Clarkson (2003) and Johnson and Gerbeaux (2004) (see Chapter II, table 2.2), the wetlands of Te Hapua are either swamp or fen. Many of the 21 wetland areas surveyed have had their hydrology modified in some way. As discussed, drains have been dug, dams have been built and culverts have been installed in various parts of the complex. Some of these have been removed and some remain. Given the extent of these modifications, only the present day water regime of each wetland was considered. Some of the wetlands might have fallen into different classes before being modified by humans. For example wetlands on the western side of the complex would have been more connected by surface flow, so there may have been large areas of marsh in topographically lower areas.

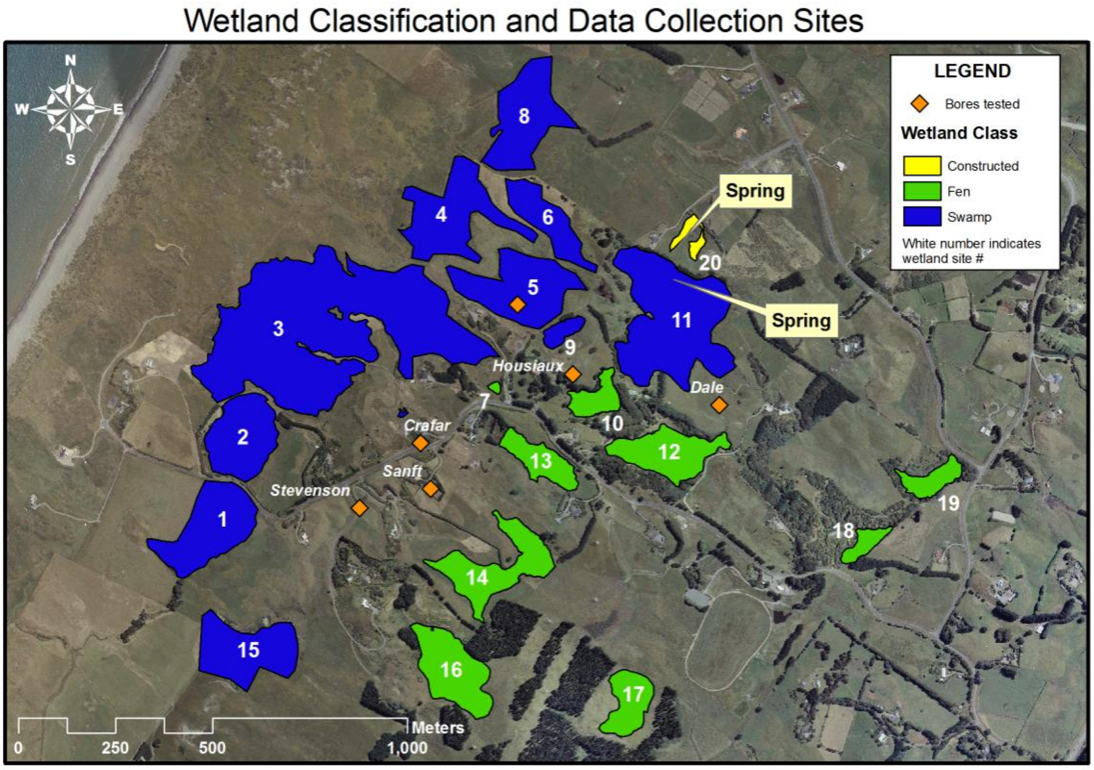


Figure 5.3.1: Location map for data collection sites and results from water quality analysis to assess wetland class.

Table 5.3.1: The attributes of wetlands from the water quality / water regime survey. Full results from the wetland / bore water quality survey are in Appendix 4.

Wetland ID #	**Size (ha)**	**Flow In**	**Flow Out**	**pH**	**Conductivity (μS)**	**Temp (°C)**	**Wetland Classification**
1 **Trotter Nth**	3.6	Very Slow	Very Slow	6.22	304	18	Swamp
2 **Jill & Joys**	3.1	No	Very Slow	6.31	235	24.3	Swamp
3 **O'Malley, Crafar, Jensen**	18	No	No	6.11	263	23.6	Swamp
4 **Shoveler**	4	No	Slow	6.51	287	20.2	Swamp
5 **Jensen Sth**	3.9	No	No	5.69	264	18.3	Swamp
6 **Jensen Nth**	1.9	No	No	6.35	277	19.4	Swamp
7 **Jensen Driveway**	0.07	No	No	6.53	181	19.6	Fen
8 **McGrath**	3.6	Med	Med	5.86	419	16.4	Swamp
9 **Housiaux Nth**	0.5	No	Very Slow	6.83	223	22.9	Swamp
10 **Pateke bore (Housiaux Sth)**	0.9	No	No	4.79	129	18.5	Fen
11 **Pateke pond Dale Nth**	7.3	No	No	7.34	291	26.8	Swamp
12 **Dale Sth**	2.5	No	No	6.18	197	22	Fen
13 **Wyman / Walker**	1.3	No	No	5.17	105	22.5	Fen
14 **Stevenson / Sanft**	3	No	No	5.8	156	23.8	Fen
15 **Trotter Sth**	3.3	No	No	6.67	213	20.5	Swamp
16 **Deanne West**	2.9	No	No	6.21	169	22	Fen
17 **Deanne East**	1.5	No	No	4.22	115	29.4	Fen
18 **Lavo Sth**	0.5	No	No	5.48	130	24.3	Fen
19 **Lavo Nth**	0.9	No	No	6.74	261	23.7	Fen
20 **Brown**	0.4	No	Fast	5.96	308	17.1	Constructed
21 **Crafar**	0.03	No	No	6.83	291	26.4	Swamp
Rainfall	N/A	N/A	N/A	5.2	55.6	19.8	N/A

Wetlands classified as ‘swamp’ tended to be in the western most areas which are lower lying and generally flatter and more open than eastern areas (see figure 5.3.2). The fens were situated amongst dune hill country, approximately 3 metres higher than western areas. Fens are mostly contained by dunes, where as swamps tended to flow, at least via through-flow, into / out of each other. The ‘constructed’ wetland is fed by a small spring; the pond being dammed at one end. Note that some of the wetlands were fen-like at one end whilst swamp-like at the other. According to Johnson and Gerbeaux (2004) this is a common phenomenon and in this case may be due to the influence of emergent shallow groundwater as wetlands that display this variation in wetland class characteristics were in areas (Pateke wetland and Stevenson / Sanft wetland) that are known to have springs or relatively static water levels. Wetlands were classed using the average characteristics across each wetland area.

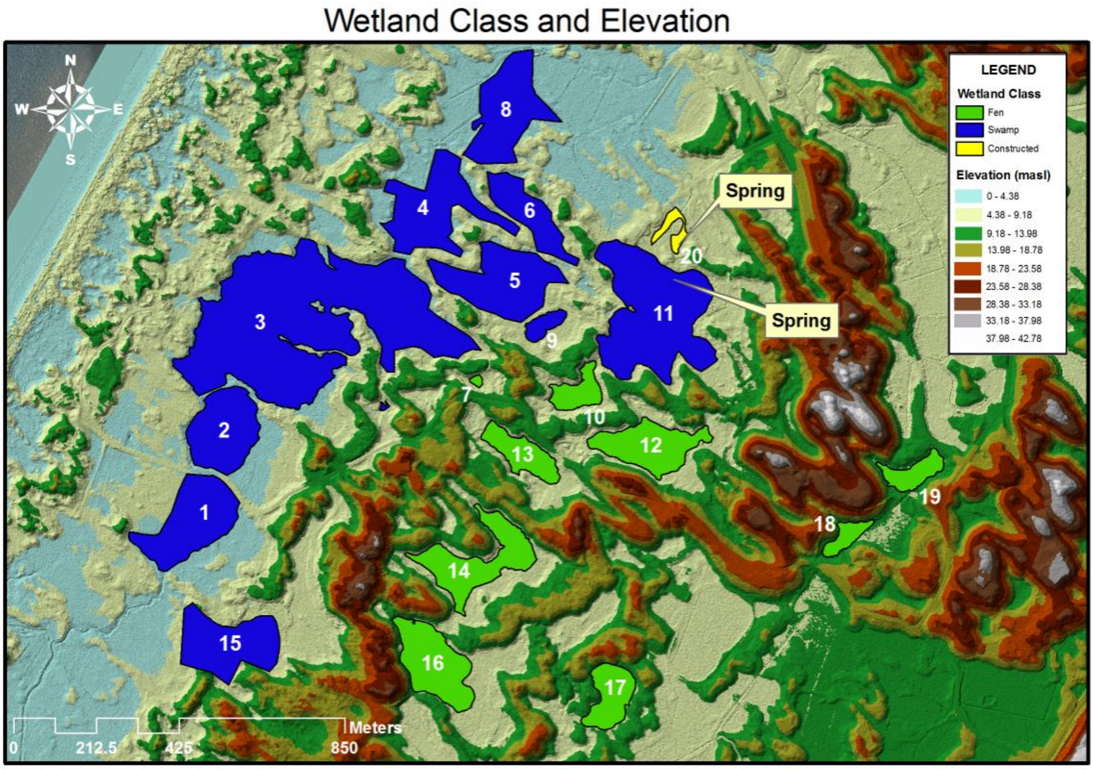


Figure 5.3.2: ArcGIS image showing elevation around Te Hapua wetland. (WRC GIS database).

When compared to the soil map (provided by Wellington Regional Council; figure 5.3.3), fens tend to be found in areas dominated by Foxton Black Sand. Swamps were surrounded by Motuiti series soils. No wetlands formed in the Waitarere sand and organic Omanuka soils featured in and immediately surrounding wetland areas, perhaps indicating the former extent of the wetlands.

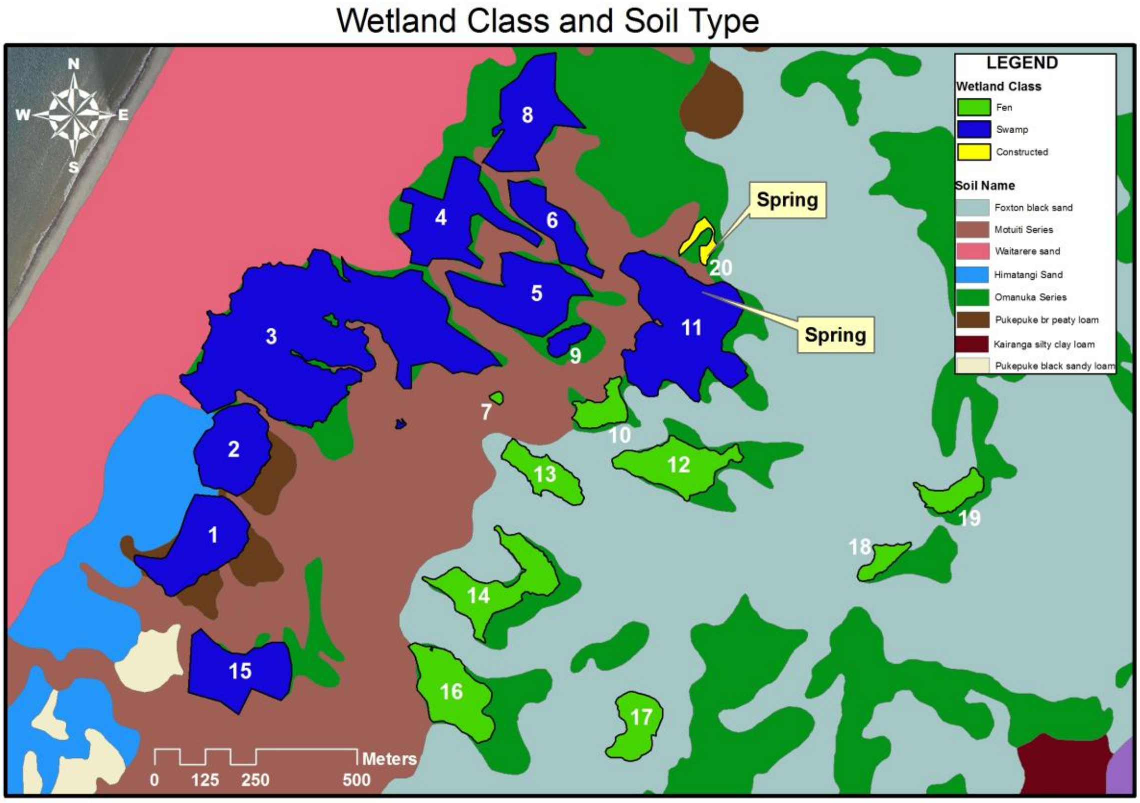


Figure 5.3.3: ArcGIS image showing distribution of soils around Te Hapua wetland. Fens have formed where the Foxton black sands preside over the Motuiti sand. There are no wetlands in the coastal belt of Waitarere sand (WRC GIS database).

Table 5.3.2: Characteristics of soils surrounding Te Hapua wetlands (Law, 2008; McFadgen, 1997; Palmer & Wilde, 1990; Wilson, 2003)

		Waitarere Series	**Motuiti Series**	**Foxton Series**	**Omanuka Series**
Accumulation began		150 to 400 years BP	900 years BP	6500 years BP	N/A
Parent Material		Quarto-feldspar wind blown sand of greywacke origin. Pumice.	Quarto-feldspar wind blown sand of greywacke origin	Quarto-feldspar wind blown sand of greywacke origin	Organic
Texture		Coarse	Coarse	Coarse	N/A
Permeability		Very Rapid	Rapid	Rapid	Moderately rapid
Soil Drainage Class		Excessively drained	Somewhat excessively drained	Somewhat excessively drained	Very poorly drained
Flooding		Nil	Nil	Nil	Ponding
Total Porosity	**Topsoil**	Moderate	Moderate	High (60%)	Very High (75-92%)
	Subsoil	Moderate	Moderate	Moderate (50%)	Very High (75-92%)
Macro-Porosity	**Topsoil**	High	High	High	Very High (17-30%)
	Subsoil	High	High	Very high	Very High (17-30%)
Water holding capacity		Low	Low	Low to moderate	N/A

Permanent wetlands have not formed on the relatively young Waitarere sand dunes (though there are areas where standing water can be found following significant rainfall).

This may be because they have very rapid permeability and are relatively unstable, so cannot retain water and have not held a significant cover of vegetation for more mature soils to form. Peat accumulates at varying rates depending largely on the water regime, climate and vegetation (Mitsch & Gosselink, 2007). McCaffrey (1997) and Delaune et al., (1983) found peat accumulation rates that vary from less than 1mm to 15mm per year in United States east coast marshes (Mitsch & Gosselink, 2007). Most of this accumulation was attributed to rising sea level (or subsiding ground level). Northern United States inland bogs were recorded to accumulate at 0.2 to 2mm / year.

The wetland classification survey indicates that fens are most likely to form in the older Foxton soils / sands, and swamps are predominantly found near Motuiti soils / sands. The Foxton soils have slightly better water holding capacity and higher porosity compared to the Motuiti soils. The higher, hummocky dune landscape associated with fens and Foxton soils creates a topographically diverse water table as water mounds beneath high dunes and emerges in the inter-dunal depressions (see figure 3.2 in chapter 3). As discussed, this is probably why the Pateke site is a discharge wetland (where groundwater is typically higher than the pond water). The Pateke site had a large range of pH and conductivity readings across the 8 sites that were tested (see Appendix 4 for full results). Note that the Pateke site encompasses two wetland areas, sites 10 and 11 on table 5.3.1. Site 10, the wetland adjacent to the Pateke bore showed very low pH and conductivity measures and was designated a fen. Site 11, Pateke wetland, had very high pH and conductivity measures, so was designated a swamp. Twenty metres of reclaimed land separates the formerly joined wetlands. South of this point is the start of the Foxton soils and higher dune areas. The Jill and Joy and Shoveler wetlands had relatively high pH and conductivity. They both fluctuate more than Pateke and following rain have water flowing via culverts as per the flow accumulation section 5.2.2. Both were therefore designated as swamps.

5.3.2 Comparative analysis of water quality measures in swamps, fens and bores.

Wetlands were characterised into wetland classes depending on their water regime, pH and conductivity. Figures 5.3.4 and 5.3.5 below show the differences in pH and conductivity measured in the swamps, fens and bores around Te Hapua. Both pH and conductivity were generally lower in fens. This is likely the result of less inflow of nutrients from adjacent land given the different water regime (see chapter II), as well as the different soil qualities discussed in chapter V above. Conductivity of groundwater was relatively high, especially in the deeper bores. This was expected because deeper groundwater generally has a longer residence time, during which it percolates through different layers of sediment and minerals. In the process more ions dissolve into solution than in shallow groundwater / surface water, so conductivity is higher. Similar to conductivity, pH also generally increased with depth (figure 5.3.4). This is consistent with a general trend for pH in New Zealand groundwater to increase with depth (Rosen, 2001). The pH of rainwater collected from the Shoveler rain gauge was 5.22. The rainfall sample was collected approximately 24 hours after significant rainfall on January 10th 2010. This is in line with other studies looking at the chemical characteristics of rain water (Likens, et al., 1987). Conductivity in the Shoveler rainfall sample measured 55.6μS. Temperature measurements from wetlands varied depending on the time of day and amount of solar radiation. The temperature of groundwater was relatively consistent, between 15.3˚C and 17.6˚C (see figure 5.3.4). The groundwater measurements were generally colder than any surface water measurement, most likely because of the warming effect of solar radiation on surface water. The only constructed wetland (# 20; Brown) is fed by a spring. Water that emerges at the spring site appeared to flow at a reasonable rate, disturbing the surface above with an up-welling of water approximately one square metre in diameter. The temperature at this site is relatively low because it is recently emerged groundwater. Table 5.3.3 summarises the water quality results for bores (see table 5.3.2 for wetlands).

Table 5.3.3: Results of water quality in bores

Bore Name	WRC bore number	Depth (m)	pH	Conductivity (μS)	Temp (˚C)
Housiaux	N/A	7	6.61	292	15.5
Jensen	R25/5199	12	7	420	14.5
Dale	N/A	8	6.49	194	17.6
Stevenson	R25/5171	51	7.86	422	16.6
Sanft	R25/5192	65 (estimate)	7.45	403	15.3
Crafar	R26/5117	92	7.9	598	15.3
Rainwater	N/A	N/A	5.2	56	19.8

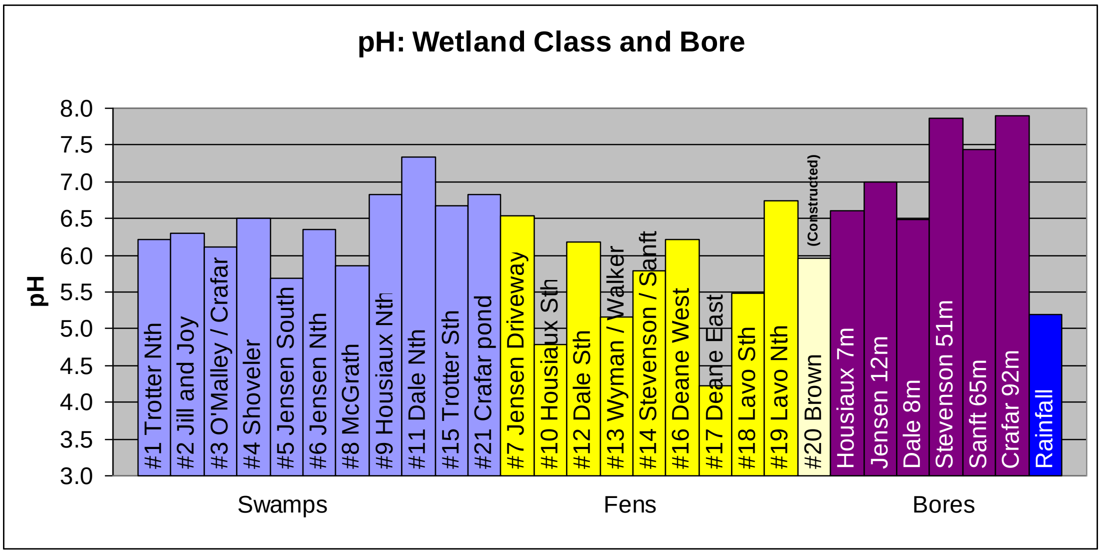


Figure 5.3.4: pH of Te Hapua wetlands, bores and rainfall.

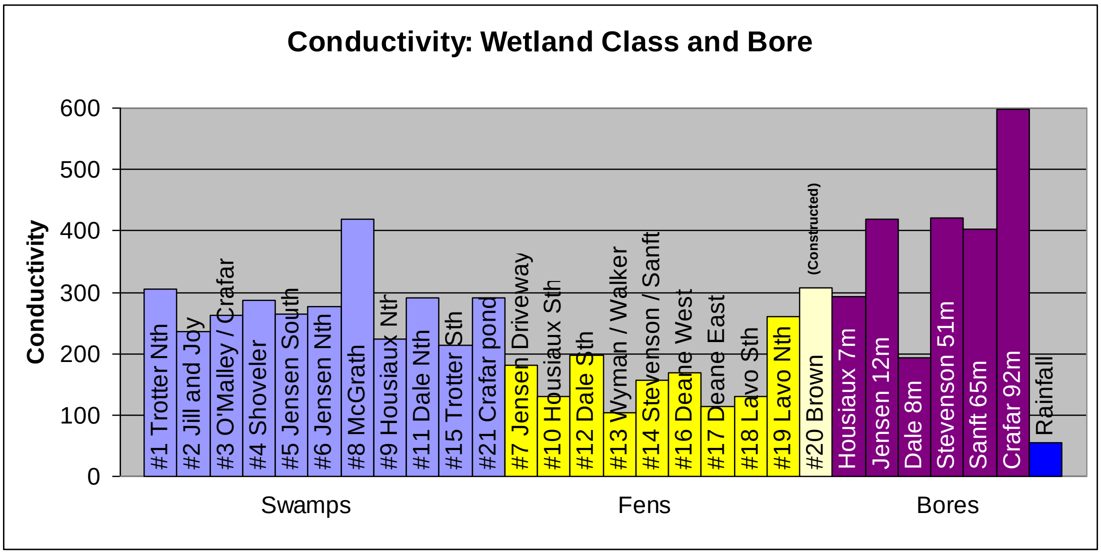


Figure 5.3.5: Conductivity of Te Hapua wetlands, bores and rainfall.

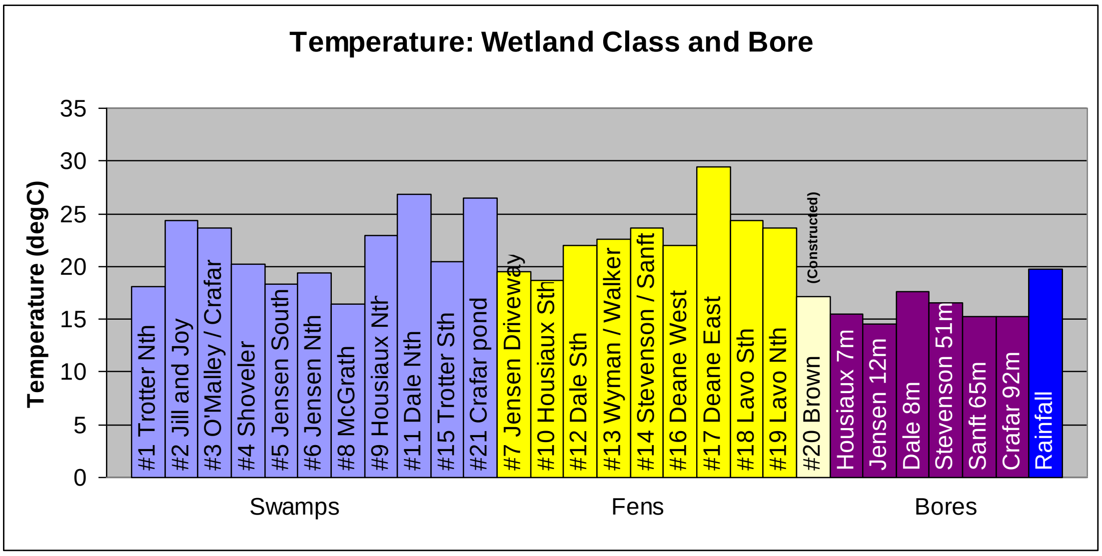


Figure 5.3.6: Temperature of Te Hapua wetlands, bores and rainfall.

Comparing water quality measurements from bores to those taken in adjacent wetlands, figures 5.3.7 and 5.3.8 show both pH and conductivity are usually higher in the groundwater than they are in the wetland pond water. pH in the deeper bores is higher relative to nearby wetlands, yet with shallow bores it is more similar. Rainwater pH is generally not far below that of the wetlands, but well below bore water pH. Rainwater conductivity is much lower than any of the other sites. Rainwater is low in ions because it has not been in contact with soil or rock substrates (Kim., et al., 2008). Hence generally, the deeper the water, the 'older' the water is and hence the further the deviation of pH and conductivity from that of rainfall.

Water quality testing indicates that the shallow groundwater is more likely to be a source of wetland pond water than the deeper groundwater. As water enters the wetland from shallow groundwater, biota starts to change the water quality. Plants take up nutrients (or ions) in the water, lowering the conductivity and the highly organic soils lower the pH. The chemistry of rain that falls on the wetland also changes as it mixes with the pond / soil water, and comes into contact with the organic soils and biota. More sampling would be necessary to draw statistically significant conclusions.

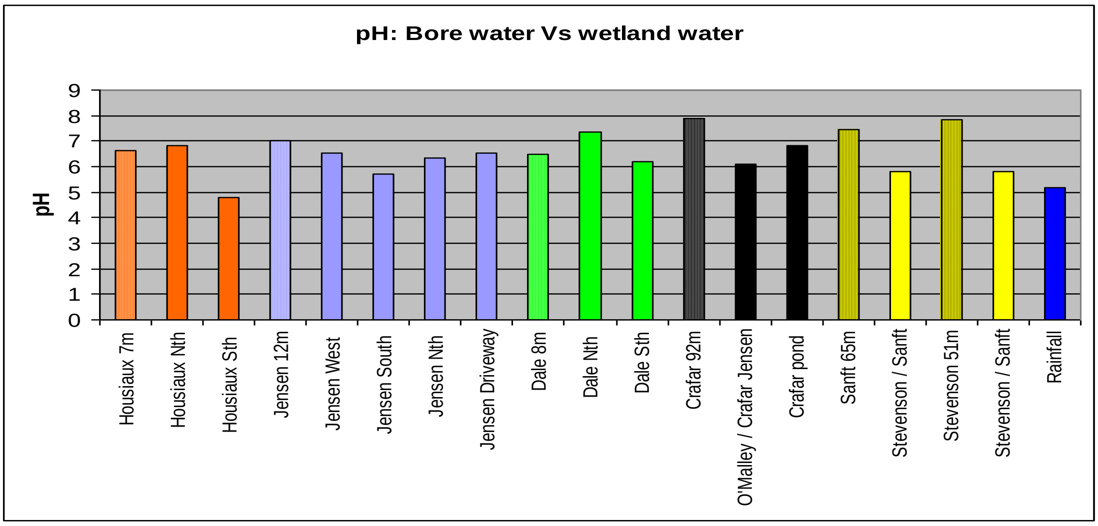


Figure 5.3.7: pH from bores, nearby wetlands, and rainwater. Shallow bore pH appears to be similar to that of the nearby wetland, but the deeper bores have higher pH than wetlands nearby.

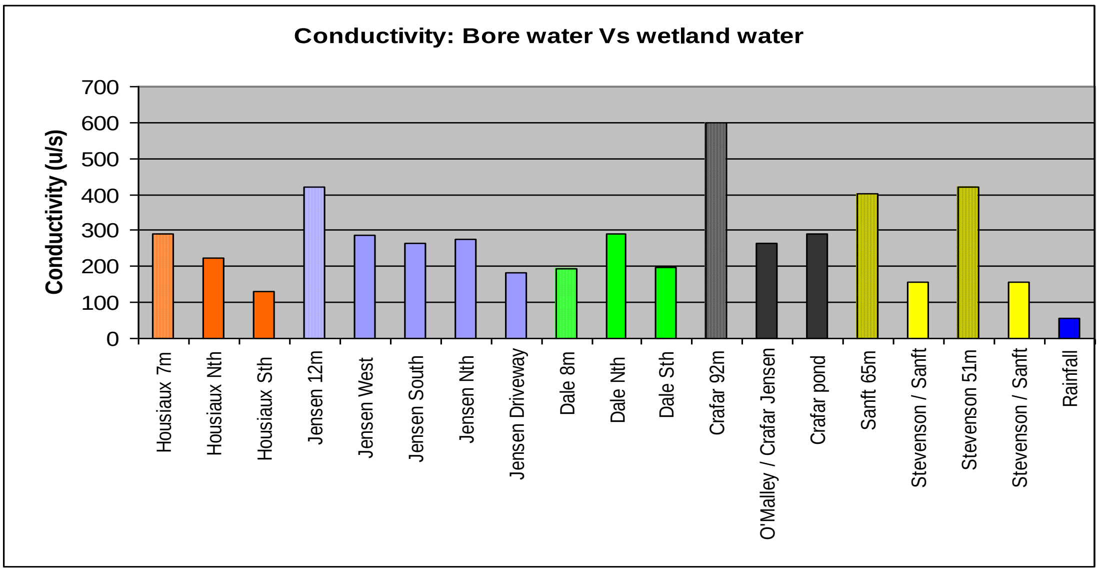


Figure 5.3.8: Conductivity of bore water, nearby wetland water and rainwater. With the exception of the Dale bore, conductivity is higher in groundwater than in nearby wetland water.

5.3.3 Summary

According to the wetland class definitions set out by Clarkson (2003) and Johnson and Gerbeaux (2004), the present day wetlands in the Te Hapua complex are either swamp or fen. Fens are found mostly in the older Foxton soils / sands along the eastern side of the complex, whilst swamps are predominantly found near Motuiti soils / sands on the western side of the complex. The Foxton soils have slightly better water holding capacity and higher porosity compared to the Motuiti soils. The higher, hummocky dune landscape associated with fens and Foxton soils creates a topographically diverse water table as water mounds beneath high dunes and emerges in the inter-dunal depressions. This is probably why the Pateke site is a discharge wetland (where groundwater is typically higher than the pond water). Topography in western areas is typically more open and individual swamps that were once continuous are now separated by low dunes, some of which are natural. Fens are mostly contained by dunes, where as swamps tend to have some amount of flow (at least via through-flow).

Water quality testing indicates that the main sources of wetland pond water are likely to be rainfall and shallow groundwater. Given the difference in pH and conductivity, deep groundwater is not likely to contribute significantly to wetland surface water (if at all). However more sampling would be necessary to draw statistically significant conclusions.

VI Discussion and Conclusion

Key questions concerning the potential threats to the wetlands were raised in Chapter 1. This chapter addresses these questions in turn and finishes with a conclusion on the future viability of the wetlands and recommendations for future study as well as future policy.

6.1 Defining the hydrology of Te Hapua wetlands – nature and dynamics

The literature review in Chapter 3 revealed that there has been a gap in knowledge concerning the hydrology of the Te Hapua complex. A better understanding of the hydrology and hydrogeology of the area may be of value when considering the future of the complex as well as regional water allocation limits and resource consent applications for groundwater abstraction near the wetlands. This section addresses two of the key questions raised in Chapter 1:

What defines the hydrology of the wetland?

- Where does the wetland water come from?
- Is this uniform across all the individual wetlands within the complex?
- Where does the water leave the system?

What is the relationship between groundwater and wetland surface water?

Before addressing these questions it is important to note that this study predominantly considers the present day wetland hydrology. Investigations into the historical extent of the wetlands were carried out to provide a context which helps to explain the present day hydrology. Section 6.1.1 gives a brief overview of the history of the wetlands over the past 50 to 60 years with regard to anthropogenic modifications to the wetlands and their influence on local hydrological processes.

Section 6.1.2 reviews the interpretation of wetland class for individual wetlands around the complex and looks at spatial patterns of class compared to patterns of soil type and elevation. The GIS analysis of flow accumulation and watershed is assessed to give a broad overview of approximate hydraulic pathways. Also in section 6.1.2 is an overview of how each monitored wetland responds to rainfall.

Section 6.1.3 discusses the relationship between the wetlands and groundwater of various depths. The relationship with shallow groundwater is discussed first along side results from the analysis of water level monitoring at the Te Hapua monitoring sites. Aquifers are then discussed with regard to their potential as wetland surface water inputs / outputs and there is a review of the estimated hydraulic characteristics of sediments that underlie the area.

6.1.1 Human Modifications

Conversations with Ian Jensen, landowner and visitor to the area for over 50 years, revealed that the hydrology of many individual wetlands around the Te Hapua complex (including all three of the monitored sites) has been modified at some stage with the installation of culverts, drains or dams. Mr Jensen described the effect of drains installed in the 1950s and 1980s that saw wetland water levels remain low or below ground for much of the year, thus allowing farmers to graze the entire region. Since then some landowners have dammed parts of the wetlands in an attempt to retain water and restore them to their former condition. Te Hapua Road was extended across the wetlands to the coast in the mid to late 1980's, creating a dam and culvert that effectively acts as a bottle neck for wetland pond water. Old drains may still be moving water away from some wetland areas in certain conditions. The collective result of these modifications is a highly complex water regime with water levels in many areas determined by anthropogenic influence as much as the natural components of climate, soil, geology and topography discussed in the literature review chapters. Water can no longer move freely between wetlands on the western side of the complex as it did at the time aerial photographs captured the area in 1967. The series of historical aerial photos displayed in chapter 3 shows that areas of open water have appeared gradually in many of the wetlands over the past 43 years. The effect that the heavy machinery used to excavate the wetlands over the years has had on the hydrology is not known. It is possible that digging into the peat matrix alters the conductivity of the wetland soils that are thought to 'seal' the pond floor (as discussed in section 2.5.6). This could change the natural rate of water exchange and the relationship between the wetlands and groundwater. Aerial photographs also show large areas of wetland have been drained permanently and replaced with pasture for grazing stock. The most expansive areas of drainage are just north of the complex, close to Pateke and Shoveler wetlands. This will have almost certainly lowered the water table in the vicinity.

6.1.2 The hydrology of Te Hapua wetland complex

Wetland classification

The first step in trying to determine the source of wetland surface water was to classify individual wetlands depending on their nutrient status and water regime. This helped to assess the probable water source, as defined by Johnson and Gerbeaux (2004).

Results from the wetland classification survey indicate there are two main classes of wetland present in the complex – swamps and fens. These were defined according to the taxonomy presented in table 2.2. Some of the individual swamps had portions where defining characteristics were more fen-like than swamp-like. These portions were restricted to topographically higher areas and, according to Johnson and Gerbeaux, it is not uncommon for an individual wetland to have spatial variations of this nature. An average value for measurements of pH and conductivity was therefore used to define the class of individual wetlands. This seemed appropriate after a search found no guidance available from literature in this regard. The water regime was also considered (i.e. presence or absence of water inflow and outflow as well as the amount of water fluctuation). Estimating water fluctuation throughout the complex was difficult because just three of the twenty one wetlands had monitoring equipment installed. For this reason more gravity was placed on the results from the water quality measures when defining the class. This may have introduced some error into the interpretation.

A change in topography, geology and soil type across the wetland correlated well with the change in wetland class (figure 5.3.2). A western band of low lying swamps runs close to and parallel with the coast. This band is associated with Motuiti series soils which formed up to 900 years ago. East of this band, high dunes are more prevalent and wetlands are mostly isolated fens, higher in elevation than wetlands in the western band. The eastern band is dominated by much older Foxton series soils which formed up to 6500 years ago. Porosity and water holding capacity in the eastern band soils are generally higher than in the western soils. This, combined with the influence of larger, more developed dune systems may significantly slow runoff between wetlands and adjacent land, decreasing the likelihood of swamp formation. It is likely that the dominance of dunes in eastern areas raises the level of the water table through the mounding of shallow groundwater below the dunes.

According to Johnson and Gerbeaux (2004), both swamps and fens are typically fed by local rainfall, runoff from nearby soils, and groundwater seepage. The difference is that swamps receive greater input via surface runoff from nutrient rich soils, so have higher pH and conductivity than fens. The specific type of runoff that transports water around the wetlands will vary but may be a combination of the runoff processes described in Chapter 2, section 2.6. Water fluctuation is less in fens indicating a more dominant groundwater influence compared to swamps. Input from groundwater seepage is most likely to be from the shallow unconfined aquifer, and is discussed in more detail later in this section.

Some of the wetlands at Te Hapua are ephemeral (Preece, 2005). Ephemeral wetlands are considered more susceptible to loss than other wetland types (Cromarty & Scott, 1995). It was not possible to identify specifically which of the wetlands are ephemeral and which are not because 2009 was particularly wet and all of the wetlands contained water throughout the study. Wetlands most likely to be ephemeral are the smaller fens in the eastern band.

GIS analysis of flow accumulation and watershed

The second step in defining the hydrology of the wetlands was to map the wetlands using elevation data supplied by Wellington Regional Council. GIS was used to calculate probable flow pathways and approximate watersheds for individual wetlands within the complex. The presence of underground drainage corrupted the results to some extent, but following ground truth field work the errors were minimised and a broad understanding flow patterns was established.

The GIS flow accumulation analysis (figure 5.2.9) indicates that there is no significant surface water inflow to any part of the wetland complex from outside the local watershed; hence the wetlands are isolated from surface water flow from the Tararua Ranges and nearby streams. There are two seasonally significant surface outflows from the wetlands. Natural and human-made land bridges separate all of the individual wetlands shown on the map. Some wetlands are linked with culverts but many of the culverts do not allow flow until the water level is sufficiently high. Given this, it is likely that runoff is mostly via through-flow from nearby soils, particularly in the western band of wetlands.

It is possible that, given the subtle changes in elevation in low lying areas, the drain north of the Shoveler site receives back-flow from downstream areas. This may occur when significant rainfall in the Mangone catchment combines with high tide and / or a consistent north-westerly wind. Mr Jensen has seen water levels in the drain north of Shoveler lagoon rise as a result of these conditions and noted the backflow of water into wetlands on his property. At the time very heavy rain had fallen on the Mangone catchment but not the coastal plain. Pressure transducers were installed in this northern drain but unfortunately some of the equipment was lost in the field, rendering the data useless.

According to GIS watershed calculations there are 5 main drainage basins within the complex (figure 5.2.10). Looking more closely at the individual wetlands monitored by Wellington Regional Council, wetland areas were calculated to have approximate sizes of 3.1ha, 4ha and 7.3ha for Jill and Joy's, Shoveler, and Pateke wetland respectively. The immediate watershed calculated for each wetland was 8.4ha, 7.4ha, and 17.8ha respectively.

There were problems with the data used for the GIS analysis. The LiDaR data gave false elevation readings in some areas where dense vegetation covered the land surface. Also, the LiDaR data could not pick up on subsurface drainage in the area. This affected the DEM and subsequent calculations of flow direction and accumulation. Ground truthing and manipulation of a new DEM to show culverts as surface depressions minimised these problems. Further problems were encountered because the wetland shape file provided by Wellington Regional Council was not accurate in some areas. This resulted in errors in the watershed calculation and could not be completely remedied without a full survey of the wetlands. Due to time constraints this was not possible but an estimate based on field observations was sufficient to fix most of the problem areas.

Water balance and wetland response to rainfall

The third step in defining the hydrology of the wetlands was to analyse the data from the three wetland monitoring sites in terms of the wetland's response to significant rainfall compared to the response of nearby shallow groundwater. A water balance (net flow) was calculated for each wetland using pond level, rainfall and evaporation data. The water balance is limited because it only uses 8 months worth of data, but still shows the differences between the three sites (see section 5.2.3). Section 5.2.4 looked at each wetland's volumetric response to five significant rainfall events by using water level and rainfall data together with wetland area and watershed calculations from the GIS analysis. These results were also limited because of the problems with the accuracy of the wetland shapes and watershed areas discussed earlier.

Jill and Joys Pond

Water level observations detailed in section 5.2.1 indicate that during the wet season the outflow culvert at Jill and Joy's wetland becomes submerged (when the water reaches approximately 3200mm above sea level), and acts as a bottle neck for water outflow. As a result, water accumulates during the wet months more so than in the other monitored wetlands. This can be seen in the net flow figures from section 5.2.3.

Calculations of the volumetric response of wetlands to given rainfall events (section 5.2.4) indicate that Jill and Joy's pond responds differently depending on the season (wet/dry). During rainfall events in the drier months the wetland volume at Jill and Joys increased by more than the amount of rainfall that has fallen in the catchment. This may be due to a difference in the wetland area between wet and dry seasons, but is difficult to explain. During rainfall events in the wetter months, the volumetric increase of the pond is less than the volume of rainfall that has fallen in the catchment. At this time, 25% to 50% of rainfall did not reach the wetland. This may be the portion that is lost to evapotranspiration or groundwater.

Shoveler Lagoon

At Shoveler, water generally flows in and out via through-flow year round. If, however, the pond level rises above a point (approximately 3150mm above sea level), then water will start to flow over the top of dam A, and consequently shallow groundwater and pond water even out at a similar level (see figures 5.2.5 and 5.2.3). However this only happens in years when water levels are particularly high (such as 2009).

The volumetric response of Shoveler Lagoon to given rainfall events in section 5.2.4 shows that the increase of water volume in Shoveler Lagoon was consistently more than the volume of rainfall that fell on the immediate catchment. Again this is difficult to explain, but in this case may indicate that the watershed area used for the calculation was not representative of the actual watershed. This problem is described in more detail in section 5.2.2.

Pateke Wetland

At Pateke, water also generally flows in and out via through-flow year round. Being a recharge wetland, the dominant water source is local rainfall and shallow groundwater from surrounding dunes. Once water level in the Pateke wetland reaches a certain height (estimated at approximately 5250mm above sea level), it tends to drain faster, so water may be flowing out via soil near the top of the dam that has relatively high conductivity. The volumetric response to given rainfall events (section 5.2.4) indicate that the increase of water volume in Pateke wetland is consistently less than the total volume of rainfall that has fallen on the catchment. 25% to 50% of the rain that fell on the catchment did not reach the wetland. It is assumed that this is the portion that is lost to groundwater and evapotranspiration for this catchment.

Comparing the three wetlands, the hydrology of the Jill and Joy and Shoveler wetlands are similar in that they are both recharge wetlands. Conversely, the hydrographs showing the long term water balance (5.2.13 through 5.2.15) and wetland response to individual rainfall events (5.2.2 through 5.2.4) indicate that Shoveler wetland is more similar to Pateke. Spatial variability of wetland hydrology at Te Hapua appears complex. It is likely that complex flow fields exist beneath the peat and sand hills as depicted in figure 2.5.5. Pressure gradients are almost certainly created by a topographically diverse water table caused by local variations in dune systems – as is shown in figure 2.5.6. Interactions between an inter-dunal wetland and shallow groundwater are often transient and can reverse seasonally (Law, 2008; WRC, 2005).

6.1.3 The relationship between groundwater and wetland surface water

With reference to the key question facing the Te Hapua wetland complex, determining the relationship between the wetlands and groundwater is fundamental. To explore the dynamics in detail, the term ‘groundwater’ needs to be broken down to differentiate between groundwater in the shallow un-confined aquifer and groundwater within the three deep confined aquifers.

Shallow groundwater: Results from the three monitoring sites

The exchange of water between a wetland and shallow groundwater is a dynamic process. In general it is thought that wetlands do not lose a significant amount of water to groundwater (Campbell & Jackson, 2004). There are two reasons for this. One is that swamps and fens are typically found at the base of hill-slopes and low-lying areas where groundwater is emergent. The other is that the low permeability of the peat that lines many wetlands acts as a confining layer that limits water movement to deeper layers. Groundwater inflow to wetlands is an important input in some palustrine wetlands, yet in others it has little or no influence (see table 2.2). When trying to determine the source of wetland water, looking at the relative levels of wetland pond water and groundwater is useful. Figure 2.5.4 depicts the possible discharge – recharge relationships in wetlands with regard to groundwater.

Wetland pond level and adjacent shallow groundwater level was monitored at three sites for 11 months in 2009. Results, displayed in Chapter 5 (section 5.2.2), indicate that Pateke wetland is a discharge wetland, where groundwater is typically higher than pond water. Hydrology in a discharge wetland is more dominated by shallow groundwater inflow, which buffers the wetland from variations in water level, hence fluctuations are less dramatic than in surface flow wetlands (Law, 2008; White, et al., 2001). This is certainly true for water level recordings from Pateke. Results also indicate that the Jill and Joys and Shoveler sites are likely to be recharge wetlands, because groundwater is typically lower than pond water. Recharge wetlands often lose water to groundwater (Mitsch & Gosselink, 2007; White, et al., 2001).

The fact that Pateke is a discharge wetland is likely to be due to the influence of the greater number and size of dunes surrounding the Pateke site. Since this topography and soil type extends out along the eastern band (as discussed in section 6.1.2), it is suggested that other fens within the complex are also likely to be discharge wetlands. Conversely it is suggested that all of the swamps in the western band are likely to be recharge wetlands, where water levels fluctuate more and are often determined by the height of culverts installed in human-made dams.

The theory that Pateke wetland is more closely connected to groundwater is backed by the fact that groundwater and surface water have a similarly timed immediate and extended response to significant rainfall. By contrast, wetland water level response to rainfall at Jill and Joy's / Shoveler wetlands lags behind the response evident in the shallow bores nearby (see table 5.2.1). Resistivity soundings in Te Horo carried out by Wilson (2003) indicate that peat soils are widespread beneath the dune areas. This is thought to reduce or inhibit infiltration to the shallow aquifer, indicating that rainfall that lands in the area will either by evaporated, transpired, or stored temporarily as surface water in streams and wetlands. It is possible that swamps in the western band are often perched above the water table. When a significant rainfall event occurs shallow groundwater rises quickly, seeping into the wetlands slowly through the peat matrix of surrounding soil. This would explain the lag response to rainfall and the large volumetric rise in wetland pond water compared to rainfall in the immediate catchment for Jill and Joys / Shoveler wetlands.

Deep groundwater: Potential input / output from the deeper confined aquifers

Deep layers were analysed in a number of ways to look for evidence that would indicate water exchange with the wetlands. The following paragraphs review results from an analysis of the geological cross section; a comparison of basic water quality measures from different aquifers and wetlands; and two pump tests carried out at the wetland.

It was established in the literature review chapter that 3 confined aquifers and one shallow unconfined aquifer are present in the region (see Chapter 3 section 3.3). Section Geological records from Te Hapua bores show that between one and three confining layers separate the first confined aquifer from the shallow unconfined aquifer at around 25m below sea level. Records from the two bores that penetrate the second confined aquifer below Te Hapua show another one or two confining layers at a depth of 65 to 80 metres below sea level (see figure 4.2.21). According to WRC (1994), another aquitard overlies the third confined aquifer in Te Horo at a depth of between 164m and 172m deep. Adding these together, there are between four and seven confining layers separating the wetlands from the third confined aquifer (including the peat lining the wetlands themselves). Multiple confining layers below the wetlands would almost certainly limit surface water exchange with deep groundwater.

Pressure heads in Te Hapua bores that penetrate the second confined aquifer generally appear to be higher than those from bores in the first confined aquifer. It is not known if this ever reverses, but if not any leakage that might occur between these layers would be in an upward direction. A Te Horo study (WRC 1994) notes that pressure head in the third confined aquifer is higher than that in the first confined aquifer, and that upward leakage occurs; moving water from the third confined aquifer into overlying aquifers. Te Hapua and Te Horo are 5 km apart and share the same geological history, so it is likely that the aquifers that underlie each area are similar. It is possible that some of the Te Hapua wetlands occasionally receive water via upward leakage from deeper layers, but without further pump testing there is currently no strong evidence for this. In any case, it is not likely to be a major water source for the wetlands.

As part of the wetland water quality survey (section 5.3.2), water from bores was compared to water from adjacent wetlands to see how similar the wetland samples were to the samples taken from various aquifers. This may give some indication as to which aquifer is the more likely source of wetland water. Further testing would be needed to provide a statistically significant result, but in all instances it was found that water from the shallow unconfined aquifer has a pH and conductivity most similar to that of the wetland water. A constructed wetland fed by a high yielding spring close to Pateke was also sampled. The water quality at this location was most similar to the shallow unconfined groundwater, indicating that shallow groundwater is emergent in this area. No more springs were located in the Te Hapua complex, but one more is said to exist at Pateke. Both of these sites are at the point that delineates a change in soil class from Foxton black sands to Motuiti and Omanuku peats.

Finally, the results of pump tests carried out in two Te Hapua bores are shown in section 5.2.5. In both tests, pumping induced a drawdown in nearby wells that share the same aquifer, but there was no evidence of drawdown in adjacent aquifers and hence no evidence of aquifer leakage. This, however, may be due to the method used to conduct the pump tests. The analysis did pick up a rise in wetland surface water level and deep groundwater level in response to non local rainfall. This is most likely to be a regional hydraulic response to rainfall higher in the catchment.

6.2 Potential threats to Te Hapua

In Chapter 1, three potential threats to the wetlands were identified: loss or damage due to a gradual lowering of regional groundwater levels; loss or damage due to increased groundwater abstraction close to the wetlands; and loss or damage due to possible future climate change. Key questions identified in Chapter 1 around these concerns are:

Is the apparent historical decline in deep groundwater level a result of abstraction from bores, climate change (i.e. natural variation), or both?

What are the local predictions for climate change and what effect could it have on existing wetland areas?

Given the current safe yield and allocation, what effect could future abstraction have on existing wetland areas?

- If a large scale groundwater abstraction was permitted near the wetland, would it impact on wetland surface water levels?

This section addresses each question with reference to literature and results presented in Chapters 2 to 5.

6.2.1 Historical groundwater trend

Section 6.1.2 established that the most likely sources of wetland surface water are local rainfall, runoff from nearby land, and shallow groundwater inflow from nearby dunes. In light of this, the threat posed by groundwater level decline in deep confined aquifers is probably not high. However over the year of monitoring there were a few instances where wetland water levels responded to a rise in groundwater level in confined aquifers. This could indicate either a hydraulic response from rainfall higher in the catchment or upward leakage into the wetlands from deeper layers. Without more comprehensive aquifer testing the potential for downward leakage over extended periods is still uncertain, so an analysis of trends in water level from confined aquifers is an important part of this study.

So, is the apparent historical decline in deep groundwater level a result of abstraction from bores, climate change (i.e. natural variation), or both? The short answer to this is that it is probably not due to bore abstraction. Regional Council records indicate that a very small portion (8%) of the safe yield[9] is currently allocated. Of the seventeen long term bores in the region (within the Coastal and Hautere groundwater zones), four showed significant decline in groundwater level and four showed a significant rise over the period they were monitored. Of the bores showing decline, one (R25/5111) dropped 1643mm in one summer (1997/98) and has since been rising. The reason for this is unexplained. Another (R26/6747) has been dropping annually by 0.48% of the range (10mm/year for 27 years), and the third (R25/5100) dropped annually by 1% of the range (1mm/year for 8 years). The fourth bore with a declining groundwater trend (S25/5208, 192m deep and 4.5km north of Te Hapua) shows a relatively high annual drop of 2.3% of the range (64mm / year for 17 years).

Net annual rises for the last few years at three of the bores discussed above (S25/5208, R25/5111 and R26/6747) indicate that groundwater levels may have recently started to reverse. Monitoring at R25/5100 was discontinued in 2003, so the recent trend is unknown. The length of the record at this bore, and arguably some or all of the others, is probably too short to pick up any naturally occurring medium and long term trend in groundwater level fluctuation. So, referring back to the key question above, short term variation of climate is the most likely explanation for the observed groundwater level trends. The 'picture' of natural groundwater fluctuation will become clearer as more data become available.

Unfortunately only nine of the seventeen bores with long term data continue to be monitored by Wellington Regional Council. Long term trends would be better understood if monitoring at some of these sites was resumed so as to be more representative of groundwater levels within each aquifer. The only bore that has shown decline and is no longer being monitored by Wellington Regional Council is R25/5100. This bore is significant because it is less than 100m from the wetlands. This would be an excellent bore to continue monitoring as it is the only bore close to the wetlands that is used to irrigate farmland, and is drilled into the first confined aquifer (to 48m). Abstraction from this bore is relatively minimal at less than 20,000m^3/year (0.3% of the assumed safe yield for the Coastal Groundwater Zone), but given its proximity it would provide a good monitoring site to look at possible groundwater-surface water interaction between the first confined aquifer and the wetlands / unconfined aquifer.

[9] The safe yield in equal to the total estimated recharge to groundwater

6.2.2 Climate change

The vulnerability of a given wetland in light of climate change falls between two extremes; those dependant primarily on precipitation for their water supply (these are highly vulnerable given changes in the hydrological cycle); and those dependant on discharge from regional groundwater flow systems (these are least vulnerable given the buffering capacity of groundwater) (Winter, 2000).

What are the local predictions for climate change? According to the IPCC fourth assessment (2008) and analysis by Mullan et al (2007), sea level is predicted to rise in New Zealand by between 0.18m to 0.59m by 2090. There may be an additional 0.2m rise depending on the impact of global ice sheet flow. Current predictions also suggest an air temperature rise of 0.6 to 5.1°C, with a mean rise of 2.1°C by 2090. By 2090, the Kapiti Coast is expected to see an average annual change of precipitation of between minus 7% and plus 14% of the current average (Mullan, et al., 2007). Summer months are predicted to be slightly drier on average whilst winter months will be slightly wetter. Extreme rainfall events are predicted to become more frequent and the intensity of the extreme rainfall events is likely to increase. This will increase runoff and surface ponding, and is also likely to impact on groundwater (IPCC, 2008; Mullan, et al., 2008). An increase in runoff would result in less water percolating down to recharge groundwater. This may put stress on wetlands fed by local shallow groundwater. Hot dry spells will likely become more frequent which may increase stress on wetlands dependant primarily on precipitation for their water supply.

What effect could these changes in climate have on existing wetland areas at Te Hapua? Te Hapua is a collection of swamps and fens, some of which are ephemeral (Preece, 2005). Ephemeral wetlands typically occupy closed depressions with no surface outlet and may dry up during times of low rainfall. They receive their water mostly from shallow groundwater and seasonal rainfall so have highly variable water levels. Some ephemeral wetlands will therefore be more susceptible to loss given a change in climate. More data and observations would be needed to assess which of the Te Hapua wetlands are ephemeral, and which are not, but generally smaller wetlands within the eastern band are situated in a geomorphological setting that is typical of ephemeral wetlands. Water level in these wetlands could be monitored by interested landowners to assess the wetland class and subsequent threat from climate change.

All of the wetlands in the Te Hapua complex are fed to some extent by shallow groundwater, so a decrease in precipitation and / or shallow groundwater recharge due to higher intensity rainfall may have an impact. The eastern band of wetlands is slightly higher in elevation than the western band and there is evidence of emergent shallow groundwater in some areas.

The western band of wetlands at Te Hapua is located within a narrow, low lying neck of land that is lined either side by relatively high dunes. Wetlands within this strip are typically no more than 3m above sea level and run parallel to the coast, which is 600 metres to the west. It is possible that a significant rise in sea level coupled with the predicted increase in frequency and intensity of storm surge events could result in saline intrusion to wetland areas and / or shallow groundwater. Wetlands are generally capable of adapting to variations of hydrology and can 'migrate' given a permanent change in hydrology. Some of the individual wetlands in the western band have sufficient space inland to migrate should sea level rise sufficiently as to induce migration. Others, however, due to both natural and anthropogenic barriers do not have this migration space, so will be at greater risk.

The values predicted for climate change in a given area should be considered within the context of the current known natural variability of the local climate. Mullan et al (2007) explains that although the predicted changes in average Kapiti Coast temperature, for example, are reasonably small, this small shift may increase the frequency of (what is currently considered) extreme temperature events. Extreme events, as a consequence, may become more extreme, and wetlands known to be vulnerable to extreme events (for example ephemeral wetlands) will therefore be at greater risk. The IPCC predications have been averaged from the results of 12 different climate models and six different scenarios. If the worst case scenario was to become a reality, then the extreme events would become a much more relevant and imminent threat to all hydrologic landscapes, especially wetlands in low lying coastal areas such as Te Hapua.

With regard to wetland management; planners and developers should allow adequate space around low lying coastal wetland areas for natural inland migration given a gradual rise in sea level (Burkett & Kusler, 2000). Appropriate re-development of current anthropogenic wetland stressors such as riparian structures, levees and dams would also help safeguard these areas.

6.2.3 Groundwater abstraction

If a large scale groundwater abstraction was permitted near the wetland, would it impact on wetland surface water levels?

Answering this question definitively requires more monitoring and testing of groundwater in bores of various depths close to the wetland. However, indications are that wetland pond levels are not likely to be affected by groundwater abstraction. There are four reasons for this:

- The main input of water for the wetlands is from local rainfall, local runoff, and shallow groundwater from nearby dunes (as discussed in section 6.1.2).
- There are multiple confining layers between the surface and the deepest confined aquifers.
- It appears that the pressure heads of deeper aquifers are higher than those of shallower aquifers, creating a hydraulic gradient that would, if conditions allowed, induce upward leakage, not downward leakage. Downward leakage is a threat to wetland water levels, not upward leakage (refer to section 6.1.3).
- The estimated transmissivity, specific yield and hydraulic gradient of the aquifers that underlie the wetlands are particularly low.

The deeper a well is drilled, the less likely it is that it would impact on wetland surface water. The third confined aquifer, for example, in 165m deep and has between 4 and 7 confining layers between the zone of abstraction and the wetland. The first confined aquifer is 30m deep and has between 2 and 4 confining layers.

Estimated values for transmissivity, specific yield and drawdown were calculated in section 4.2.3. These values, combined with the low hydraulic gradient (as shown in figure 3.8) indicate that sediments that underlie the wetland are likely to have very low conductivity. If the aquifers that underlie the wetlands are low yielding then they are not likely to be targeted for large scale abstraction.

6.2.4 Water allocation

Are the water allocation limits used today appropriate for future increases in population, historical trends in groundwater level, and estimates of future climate change?

It is common practise to use ‘safe yield’ to establish water allocation limits for groundwater resources - Wellington Regional Council’s Freshwater Plan uses it to manage groundwater allocation across the region, including the Kapiti Coast (personal communication with Mark Gyopari, Wellington Regional Council, May 3rd 2010). Safe yield assumes that 100% of rainfall recharge can be safely allocated, so does not allow for groundwater discharge to surface water ecosystems such as wetlands. Despite being repeatedly discredited in the literature, safe yield continues to be used as the basis of water management policies, leading to continued groundwater depletion, stream de-watering, and loss of wetland and riparian ecosystems (Sophoscleous, 2000).

Given that groundwater in the Coastal Zone is just 8% allocated, having an inaccurate limit to ‘safe’ groundwater abstraction is unlikely to be a major issue at present. However this may change in the future as predicted population increase and changes in climate put water resources under increased pressure. Wellington Regional Council is currently reviewing the use of safe yield for water allocation and is building numerical models to deal with the problem in the Wairarapa where water resources are under pressure and may be over allocated.

6.3 Future work and implications for the management of wetlands and groundwater

6.3.1 Recommendations for local authorities and planners

With regard to wetland management in the face of predicted climate change; planners and developers should allow adequate space around low lying coastal wetland areas for natural inland migration given a gradual rise in sea level. Appropriate re-development of current anthropogenic wetland stressors such as riparian structures, levees and dams would also help safeguard these areas.

If in the future a large scale groundwater abstraction is proposed in the area, the environmental impact assessment would benefit from a series of pumping tests to look for downward leakage between aquifers (see section 6.3.2 below).

6.3.2 Recommendations for future studies at Te Hapua

This research would be strengthened considerably with a comprehensive groundwater study to assess leakage in each aquifer. Pump testing would put significant strain on the aquitards and monitoring the wetlands and various bores would be easy to set up. It would be necessary to open up bores that are currently sealed. The equipment and time was not available in this study to carry out testing of this nature.

Monitoring of the long term trend in groundwater level from the first confined aquifer should be resumed at R25/5100. This would not only help to determine the influence of local abstraction from this bore, but would also be beneficial in monitoring the hydraulic relationship between the first and second confined aquifers to assess potential for downward leakage. This would only work if the bore is seldom used so as to have a relatively steady head. Alternatively some monitoring equipment installed in an unused bore that penetrates the first confined aquifer close to the wetland would be beneficial. There is currently no reliable high resolution monitoring of the first confined aquifer in the Coastal / Hautere groundwater zones.

More work could be done to monitor and assess the influence of the Mangone Stream on wetland surface water and shallow groundwater; although it appears that there is seldom a hydraulic connection between the waters.

Landowners could help monitor individual wetlands to ascertain which are ephemeral and which are not. This would give landowners an idea of how susceptible their wetland is to climate change.

6.3.3 Recommendations for future studies on wetland hydrology

Using GIS and LiDaR data to assess hydrological characteristics in areas where there has been significant modification to natural drainage is difficult and the results are not necessarily fool proof. If one was to undertake a similar investigation of a wetland area, it is recommend that the researcher first finds and maps all culverts, drains and dams before adding them to the LiDaR data and calculating drainage pathways / watersheds. It is also recommended that the researcher accurately surveys the wetland perimeters to encompass all possible drainage pathways and watersheds. Using the highest possible wetland water level as the wetland perimeter should achieve this. Although more time consuming, using the highest resolution DEM available will provide the best results when calculating flow direction around the wetland. This will help to minimise 'edge effect'.

6.4 Conclusion: The future prognosis for Te Hapua wetlands

Overall, the future viability of the Te Hapua wetland complex appears promising. Historical groundwater declines appear to be minimal and show signs of reversing. Abstraction from deep confined aquifers is not likely to impact on wetland water levels. Climate change is likely to have an impact on the hydrological cycle and may increase pressure on some areas, especially ephemeral wetlands. The effect of climate change on groundwater level is more difficult to forecast, but may lower water level in the long term.

All of these statements, however, are associated with a degree of uncertainty. A better understanding of the potential for threat would likely be gained from further research as described in section 6.3, but some amount of uncertainty will always remain. Science will never know all there is to know. Rather than allowing the unknown or uncertain to paralyze us, we should apply what we know with a good measure of common sense when choosing the most suitable locations for groundwater abstraction. Possible problems in the future may be averted if our policies are flexible enough to allow us to respond and modify our approaches as new knowledge becomes available.

VII References

Anderton, J. (2006). *Report from Dr Joy Anderton to the Environment Court mediator, Mr John Mills* (No. ENV 2006 WLG00033).

Ausseil, A. G., Gerbeaux, P., Chadderton, W. D., Stephens, T., Brown, D., & Leathwick, J. (2008). *Wetland ecosystems of national importance for biodiversity: Criteria, methods and candidate list of nationally important inland wetlands* (No. LC0708/158). Wellington: Landcare Research.

Baird, A. J. (1997). Continuity in Hydrological Systems. In R. L. Wilby (Ed.), *Contemporary Hydrology* (pp. 25-58). Chinchester: John Wiley and Sons Ltd.

Balmford, A., Bruner, A., Cooper, P., Costanza, R., Farber, S., Green, R. E., et al. (2002). Ecology - Economic reasons for conserving wild nature. [Review]. *Science, 297*(5583), 950-953.

Bardsley, W. E., & Campbell, D. I. (1994). A new method for measuring near-surface moisture budgets in hydrological systems. *Journal of Hydrology, 154*(1-4), 245-254.

Beadel, S. (2003a). *Kapiti Coast District Wetlands* (No. 669). Rotorua: Wildlands Consultants.

Beadel, S. (2003b). *KCDC 2002-2003 Ecological Site Survey* (No. 662). Rotorua: Wildlands Consultants.

Begg, J. G., & Johnston, M. R. (2000). *Geology of the Wellington area* (No. ISBN 0-478-09685-2). Levin: Institute of geological and nuclear sciences.

Bergkamp, G., & Orlando, B. (1999). Wetlands and Climate Change. Exploring collaboration between the Convention on Wetlands (Ramsar, Iran, 1971) and the UN Framework Convention on Climate Change. Retrieved November 2009, from Ramsar Convention on Wetlands: http://www.ramsar.org/key_unfccc_bkgd.htm http://www.ramsar.org/cda/en/ramsar-pubs-manual-wetlands-and-climate/main/ramsar/1-30-35%5E21076_4000_0__

Birkeland, P. (1999). *Soils and Geomorphology* (3rd Edition ed.). New York: Oxford University Press.

Burkett, V., & Kusler, J. (2000). Climate Change: potential impacts and interactions in wetlands of the United States. *Journal of American Water Resources Association, 36*(2), 313-320.

Buxton, R. (1991). *New Zealands Wetlands; A management guide.*

Campbell, & Jackson, R. (2004). Hydrology of Wetlands. In J. Harding & P. Mosely (Eds.), *Freshwaters of New Zealand* (pp. 20.21-20.14). Christchurch: New Zealand Hydrological Society.

Campbell, Laybourne, C. E., & Blair, I. J. (2002). Measuring peat moisture content using the dual-probe heat pulse technique. *Australian Journal of Soil Research, 40*(1), 177-190.

Campbell, & Williamson (1997). Evaporation from a raised peat bog. *Journal of Hydrology, 193*(1-4), 142-160.

Clair, T. A., Warner, B. G., Roberts, R., Murkin, H., Lilley, J., Mortsch, L., et al. (1995). *Canadian Wetlands and Climate Change: Canadian Country Study: Climate Impacts and Adaptations.* : Environment Canada.

Clarkson, B. R., Sorrell, B. K., Reeves, P. N., Champion, P. D., Partridge, T. R., & Clarkson, B. D. (2003). *Handbook for monitoring wetland condition* (No. Ministry for the Environment Sustainable Management Fund Project (5105)). Hamilton: Landcare Research, NIWA, University of Waikato.

Cowie, J. D. (1963). Dune building phases in the Manuatu District. *New Zealand Journal of Geology and Geophysics, 6*, 268-280.

Cromarty, P., & Scott, D. (1995). *A directory of wetlands in New Zealand* (No. ISBN 0-478-01776-6). Wellington: GP Print.

Cussins, A. P. (1994). *Hydrology and Hydraulic Characteristics of the Unconfined Aquifers of the Otaki - Te Horo area.*, University of Victoria thesis, Wellington.

Davie, T. (2004). Soil water, runoff and streamflow generation. In J. H. P. Mosely (Ed.), *Freshwaters of New Zealand* (pp. 4.1-4.10). Christchurch: New Zealand Hydrological Society.

De Groot, R., Stuip, M., Finlayson, M., & Davidson, N. (2006). Valuing Wetlands: Guidance for valuing the benfits derived from wetland ecosystem services. Retrieved February 2010, from Ramsar online report (accessed 01/08/2009): http://www.ramsar.org/pdf/lib/lib_rtr03.pdf

Dugan, P. (1993). *Wetlands in Danger*. London: Reed International Books.

Eutech (2004). Instruction Manual: CON 400 and CON 410. In E. I. P. Ltd & O. Instruments (Eds.) (Vol. Rev 3 01/04).

Fahey, B., Bowden, W. B., Smith, J., & Murray, D. L. (1998). Hillslope-wetland hydrological linkages in the headwaters of a tussock grassland catchment at Glendhu, South Island, New Zealand. In K. Kovar, U. Tappeiner, N. E. Peters & R. G. Craig (Eds.), *Hydrology, Water Resources and Ecology in Headwaters* (pp. 157-164). Wallingford: Int Assoc Hydrological Sciences.

Fetter, C. W. (2001). *Applied Hydrogeology* (4th Edition ed.). Saddle River: Prentice-Hall.

Finlayson, C. M., & Davidson, N. C. (2007). Global review of wetland resources and priorities for wetland inventory: Report to the Bureau of the Convention on Wetlands. Retrieved October 2009, from Wetlands International & Environment

Research Institute of the supervising scientist: http://www.ramsar.org/cop7/cop7_doc_19.3_e.htm

Freeze, R., & Cherry, J. A. (1979). *Groundwater*. Englewood Cliffs: Prentice Hall Inc.

Fuller, S. (1993). *Wetlands in the Wellington Region* (No. WRC/PP-G-93/16). Wellington: Wellington Regional Council.

Hails, S. (2000a). The Ramsar Convention on Wetlands. Background papers on Wetland Values and Functions. Climate Change Mitigation. Retrieved April 2009: http://www.ramsar.org/info/values_climate_e.htm

Hails, S. (2000b). The Ramsar Convention on Wetlands. Background papers on Wetland Values and Functions. Wetland Products. Retrieved April 2009: http://www.ramsar.org/cda/en/ramsar-pubs-info-background-papers-on-22185/main/ramsar/1-30-103%5E22185_4000_0__

Heron, D. W., & Van Dissen, R. J. (1992). *Geology of the Kapiti Coast (Pukerua Bay to Otaki), Wellington* (No. CR 1992/19). Wellington: Wellington Regional Council.

Hillewaert, H. (2007). Aquifer (vectorised). Retrieved 10/07/2009, from Creative Commons <http://en.wikipedia.org/wiki/Creative_Commons> Attribution ShareAlike 2.5 <http://creativecommons.org/licenses/by-sa/2.5/>: http://en.wikipedia.org/wiki/File:Aquifer_en.svg

Holden, J. (2008). *An Introduction to Physical Geography and the Environment*. Harlow: Pearson Education Ltd.

Hughes, B. (1997). *Nitrate Contamination on the Kapiti Coast, December 1996* (No. WRC/RINV-T-97/26). Wellington: Wellington Regional Council.

IPCC (1996). *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific Technical Analyses* New York: Intergovernmental Panel on Climate Change.

IPCC (2007). IPCC Fourth Assessment Report: Freshwater resources and thier management. Retrieved October 2009, from Intergovernmental Panel on Climate Change: http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter3.pdf

IPCC (2008). Climate Change 2007 synthesis report: Summary for policy makers. Retrieved October 2009: www.ipcc.ch/ipccreports/ar4-syr.htm
http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-spm.pdf

Johnson, P. N., & Gerbeaux, P. (2004a). *Wetland types in New Zealand* (No. 3711). Wellington: Department of Conservation.

Johnson, P. N., & Gerbeaux, P. (2004b). Wetland Types in New Zealand. Retrieved May 2009, from DOC, Ministry for the Environment: http://www.doc.govt.nz/upload/documents/science-and-technical/WetlandsBW.pdf

Jones, A. (2002). *Sims Road Pump Tests, Mourie Property, Te Horo* (No. WRC/RI-T-02/05). Wellington: Wellington Regional Council.

Kampman, I., & Caldwell, K. J. (1985). *Groundwater resources of the Waitohu, Otaki and Mangone.* (No. 65): Manawatu Catchment Board.

Keller, J. (1988). *Wetland Policy: The need for Change.* University of Canterbury, Christchurch.

Kim., K.-Y., Chon., C.-M., Park., K.-H., Park., Y.-S., & Woo., N.-C. (2008). Multi-depth monitoring of electrical conductivity and temperature of groundwater at a multilayered coastal aquifer: Jeju Island, Korea. *Hydrological Processes, 22*(18), 3724-3733.

Kursler, J., CBrinson, M., Niering, W., Patterson, J., Burkett, V., & Willard, D. (1999). *Wetlands and Climate Change: Scientific Knowledge and Management Options.*: Wetlands International.

Law, R. (2008). *The Hydrological viability of Te Harikiki wetland, Waikanae.*, Victoria University thesis, Wellington.

Likens, G. E., Keene, W. C., Miller, J. M., & Galloway, J. N. (1987). Chemistry of precipitation from a remote terrestrial site in Australia. [Article]. *Journal of Geophysical Research-Atmospheres, 92*(D11), 13299-13314.

McFadgen, B. (1997). *Archeology of the Wellington Conservancy, Kapiti - Horowhenua: A prehistoric and palaeoenvironmental study.* Wellington: Department of Conservation.

McLay, Allbrook, R. F., & Thompson, K. (1992). Effect of development and cultivation on physical properties of peat soils in New Zealand. *Geoderma, 54*(1-4), 23-37.

Mitsch, W. J., & Gosselink, J. G. (2000). *Wetlands* (Third Edition ed.): John Wiley & Sons, Inc.

Mitsch, W. J., & Gosselink, J. G. (2007). *Wetlands* (4 ed.). Danvers, MA: John Wiley and Sons Inc.

Morgan, M., & Hughes, B. (2001). Wellington. In M. R. Rosen & P. A. White (Eds.), *Groundwaters of New Zealand* (pp. 397-410). Wellington: New Zealand Hydrological Society Inc.

Mullan, B., Baldi, M., Burgess, S., Salinger, J., Ramsay, D., & Bell, R. (2007). *Updated climate change scenarios for the Kapiti Coast* (No. KDC08301). Wellington: NIWA report for Kapiti Coast District Council.

Mullan, B., Wratt, D., Dean, S., & Hollis, M. (2008). *Climate Change Effects and Impacts Assessment: A guide manual for local government in New Zealand* (No. 978-0-478-30217-2). Wellington: Ministry for the Environment.

NIWA (2010). Tipping bucket type rain gauge (OSK 15180T).

Oke, T. R. (1987). *Boundary Layer Climates*. New York: Routledge.

Osbourne, A. M. (2006). *Movement of water within the Waikanae shallow gravel aquifer and its interaction with the Waikanae River.* Unpublished MSc, Victoria University of Wellington, Wellington.

Palmer, A. S., & Wilde, R. H. (1990). *Soil Definitions and Interpretations for Otaki District Soil Resources Study, North Island, New Zealand.* (No. 631.401 PAL): DSIR Land Resources. Massey University.

Peck, D. (1996). The Ramsar Convention on Wetlands. The Convention on Wetlands text, as amended in 1982 and 1987. Convention on Wetlands of International Importance especially as Waterfowl Habitat. Retrieved April 2009: http://www.ramsar.org/key_conv_e.htm http://www.ramsar.org/cda/en/ramsar-about-faqs-what-are-wetlands/main/ramsar/1-36-37%5E7713_4000_0__

Peck, D. (1998). The Ramsar Convention on Wetlands: A Global Overview of Wetland Loss and Degradation. Retrieved April 2009, from Ramsar Convention on Wetlands: http://www.ramsar.org/about/about_wetland_loss.htm

Phreatos (2002). *Te Harakeke wetland, Kapiti Coast: Hydrological study final report.* (No. 12816/23580): Phreatos Groundwater Consulting.

Preece, J. (2005). *Te Hapua Wetland landowner report: An ecological assessment of the Housiaux property with options for future management*: Wetlands New Zealand.

Ramsar (1986). New Zealand Wetlands Management Policy. Retrieved June 2009: http://www.ramsar.org/wurc/wurc_policy_newzealand.htm

Ramsar (2010a). About the Ramsar Convention. Retrieved February 2010: http://www.ramsar.org/cda/en/ramsar-about/main/ramsar/1-36_4000_0__

Ramsar (2010b). What are wetlands. Retrieved 18/2/2010: http://www.ramsar.org/cda/en/ramsar-about-faqs-what-are-wetlands/main/ramsar/1-36-37%5E7713_4000_0__

Ravine, D. A. (1992). *Foxton Ecological District: Survey for the Protected Natural Areas programme* (No. 0112-9252: 0-478-01300-0). Wanganui: Department of Conservation.

Reynolds, T. I. (1992). *Kapiti Coast sub region - groundwater review* (No. WRC/CI-T-92/44). Wellington: Wellington Regional Council.

Rosen, M. R. (2001). Hydrochemistry of New Zealand's aquifers. In M. R. Rosen & P. A. White (Eds.), *Groundwaters of New Zealand* (pp. 77 - 110). Wellington: New Zealand Hydrological Society Inc.

Schwartz, F. W., & Zhang, H. (2003). *Fundamentals of Groundwater*. New York: John Wiley and Sons, Inc.

Scott, B. E. (1995). Hydrogeology. In A. D. Ward & W. J. William (Eds.), *Environmental Hydrology* (pp. 285-292). Boca Raton: CRC Press.

Singh, V. P. (1992). *Elementary Hydrology*. Englewood Cliffs: Prentice - Hall.

Smith, L., & Wheatcraft, S. (1993). Groundwater Flow. In D. Maidment (Ed.), *Handbook of Hydrology* (pp. 6.1-6.53): McGraw-Hill Professional.

Sokkia (2006). Series 03R Electronic Total Station Manual. In S. Co.Ltd (Ed.) (pp. 230).

Sophoscleous, M. (2000). From safe yield to sustainable development of water resources - the Kansas experience. *Journal of Hydrology (Wellington North), 235*(2000), 27-43.

Sorrell, B., & Gerbeaux, P. (2004). Wetland ecosystems. In J. Harding & P. Mosely (Eds.), *Freshwaters of New Zealand* (pp. 28.21-28.16). Christchurch: New Zealand Hydrological Society.

Statistics NZ (2006). Statistics NZ: Regional summary tables. Retrieved May 3rd 2010, from Statistics New Zealand: http://www.stats.govt.nz/Census/about-2006-census/regional-summary-tables.aspx
http://www2.stats.govt.nz/domino/external/pasfull/pasfull.nsf/7cf46ae26dcb6800cc256a62000a2248/4c2567ef00247c6acc256aff00093335?OpenDocument

Stevenson, G. K., Card, B., Mark, A., McLean, R., & Thompson, K. (1983). *Wetlands: a diminishing resource* (No. 58). Wellington.

Sutherland, F. M. (1982). Wetlands - their role in the hydrology of catchments. *Freshwater Catch, 15*, 16-18.

Tesoriero, A. J., Spruill, T. B., & Eimers, J. L. (2004). Geochemistry of shallow groundwater in coastal plain environments in the Southeastern United States: implications for aquifer susceptibility. *Applied Geochemistry, 19*, 1471-1482.

Thompson, M. A., Campbell, D. I., & Spronken-Smith, R. A. (1999). Evaporation from natural and modified raised peat bogs in New Zealand. *Agricultural and Forest Meterorology, 95*, 85-98.

Trimble (2005). Mapping and GIS with the Terrasync software: Training guide. In T. N. Ltd (Ed.) (pp. 182).

Trimble (2006). Trimble GeoXT 2005 series handheld datasheet. In T. N. Ltd (Ed.) (pp. 3).

URS (2003). *Waikanae / Otaihanga borefield drilling strategy.* . Waikanae: URS New Zealand and Strategraphic Solutions (URS).

URS (2004). *Waikanae Borefield: Assessment of Environmental Impacts*. Paraparaumu: Kapiti Coast District Council.

USGS (1998). *Groundwater and Surface Water: A Single Resource* US Geological Survey.

Wade, T., & Sommer, S. (2006). *A to Z GIS. An illustrated dictionary of GIS systems* (2 ed.). Redlands, CA: ESRI Press.

Ward (1967). *Principles of Hydrology*. Maidenhead: McGraw-Hill Publishing Compant Ltd.

Ward, & Elliot, W. J. (1995). *Environmental Hydrology*: CRC Press.

Warren, R. S., & Niering, N. A. (1993). Vegetation change on a Northeast Tidal Marsh: Interaction of sea level rise and marsh accretion. *Ecology, 74*, 96-103.

Wetlands International (2010). Peatland and CO^2 Emision. Retrieved January 2010: http://www.wetlands.org/Whatwedo/PeatlandsandCO2emissions/tabid/837/Default.aspx

White, P. A., Clausen, B., Hunt, B., Cameron, S., & Weir, J. (2001). Groundwater-surface water interaction. In M. R. Rosen & P. A. White (Eds.), *Groundwaters of New Zealand* (pp. 133-160). Wellington: New Zealand Hydrological Society.

Wilson, S. R. (2003). *The Saltwater - Freshwater Interface, Te Horo Beach, Kapiti Coast.* Victoria University, Wellington.

Winter (1986). Effect of ground-water recharge on configuration of the water table beneath sand dunes and on seepage in lakes in the sandhills of Nebraska, U.S.A. *Journal of Hydrology, 86*(3-4), 221-237.

Winter (2000). The vulnerability of wetlands to climate change: A hydrologic landscape perspective. [Article]. *Journal of the American Water Resources Association, 36*(2), 305-311.

World Meteorological Organisation (1994). *Guide to hydrological practices* (5th ed. Vol. WMO 168).

WRC (1994). *Hydrology of the Kapiti Coast* (No. WRCICI-TIG-94/13): Wellington Regional Council: Hydrological Services Group.

WRC (2005). *Understanding the 'wet' in wetlands* (No. GW/RP-G-05/35: 0-909016-86-0). Wellington: Wellington Regional Council.

WRC (2009). Key native Ecosystems. Retrieved 02 August 2009, from Greater Wellington Regional Council: http://www.gw.govt.nz/section991.cfm

YSI (2008). Operations manual: Ecosense ph100. In Y. Inc (Ed.). Yellow Springs,OH.

Zedler, J. B., & Kercher, S. (2005). Wetland Resources: Status, Trends, Ecosystem services and Restorability. . *Annual Review of Environment and Resources., 30*, 39-74.

VIII Appendices

Appendix 1: Wetland Class in New Zealand (Johnson & Gerbeaux, 2004b)

Wetland classes

Wetland classes are governed by distinctive combinations of substrate factors, water regime, and the consequent factors of nutrient status and pH. Nine wetland classes are recognised: bog, fen, swamp, marsh, seepage, shallow water, ephemeral wetland, pakihi and gumland, and saltmarsh.

This third level of wetland classification is the most important one for the practical business of assigning a name to a functional wetland unit. Table 2 lists the characters of water regime, substrate, and chemistry. Note that there is much overlap of shared character states between wetland classes. Accordingly, each class is circumscribed by a particular combination of character states that are most distinctive to it.

Being based upon function – the ways in which wetlands work – wetland classes are not differentiated by the situations they occupy or the vegetation they contain. Nevertheless, particular landforms, vegetation structural classes, and plants are associated with each wetland class (Table 3 on p. 39). Note, however, that so far as the classification method is concerned, these features are secondary to the factors of physical and chemical environment which primarily delimit wetland classes.

Wetland classes fit beneath hydrosystems (Table 1). Most wetland classes can occur within more than one hydrosystem, and indeed some will actually span a hydrosystem boundary at particular sites. The wetland classes are described below in no particular order.

Bog

A peatland only receives water from precipitation; not from groundwater or surface runoff. Nutrients from adjacent or underlying mineral soils are negligible. Bogs are oligotrophic (nutrient-poor), poorly aerated, and usually markedly acid. Bog peat is poorly drained, having almost no water movement, and the water table is generally close to or just above the ground surface, and relatively constant.

Bogs occur most often on relatively level or very gently sloping ground, including hill crests, basins, terraces, and within other wetland types. Their vegetation types are very wide-ranging, dominants including mosses, lichens, cushion plants, sedges, grasses, restiads, ferns, shrubs, and trees.

Fen

A fen is a wetland with a predominantly peat substrate that receives inputs of groundwater and nutrients from adjacent mineral soils. The water table is usually close to or just below the peat surface, and relatively constant. Water flow is slow to moderate. Fens have low to moderate acidity and are oligotrophic to mesotrophic.

Fens have slightly higher nutrient status than bogs, often because they occupy slight slopes, such as fans or the toes of hillsides (see Fig. 24) where they may grade down slope to swamp. Fens also occur on level ground where relatively shallow peat has not accumulated much above the influence of underlying mineral substrate, including situations around the margins of domed bogs. Fen vegetation is often composed of sedges, restiads, ferns, tall herbs, tussock grasses, or scrub.

Swamp

A swamp is a wetland that receives a relatively rich supply of nutrients and often also sediment via surface runoff and groundwater from adjacent land. Swamps usually have a combination of mineral and peat substrates. Leads of standing water or surface

channels are often present, with gentle permanent or periodic internal flow, and the water table is usually permanently above some of the ground surface, or periodically above much of it.
Swamps usually occur in basins, and on valley floors, deltas, and plains. Vegetation cover is often sedge, rush, reed, flax, tall herb, or scrub types, often intermingled, and also forest.

Marsh
A mainly mineral wetland, having moderate to good drainage, fed by groundwater or surface water of slow to moderate flow, and characterised by moderate to great fluctuation of water table or water level. Marshes are often periodically inundated by standing or slowly moving water. They are usually mesotrophic to eutrophic, and slightly acid to neutral in pH. Marshes differ from swamps by having better drainage, a generally lower water table, a usually more mineral substrate, and a higher pH.
Marshes occur mainly on slight to moderate slopes, especially on valley margins, valley floors, and alongside water bodies such as rivers and lakes. Vegetation is most often rushland, grassland, sedgeland, or herbfield.

Seepage
An area on a slope which carries a moderate to steady flow of groundwater, often also surface water, including water that has percolated to the land surface, the volume being less than that which would be considered as a stream or spring. Substrate ranges all the way from raw or well-developed mineral soil to peat; nutrient status and pH range from low to high; and the water table varies from just above the ground surface to a slight depth below. Seepage is found primarily where groundwater diffuses to the surface, especially at a change of slope, or where an impermeable basement raises the water table.
Flushes are considered here as falling within the wetland class of seepage. Flushing occurs when a periodic pulse of water, usually associated with rain (or seasonally with snow-melt), produces a sheet-flow of surface water, providing nutrients from higher ground, replenishing oxygen, and sometimes scouring the ground surface. Surface wetness is not always constant. Flushes are usually elongated downhill. The term flush has been commonly used in New Zealand for sloping wetlands in the mountains; it could validly be considered as a distinct wetland class.
Seepages (including flushes) are often relatively small and localised but occur both as stand-alone wetlands and as features which feed, drain, or are contained within other wetland classes. They intergrade with bogs and fens, but differ partly on the basis of their size and slope: seepages occupy sites of active water movement having enhanced aeration and nutrient supply. Vegetation is usually of low stature: moss, cushion, or sedge types; sometimes scrub or forest.

Shallow water
Aquatic habitats, generally less than a few metres deep, having standing water for most of the time. This wetland class accommodates the margins of lakes, rivers, and estuary waters, in which case the term ‘shallow open water’ is sometimes used to acknowledge the presence of an open body of water further from the shore. This wetland class also encompasses bodies of water that are not sufficiently large or lake-like in character to warrant lacustrine classification, yet of greater significance than just as water body forms contained within a wetland. The dominant unifying determinant is the presence of standing water. Nutrient and water chemistry factors are basically those of the water, rather than the substrate. In practice, the shallow water wetland class provides for habitats that ‘land-based’ wetland workers would meet with at land / water margins. For

purposes of mapping or categorising fully aquatic habitats of lacustrine or riverine hydrosystems, the term ‘deep open water’ is available as an additional wetland class.

Ephemeral wetland

A distinctive class most frequently found in closed depressions lacking a surface outlet, in climates where seasonal variation in rainfall and evaporation leads to ponding in winter and spring, and with fluctuation so pronounced that it can lead to complete drying in summer months or in dry years (Johnson & Rogers 2003). Water source is groundwater or an adjacent water body. Substrates are usually wholly mineral, upon an impervious underlying horizon. Water flow is slow to nil, nutrient status moderate, and pH neutral. Closed depressions occur especially on moraines, bedrock, dunes, and tephra. Vegetation is a characteristic marginal zone of turf and sward, and sometimes also rushland and scrub. Extreme cases of ephemeral wetland alternate between aquatic and terrestrial plants at different seasons.

Pakihi and gumland

Characterised by mature or skeletal soils of very low fertility and low pH, wholly mineral or sometimes with peat, rain-fed and with poor ability to transport water, frequently saturated but seasonally dry. Usually on level to rolling or sloping land in districts of high rainfall, the soils are old and severely leached of most nutrients.

This problematical wetland class embraces a medley of habitats including some, but not all, of the West Coast pakihi (Mew 1983) and Northland gumlands (e.g. Esler & Rumball 1975), but can extend also to sites having soils of extreme infertility because of their skeletal nature or lack of nutrients from inhospitable substrates such as ultramafic rock. Many of the peaty sites that have traditionally been referred to as pakihi can be classified as bog or fen. Nevertheless, the wetland class of pakihi and gumland is needed to accommodate habitats which may completely lack peat, and where wetness, sufficient for them to be regarded as a type of wetland, results in frequent soil waterlogging, even though this may alternate with periods when soils are relatively dry.

The wetland class pakihi and gumland is admittedly difficult to circumscribe on the basis of substrate and water regime. No simple and embracing name suggests itself for this wetland class and we are loath to confuse the issue by suggesting one. ‘Wet heath’ (e.g. Wardle 1991) might be a contender, but the vegetation connotation does not sit well with the wetland class level of the present classification system.

Despite these problems, the pakihi and gumland wetland class nevertheless has the unifying factors of a flora typical of wetlands, and vegetation that is usually heathland (shrubland in combination with restiads, sedges, and ferns; a mix of several vegetation structural classes, see Section 2.7). Such heathland, often fire-induced, poses difficulties for wetland classification because it can extend also to relatively dry habitats and also to blanket peatlands.

Saltmarsh

A wetland class embracing estuarine habitats of mainly mineral substrate in the intertidal and subtidal zones, but also including those habitats in the supratidal zone (such as wet coastal platforms) and in the inland saline hydrosystem, which although non-tidal have similar saline substrates and constancy of soil moisture. Water source is from groundwater and adjacent saline or brackish estuary waters. The saltmarsh wetland class includes non-vegetated habitats such as mudflats, and the full range of vegetation types typical of the intertidal zone, from herbfield to rushland, scrub, and mangrove scrub or low forest.

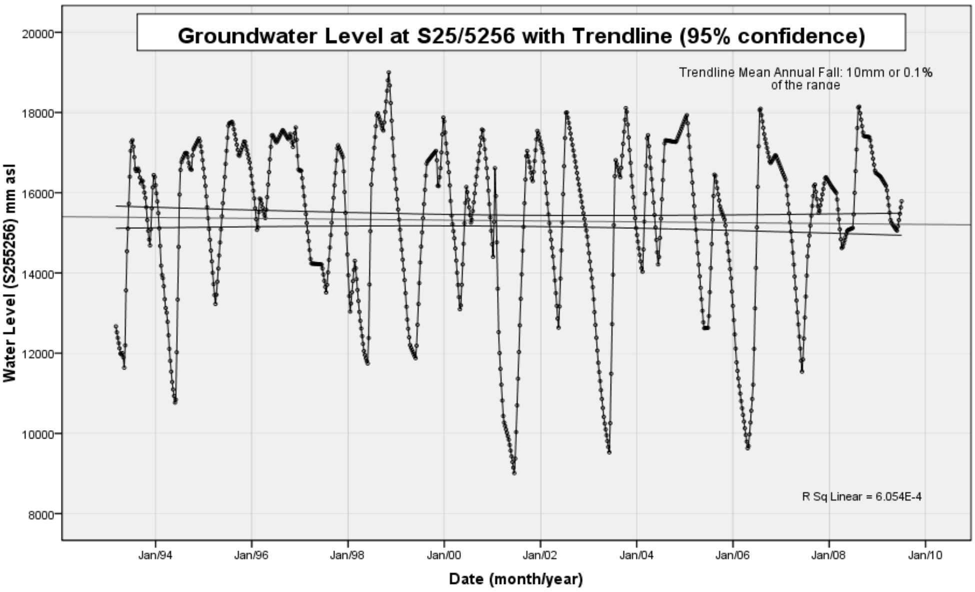
Other wetland classes

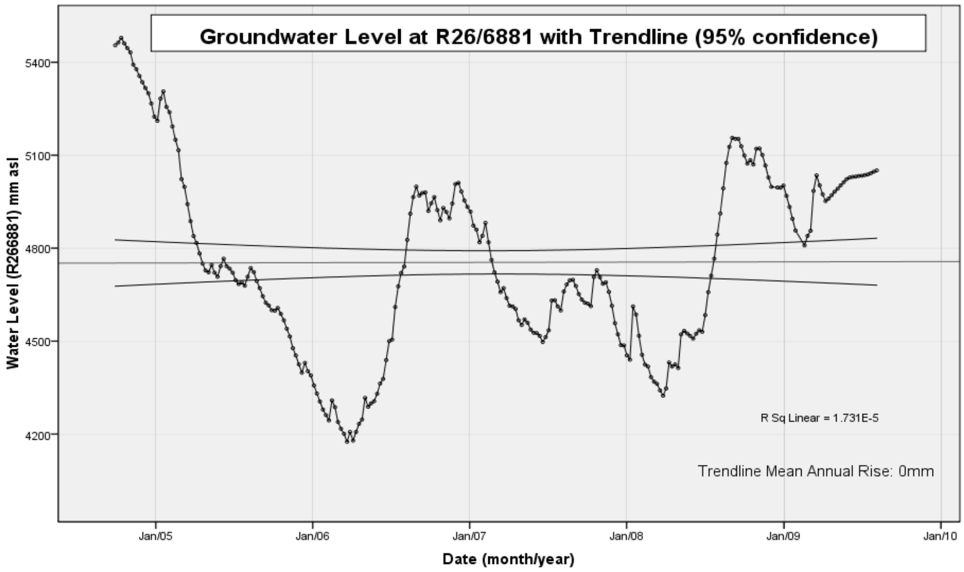
The nine wetland classes outlined above should accommodate most of the broad level variants of palustrine, estuarine, and inland saline hydrosystems, along with those habitats associated with land / water margins of the riverine and lacustrine hydrosystems. Wetland workers may find the need to erect additional wetland classes, and this is valid as long as they are able to be circumscribed on the basis of distinctive combinations of substrate factors, water regime, nutrient status, and pH. It should be noted that our circumscription of the saltmarsh wetland class is a broader one than that outlined by Ward & Lambie (1999b). Their table 2 includes several additional wetland classes for the estuarine hydrosystem, such as seagrass meadow and algal flat: units which we treat as able to be described at the subsequent classification levels of structural class and composition of vegetation.

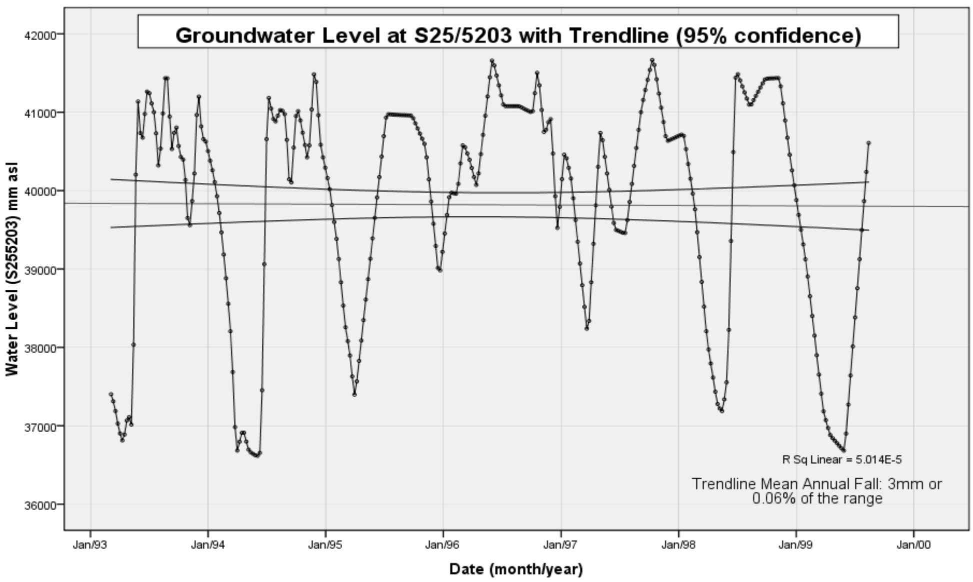
Although this book does not attempt to give any detailed coverage of wetland classes of lacustrine and riverine open waters, a draft classification of these is included in table 4 of Ward & Lambie (1999b). In summary, however, it can be noted that their lacustrine wetland classes are based upon combinations of two sets of descriptors, the first being nutrient status (oligotrophic, mesotrophic, eutrophic, dystrophic) and the second being the nature of lake stratification (monomictic, amictic, polymictic). These terms are discussed in sections 2.5.3 and 4.2. For naming riverine wetland classes Ward & Lambie use descriptors concerned with the two factors of water flow (stable, variable, flashy) and channel gradient (steepland, midland, lowland). These terms are discussed in Section 4.1.2.

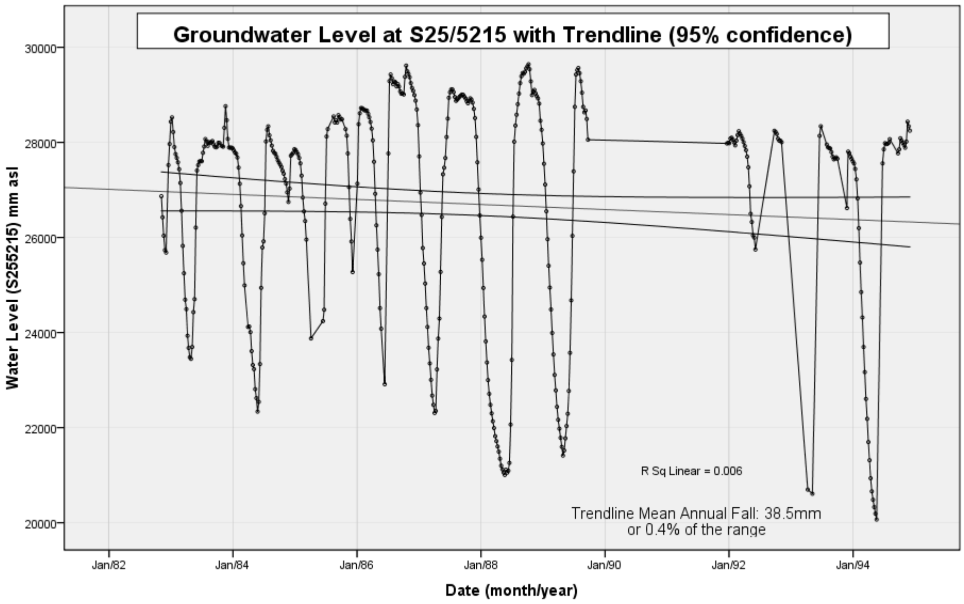
Ward and Lambie (1999b) also provide draft structures for classifying wetland classes in the geothermal, plutonic, and marine hydrosystems.

Appendix 2: Hydrographs for groundwater level in bores that did not show significant rise / fall over the monitored years.

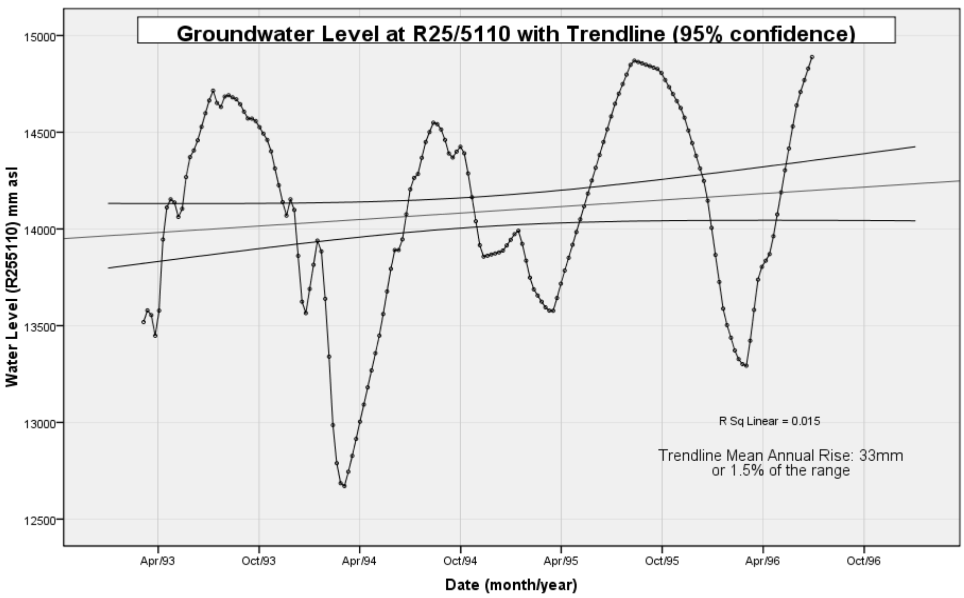




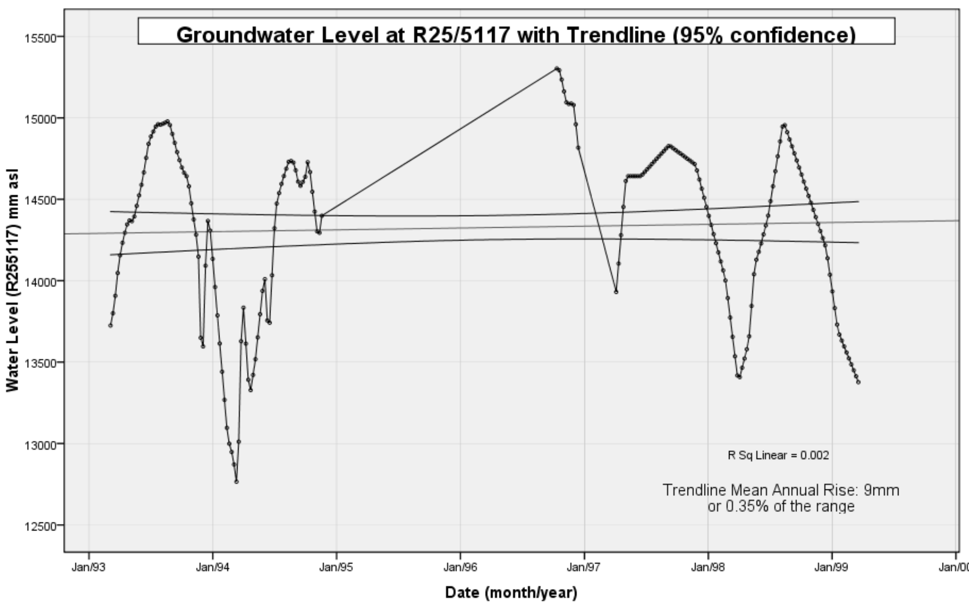




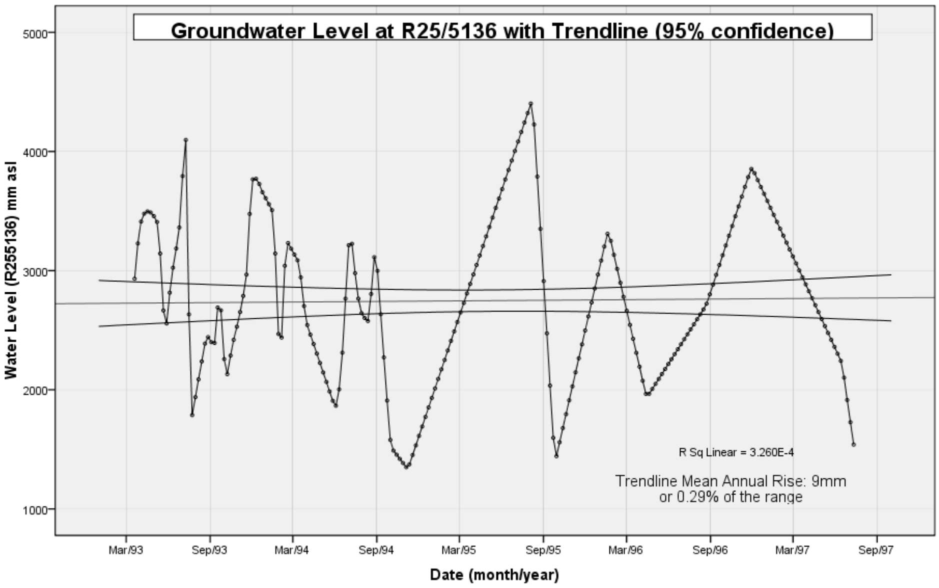
Groundwater Level at S25/5215 with Trendline (95% confidence)
Water Level (S255215) mm asl
Date (month/year)
R Sq Linear = 0.006
Trendline Mean Annual Fall: 38.5mm
or 0.4% of the range



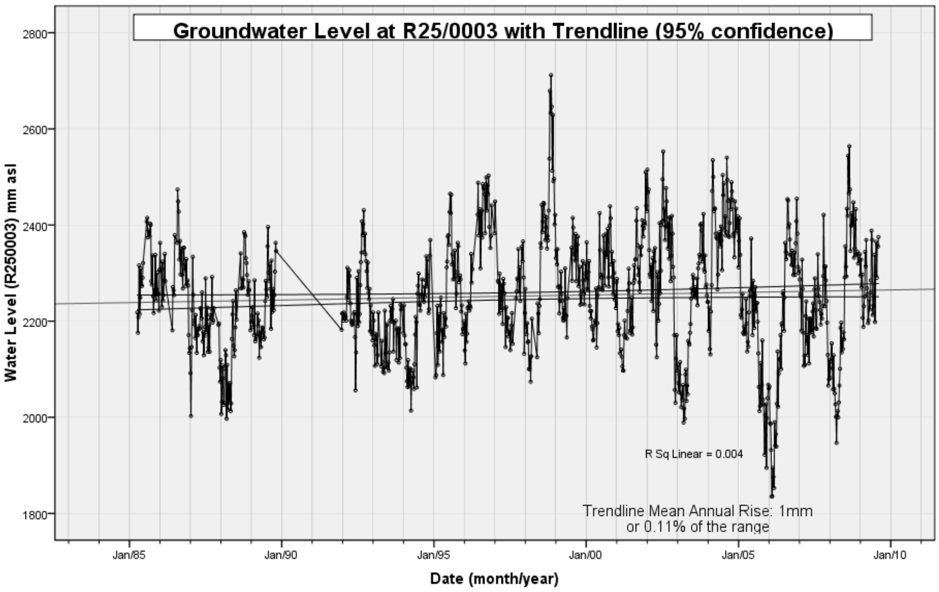
Groundwater Level at R25/5110 with Trendline (95% confidence)
Water Level (R255110) mm asl
Date (month/year)
R Sq Linear = 0.015
Trendline Mean Annual Rise: 33mm
or 1.5% of the range



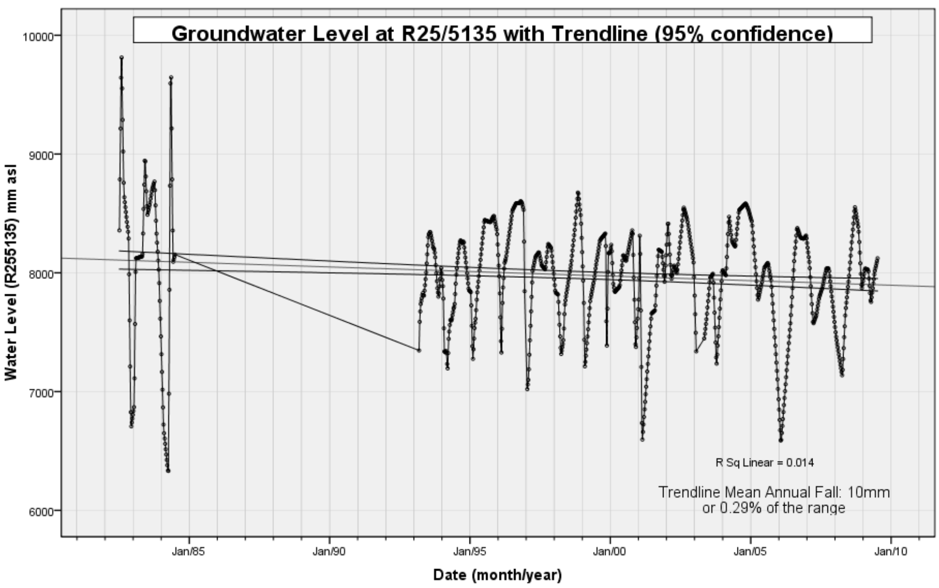
Groundwater Level at R25/5117 with Trendline (95% confidence)
Water Level (R255117) mm asl
Date (month/year)
R Sq Linear = 0.002
Trendline Mean Annual Rise: 9mm
or 0.35% of the range



Groundwater Level at R25/5136 with Trendline (95% confidence)
Water Level (R255136) mm asl
Date (month/year)
R Sq Linear = 3.260E-4
Trendline Mean Annual Rise: 9mm
or 0.29% of the range



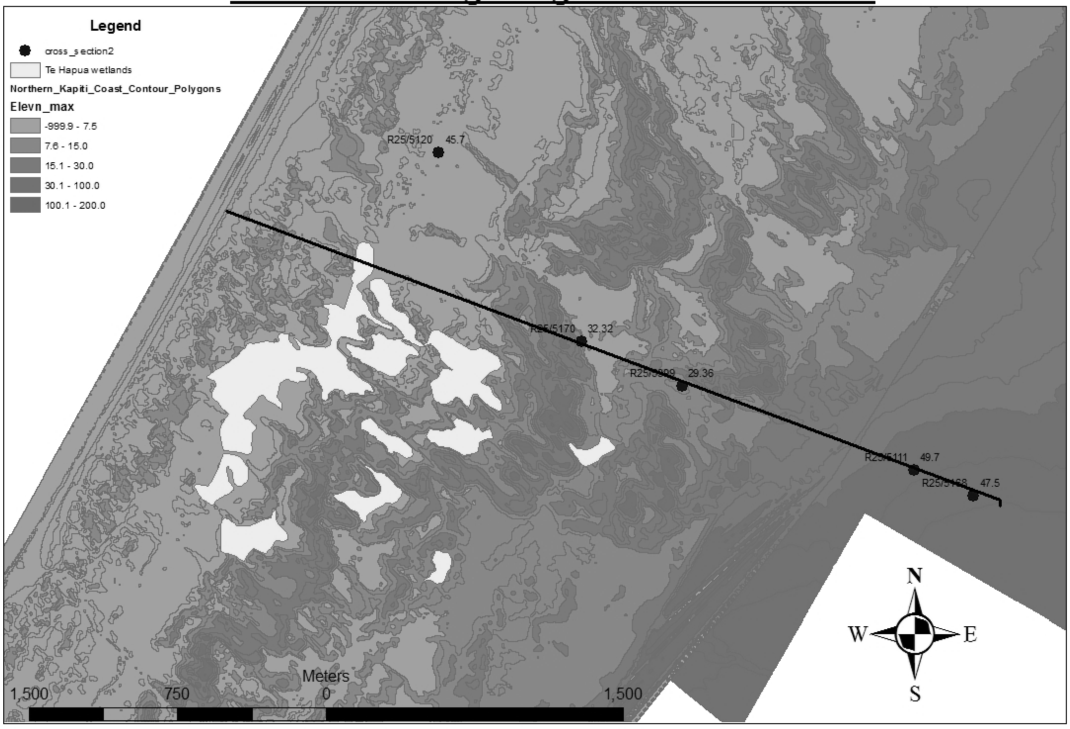
Groundwater Level at R25/0003 with Trendline (95% confidence)
Water Level (R250003) mm asl
Date (month/year)
R Sq Linear = 0.004
Trendline Mean Annual Rise: 1mm
or 0.11% of the range



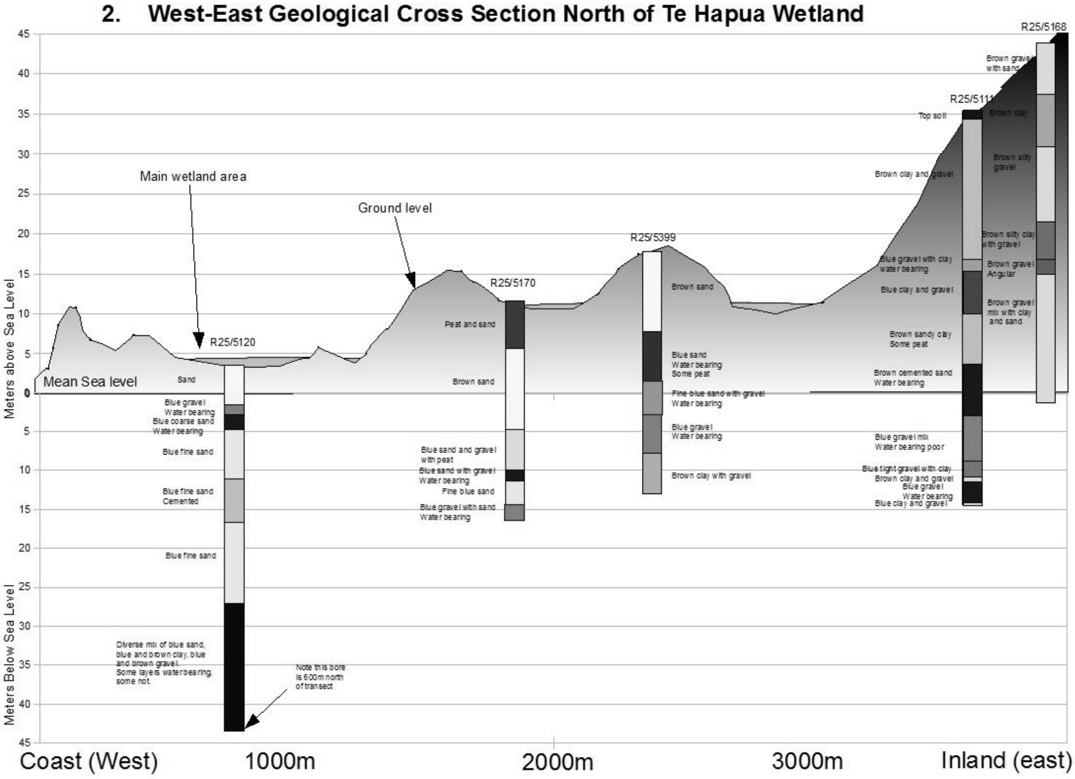
Groundwater Level at R25/5135 with Trendline (95% confidence)
Water Level (R255135) mm asl
Date (month/year)
R Sq Linear = 0.014
Trendline Mean Annual Fall: 10mm
or 0.29% of the range

Appendix 3: Geological cross sections

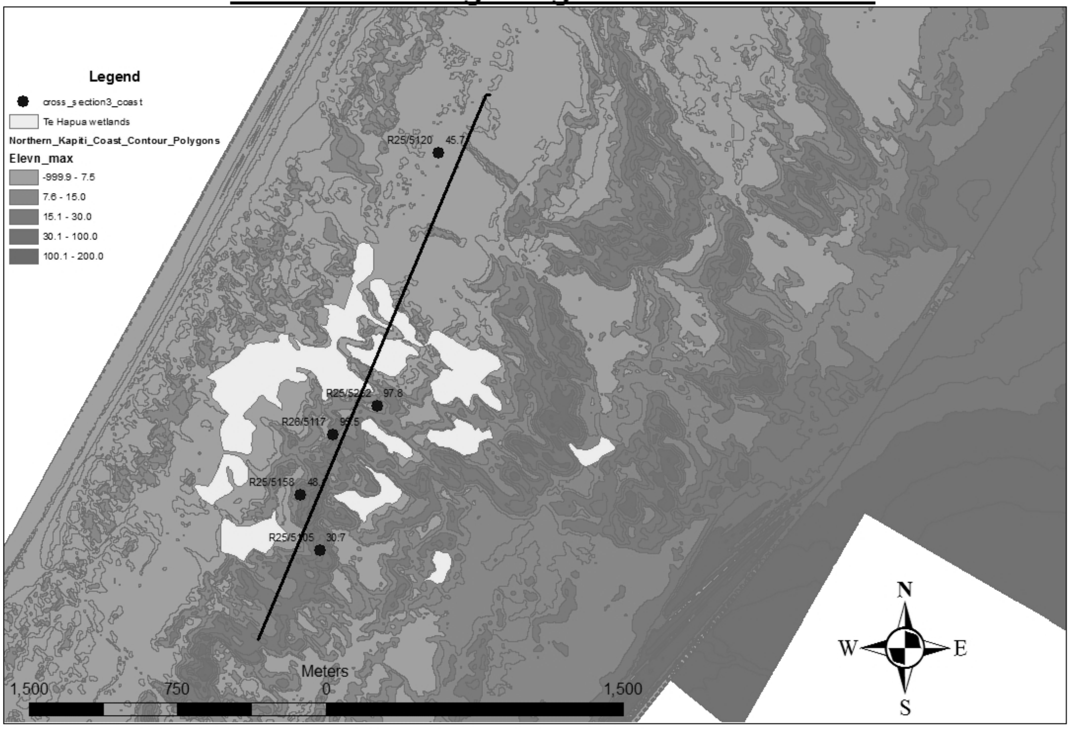
Wells used for geological cross-section 2



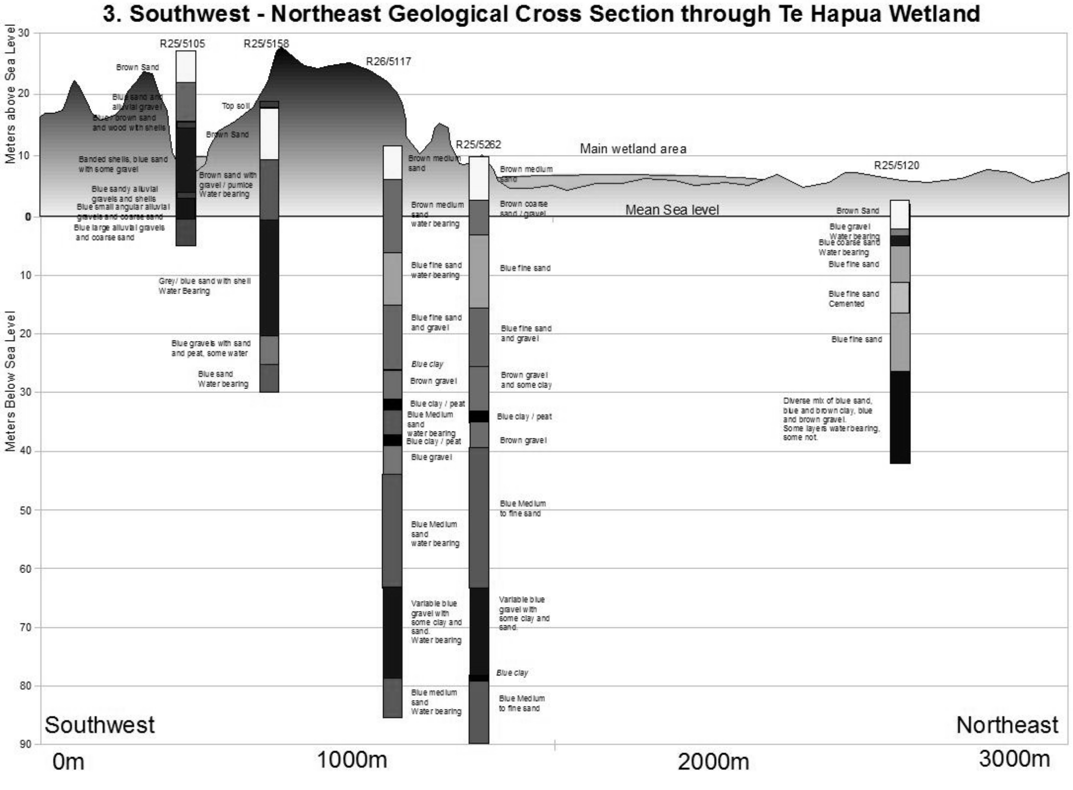
2. West-East Geological Cross Section North of Te Hapua Wetland



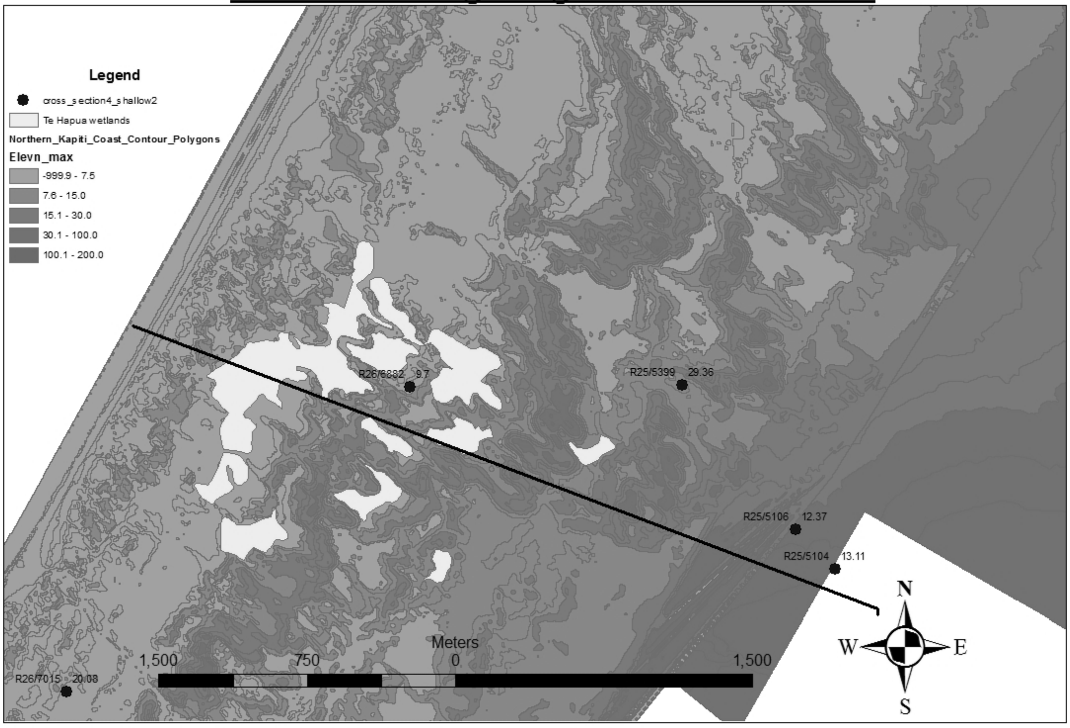
Wells used for geological cross-section 3



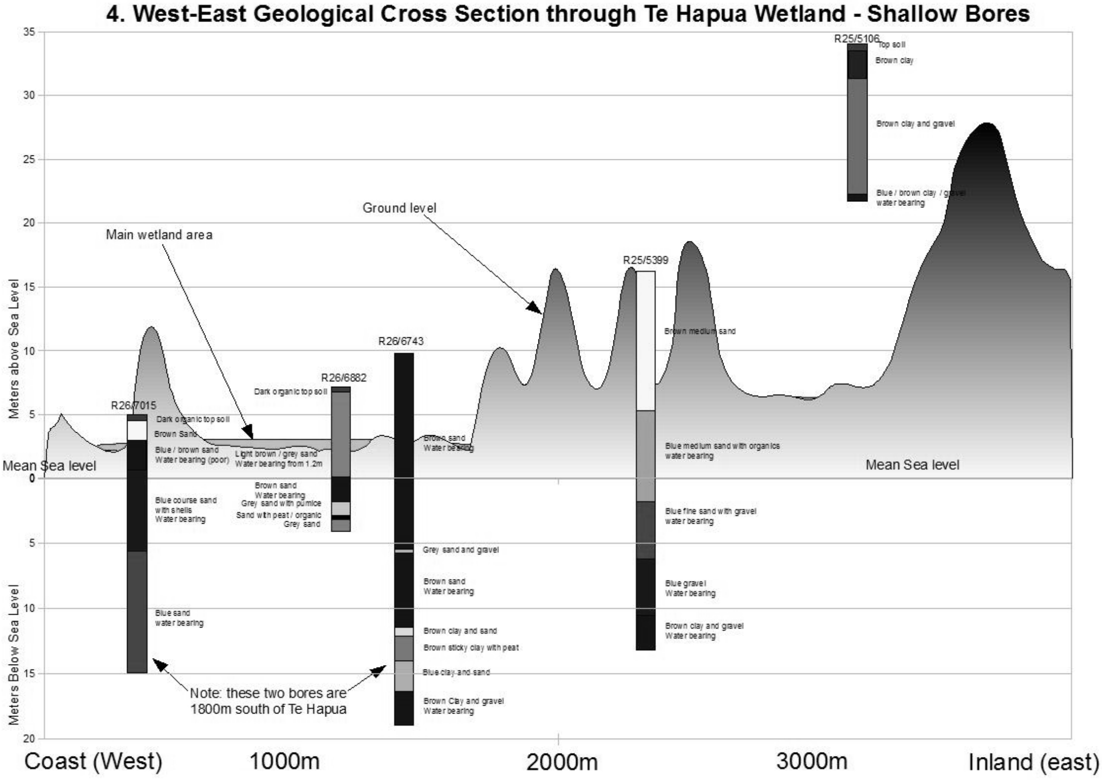
3. Southwest - Northeast Geological Cross Section through Te Hapua Wetland



Wells used for geological cross-section 4



4. West-East Geological Cross Section through Te Hapua Wetland - Shallow Bores



Appendix 4: Water Quality / wetland classification results

Wetland #	Name	pH	Conductivity (us)	Temperature (Deg C)	TDS (ppm)	Surface Flow (in / out)	Hydro Period	Fluctuation
1	**Trotter Nth**	6.20	337.00	20.70	169.00	IN: Yes v slow	Seasonal	Less
		6.16	291.00	16.20	147.00	OUT Yes v slow		
		6.29	285.00	17.50	143.00			
	Trotter Nth Mean	6.22	304.33	18.13	153.00			
2	**Jill and Joy**	5.82	216.00	21.40	109.00	IN: No	Permanent	More
		6.30	237.00	23.70	121.00	OUT: Yes v slow		
		6.63	245.00	27.20	123.00			
		6.47	242.00	25.00	120.00			
	Jill and Joy Mean	6.31	235.00	24.33	118.25			
3	**O'Malley / Crafar Jensen**	6.17	270.00	23.70	136.00	IN: No	Permanent	More
		6.22	258.00	23.90	130.00	OUT: No		
		5.94	261.00	23.20	128.00			
	O'Malley / Crafar Jensen Mean	6.11	263.00	23.60	131.33			
4	**Jensen West**	6.42	288.00	20.10	143.00	IN: No	Permanent	More
		6.55	288.00	20.20	144.00	OUT: Yes slow		
		6.56	286.00	20.20	145.00			
	Jensen West Mean	6.51	287.33	20.17	144.00			
5	**Jensen South**	5.53	277.00	17.00	104.00	IN: No	Permanent	More
		5.80	208.00	18.30	138.00	OUT: No		
		5.74	306.00	19.70	153.00			
	Jensen South Mean	5.69	263.67	18.33	131.67			
6	**Jensen Nth**	6.04	265.00	18.40	129.00	IN: No	Permanent	More
		6.15	273.00	18.00	138.00	OUT: No		
		6.86	285.00	20.60	143.00			

		6.36	286.00	20.60	143.00			
	Jensen Nth Mean	6.35	277.25	19.40	138.25			
7	**Jensen Driveway**	6.46 6.48 6.65	181.70 187.50 174.90	19.60 19.50 19.60	90.70 87.40 87.40	IN: No OUT: No	Permanent	Less
	Jensen Driveway Mean	6.53	181.37	19.57	88.50			
8	**McGrath**	5.89 5.96 5.72	409.00 430.00 418.00	16.60 16.60 16.10	205.00 210.00 215.00	IN: Yes Med OUT: Yes Med	Permanent	More
	McGrath Mean	5.86	419.00	16.43	210.00			
9	**Housiaux Nth**	6.71 6.74 7.07 6.78	225.00 222.00	23.30 23.10 22.50 22.80	112.00 110.00	IN: No OUT: Yes	Permanent	More
	Housiaux Nth Mean	6.83	223.50	22.93	111.00			
10	**Housiaux Sth (Pateke Bore)**	4.12 5.14 5.10 4.79	116.60 133.80 137.10	17.20 15.70 20.00 21.60	58.50 64.70 68.70	IN: No OUT: No	Permanent	Less
	Housiaux Sth Mean	4.79	129.17	18.63	63.97			
11	**Dale Nth (Pateke wetland)** **Note very diff results dep on location in wetland**	6.70 7.23 8.60 6.84	300.00 275.00 287.00 305.00	26.40 26.00 26.20 28.70	155.00 142.00 139.00 150.00	IN: No OUT: No	Permanent	More
	Dale Nth Mean	7.34	291.75	26.83	146.50			
12	**Dale Sth**	5.91 6.08 6.56 6.15	195.50 191.90 194.80 206.00	18.00 19.40 27.60 23.10	97.40 96.00 103.00 97.80	IN: No OUT: No	Permanent	More

	Dale Sth Mean	6.18	197.05	22.03	98.55			
13	**Wyman / Walker**	5.24 5.09 5.17	103.80 104.30 106.00	22.80 22.70 22.40	52.30 53.00 52.20	IN: No OUT: No	Permanent	More
	Wyman / Walker Mean	5.17	104.70	22.63	52.50			
14	**Stevenson / Sanft** **Note very diff results dep on location in wetland**	6.23 6.27 5.27 5.42	170.40 172.80 142.70 139.30	23.80 23.80 23.70 23.40	73.00 70.70 85.20 69.10	IN: No OUT: No	Permanent	
	Stevenson / Sanft Mean	5.80	156.30	23.68	74.50			
15	**Trotter Sth**	6.18 6.93 6.90	213.00 213.00 212.00	20.60 20.30 20.50	107.00 107.00 107.00	IN: No OUT: No	Permanent	
	Trotter Sth Mean	6.67	212.67	20.47	107.00			
16	**Deane West**	6.18 6.22 6.22	168.00 168.40 169.10	22.10 21.90 21.90	84.10 84.20 84.60	IN: No OUT: No		
	Deane West Mean	6.21	168.50	21.97	84.30			
17	**Deane East**	4.20 4.21 4.24	115.40 114.10	28.60 29.80 29.80	57.70 57.20	IN: No OUT: No		
	Deane East Mean	4.22	114.75	29.40	57.45			
18	**Lavo Sth**	5.54 5.54 5.37	130.50 129.80 129.60	24.40 24.30 24.30	65.30 63.30 64.90	IN: No OUT: No		
	Lavo Sth Mean	5.48	129.97	24.33	64.50			
19	**Lavo Nth**	6.53 6.95	264.00 261.00	24.00 23.40	130.00 130.00	IN: No OUT: No		

		6.73	258.00	23.60	131.00			
	Lavo Nth Mean	6.74	261.00	23.67	130.33			
20	**Brown**	5.46 5.94 6.48	311.00 305.00	17.40 17.00 16.90	159.00 153.00	IN: No OUT: Yes	Permanent	Less
	Brown Mean	5.96	308.00	17.10	156.00			
21	**Crafar pond**	6.95 6.77 6.78	293.00 288.00	26.40 26.50 26.40	145.00 145.00	IN: No OUT: No	Permanent	
	Crafar pond Mean	6.83	290.50	26.43	145.00			

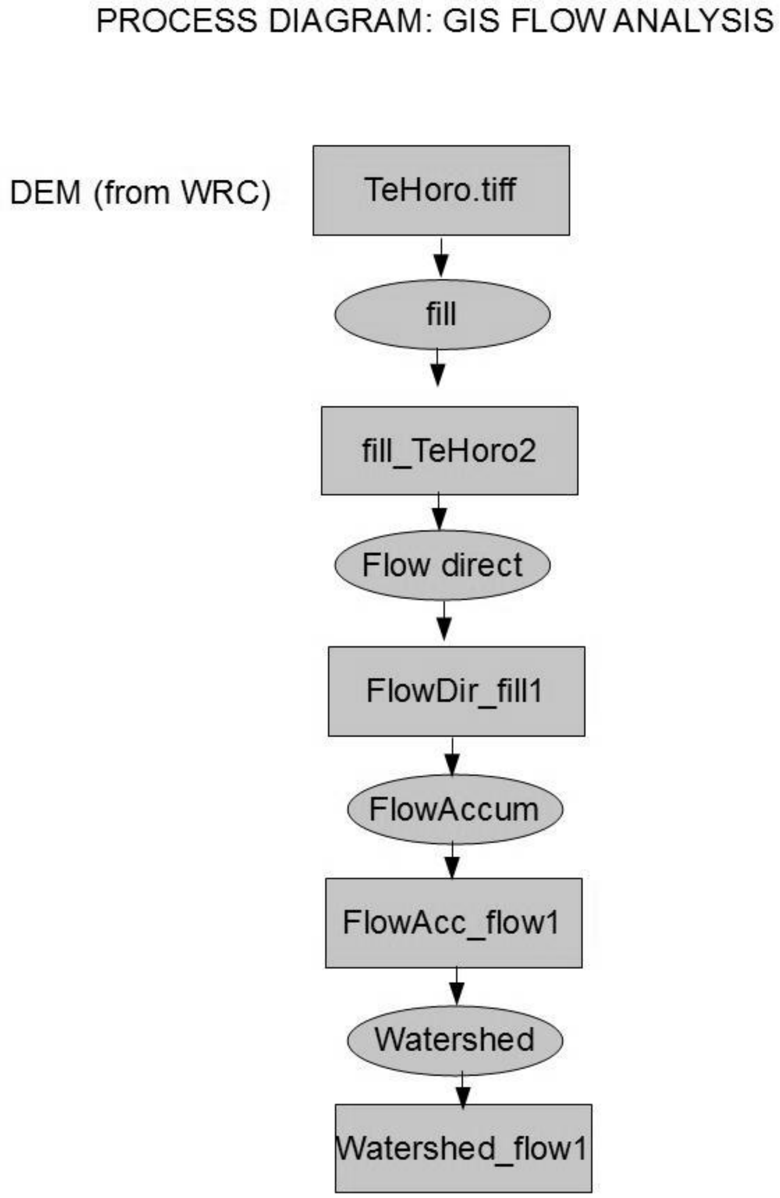
Wetland #	Notes / Modifications	Wetland Class (using table 2.2)
1 Trotter Nth	Excavated where standing water exists Drains installed still functioning, hence less fluctuation Water inflow possibly restricted by culvert in road	SWAMP / EPHEMERAL SWAMP Natural state is swamp Modifications have created ephemeral swamp
2 Jill and Joy	Excavated where standing water exists Drains installed no longer functioning Natural inflow permanently dammed (north culvert not functioning even in high water) Natural outflow restricted by southern culvert and mounded earth surrounding culvert	SWAMP / EPHEMERAL SWAMP Natural state is swamp Modifications have created ephemeral swamp
3 O'Malley Crafar Jensen	Deepest part of wetland Excavated where standing water exists Drains removed or partly removed Natural south outflow permanently dammed (culvert not functioning even at high water) Natural north in/outflow restricted (north culvert only flows at very high water)	SWAMP / EPHEMERAL SWAMP Natural state is swamp Modifications have created ephemeral swamp in places
4	Excavated where standing water exists	SWAMP / EPHEMERAL SWAMP

Jensen West	Drains removed or partly removed Soil mounded high at north boundary to reduce outflow / dam wetland Natural south in/outflow restricted (south culvert only flows at very high water) Natural north outflow restricted (north culvert flows slowly at mid / high water)	Natural state is swamp Modifications have created ephemeral swamp
5 Jensen South	Excavated where standing water exists Wetland naturally contained and formerly joined to Jensen North wetland and Housiaux North wetland	SWAMP / EPHEMERAL SWAMP Current state is swamp but poss. fen before human modifications Modifications have created ephemeral swamp
6 Jensen Nth	Excavated where standing water exists Wetland naturally contained and formerly joined to Jensen South wetland	SWAMP / EPHEMERAL SWAMP Natural state is swamp but poss. fen before human modifications Modifications have created ephemeral swamp
7 Jensen Driveway	Less fluctuation noted by landowner Lower conductivity / TDS indicates low / mod nutrient status	FEN
8 McGrath	Excavated where standing water exists Drains installed still functioning, slow / moderate outflow towards the north High conductivity / TDS indicates high nutrient status High nutrient status from increased pastural farming practices surrounding wetland	SWAMP / EPHEMERAL SWAMP Natural state is swamp but poss. fen before human modifications Modifications have created ephemeral swamp
9 Housiaux Nth	Excavated where standing water exists Formerly joined to much larger Jensen South wetland Culvert now joins to Jensen South	SWAMP / EPHEMERAL SWAMP Natural state is swamp but poss. fen before human modifications Modifications have created ephemeral swamp
10 Housiaux Sth	Possibly excavated by former owner? Formerly joined to Dale North, now contained with no culvert. Low pH Low conductivity and TDS	FEN Current state is fen but poss. swamp when joined to Dale North Inflow via groundwater seepage visible at some levels

	Influence of large pine trees?	
11 Dale Nth	Excavated where standing water exists Drains installed no longer functioning Soil mounded / dam created at natural northern outflow point Natural spring inflow from Brown property now diverted and does not enter Dale North Low yielding groundwater seepage / spring on northern side of wetland	SWAMP / EPHEMERAL SWAMP Natural state is swamp Springs in this area may contribute to lower fluctuating water level
	High pH at northern end where birds nesting / feeding	
12 Dale Sth	Excavated where standing water exists Low conductivity and TDS - mod nutrient status Influence of large eucalyptus trees?	FEN
13 Wyman / Walker	Excavated where standing water exists Low conductivity, TDS and nutrient status Low pH Influence of large pine trees?	FEN
	Dystophic (significant dark staining from humic matter and associated deficient nutrients)	
14 Stevenson Sanft	Historically the most permanent of all wetlands	FEN
15 Trotter Sth	Excavated where standing water exists	SWAMP / EPHEMERAL SWAMP Natural state is swamp
16 Deane West	Excavated where standing water exists Low conductivity / TDS indicates low nutrient status	FEN
17 Deane East	Recently excavated pond, heavily modified, stock in water Low pH Low conductivity / TDS indicates low nutrient status High temp Influence of large pine trees?	FEN

	Dystophic (significant dark staining from humic matter and associated deficient nutrient)	
18 Lavo Sth	Low conductivity / TDS indicates low nutrient status	FEN
	Dystophic (significant dark staining from humic matter and associated deficient nutrient)	
19 Lavo Nth	High pH and nutrient status for a fen, poss. input of nutrients from???	FEN
20 Brown	High yielding spring visible at all times	CONSTRUCTED
21 Crafar pond	Small wetland tested for comparison to Jensen Driveway and main area	SWAMP / EPHEMERAL SWAMP

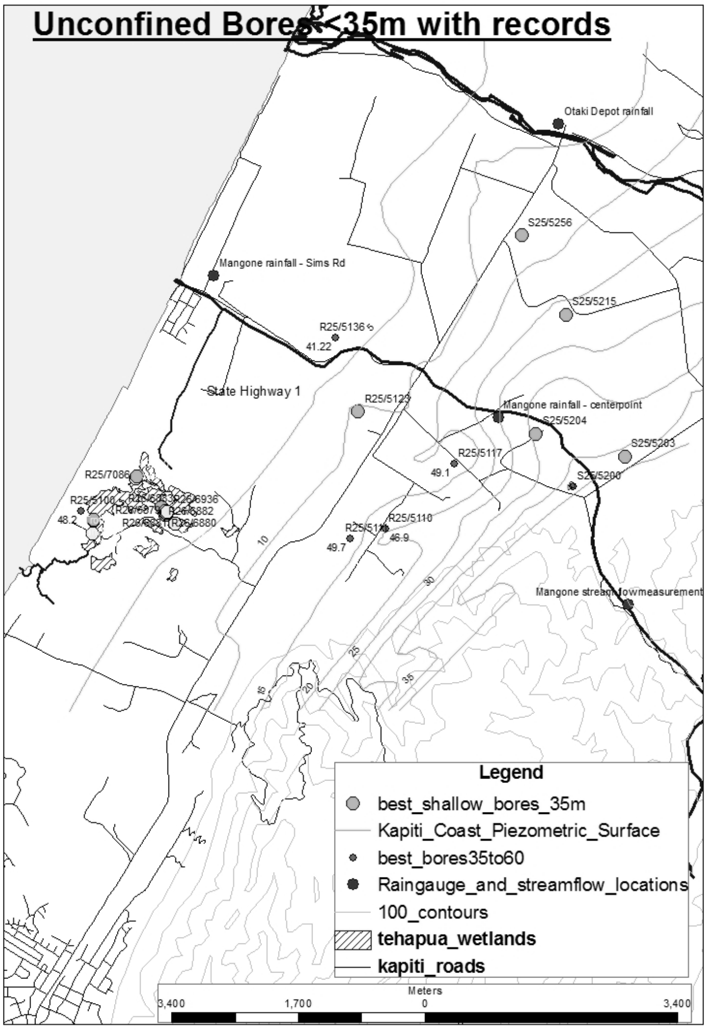
Appendix 5: GIS Flow surface analysis



Appendix 6: Bore records used

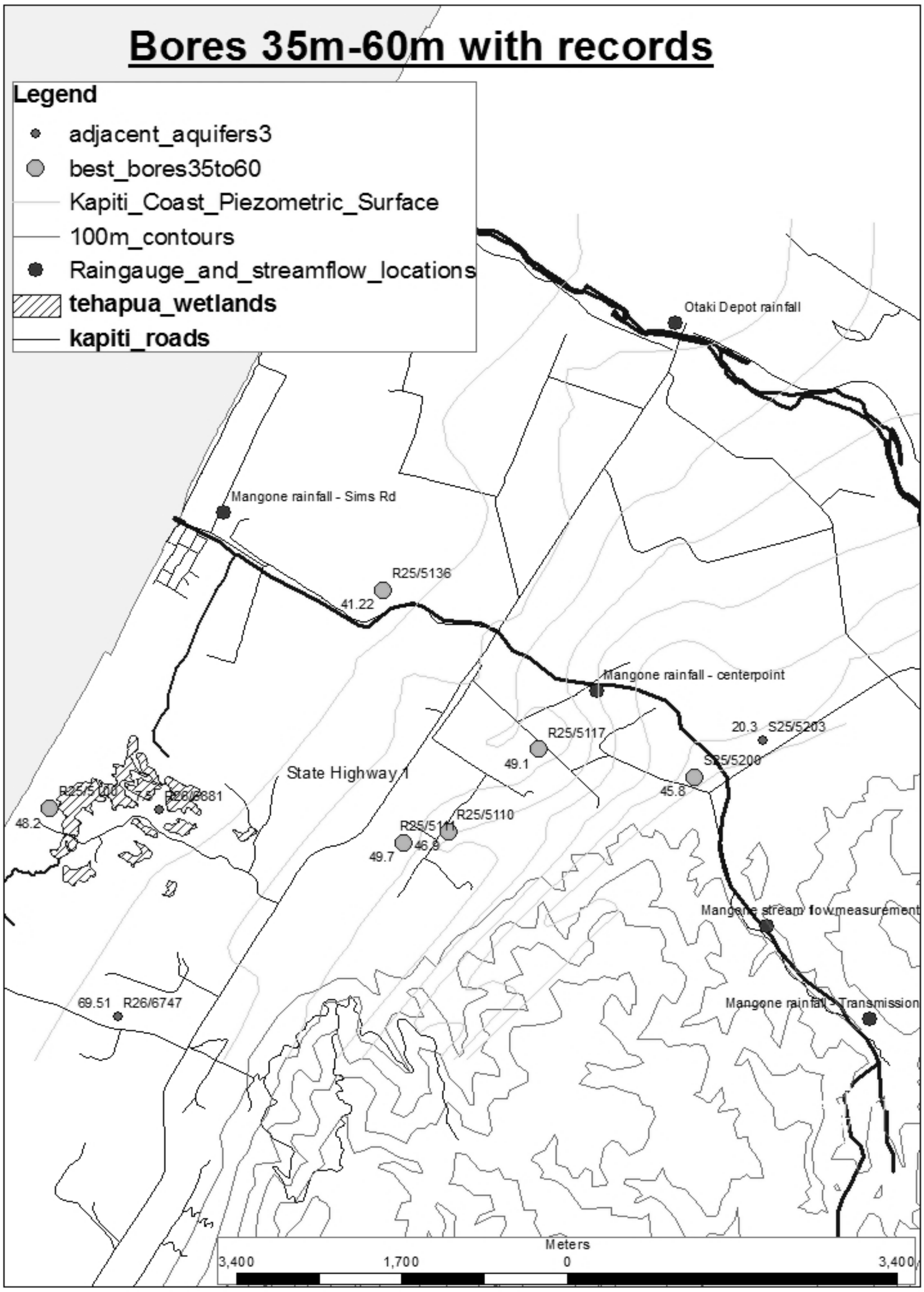
All Shallow Bores (<35m) with records

Bore depth and approximate location	Bore #	Recording	Sampling Frequency
30m bore north of Te Horo	S25/5256	(1993-2009)	5-8 weeks
22m bore in Te Horo	S25/5204	(1993-2000)	3-6 weeks
21m Bore north of Te Horo	S25/5215	(1982-1994)	15 minutes
20m bore up Mangone	S25/5203	(1993-1999)	2-5 weeks
13m bore in Te Horo	R25/5123	(1993–2009)	2-5 weeks
7.5m bore Te Hapua (Housiaux)	R26/6881	(2004-2009)	15 minutes
9.7m bore Te Hapua (Housiaux)	R26/6882	(2004-2009)	5-10 weeks
7.6m bore Te Hapua (Housiaux)	R26/6880	(2004-2009)	5-10 weeks
7m bore Te Hapua (Housiaux)	R26/6861	(2004-2009)	5-10 weeks
5.3m bores(x3)Te Hapua (Housiaux)	R26/6879	(2004-2009)	5-10 weeks
	R26/6936	(2004-2009)	5-10 weeks
	R26/6883	(2004-2009)	5-10 weeks



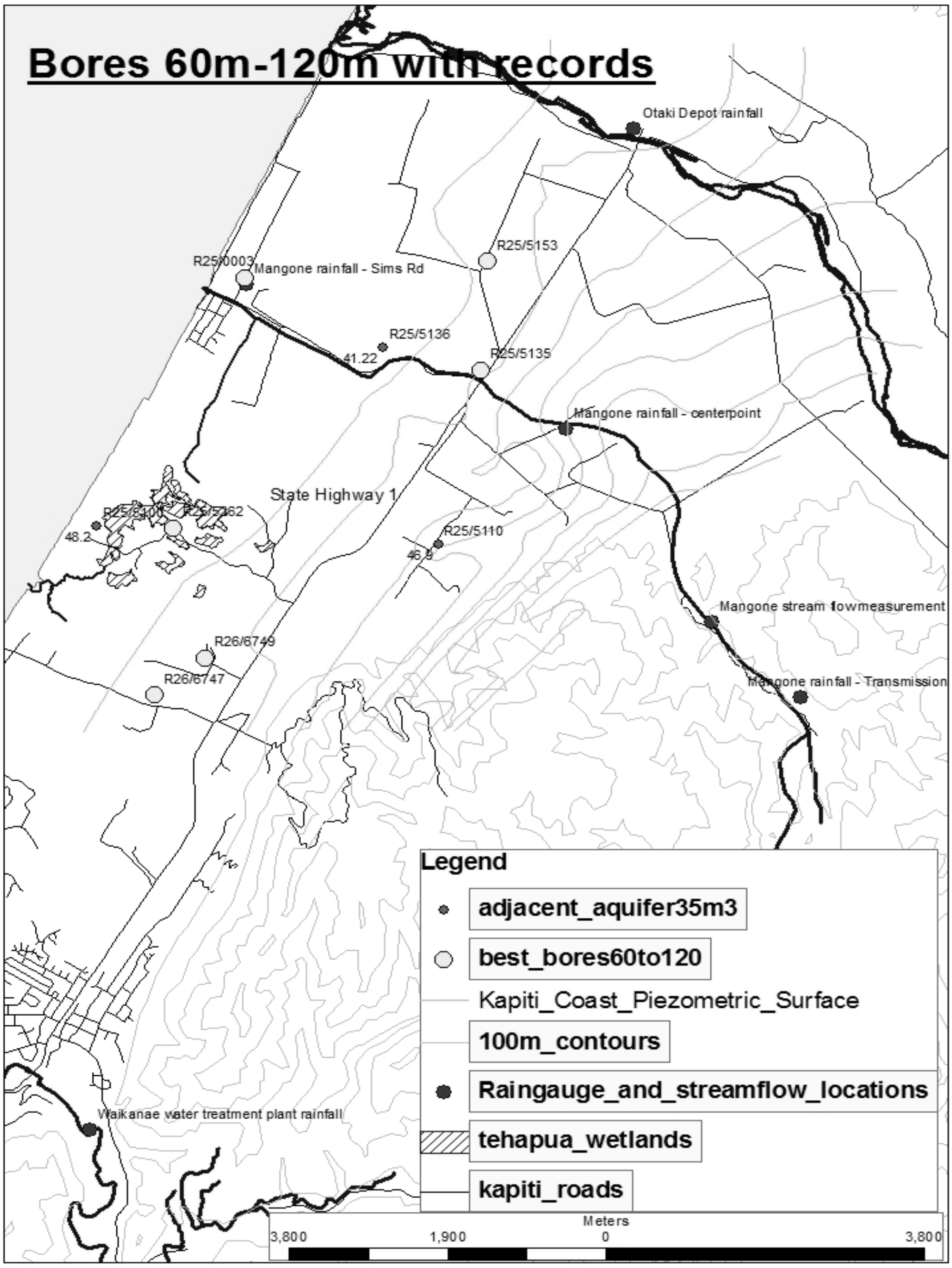
All confined bores 35-60m with records

Bore depth and approximate location	Bore #	Recording	Sampling Frequency
48m bore in Te Hapua	R25/5100	(1993-2000)	4-6 weeks
47m Bore in Te Horo	R25/5110	(1993-1996)	2-4 weeks
49m bore east of Te Hapua	R25/5111	(1993-2009)	2-4 weeks
49m bore east of Te Hapua and Te Horo	R25/5117	(1993-1999)	2-4 weeks
41m bore in Te Horo	R25/5136	(1993-1997)	2-4 weeks
46m bore up Mangone	S25/5200	(1993-2009)	4-6 weeks



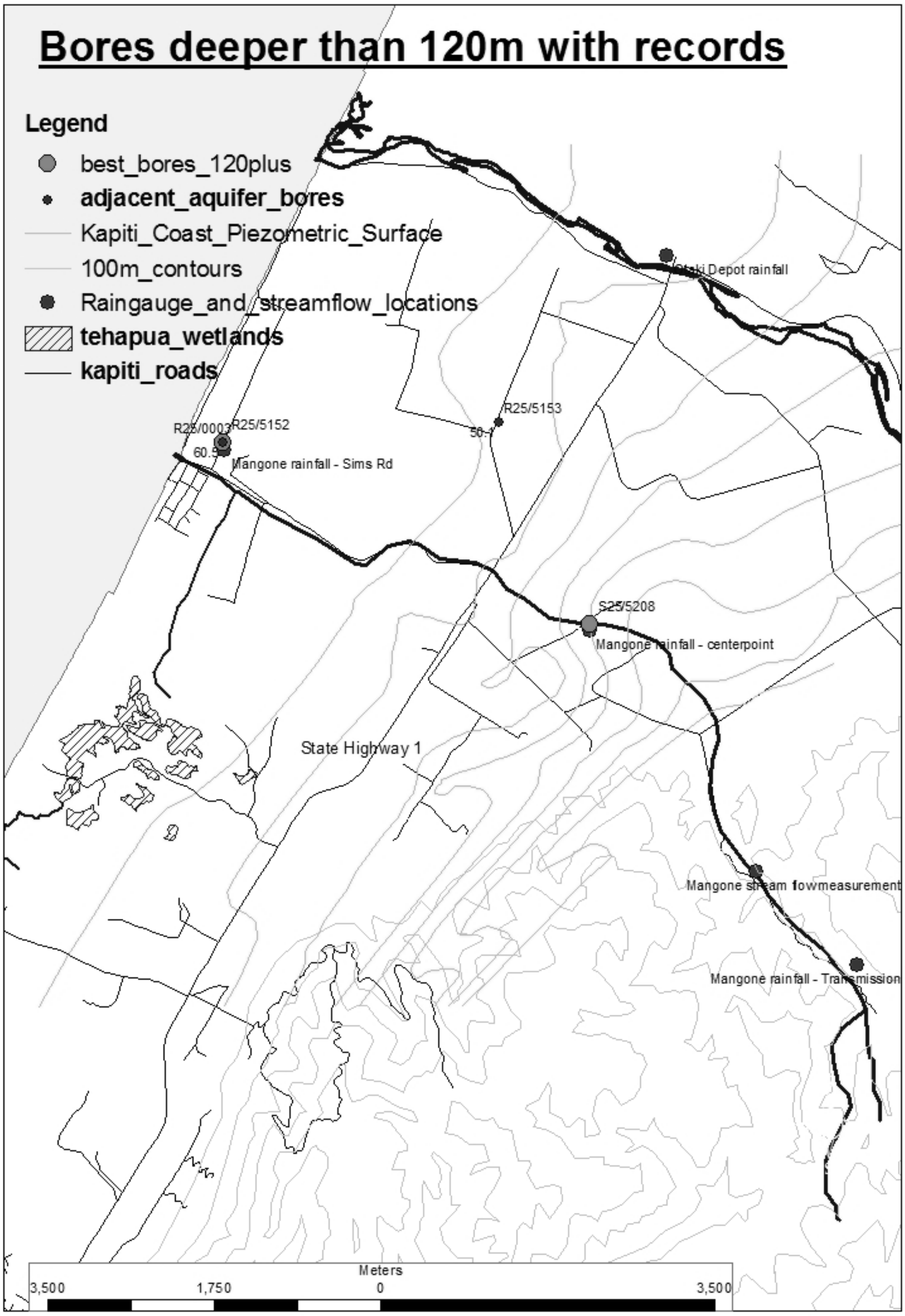
All confined bores 60-120m with records

Bore Depth and approx location	Bore #	Recording	Sampling Frequency
60m bore in Te Horo	R25/0003	(1985-2009)	30 mins
69m bore Peka Peka Rd	R26/6747	(1982-2009)	4-6 weeks
75m bore between Peka Peka and Te Hapua	R26/6749	(1982-1984)	4 weeks
93m bore in Te Horo SH1	R25/5135	(1982-2009)	4-6 weeks
98m Bore Te Hapua	R25/5262	(March 2009)	15 mins
50m bore north of Te Horo	R25/5153	(short record '93)	



All confined bores Deeper than 120m with records

Bore Depth and approx location	Bore #	Recording	Sampling Frequency
192m bore on Mangone at Centerpoint	S25/5208	(1992-2009)	30 mins
172m bore in Te Horo Beach	R25/5152	(1983-1999)	15 mins



Appendix 7: Glossary of Terms

- *Specific storage (S_s)* - when hydraulic head declines, the pressure will drop (for example in summer when the water tables of the aquifers that feed the wetland drop). Specific storage is the volume of water that a unit volume of aquifer releases from storage per unit change in hydraulic head (Freeze & Cherry, 1979; Smith & Wheatcraft, 1993).

- *Storativity* (S) – the volume of water that an aquifer releases from storage; per unit surface area of the aquifer, per unit decline in hydraulic head (Freeze & Cherry, 1979; Smith & Wheatcraft, 1993). Also known as the storage coefficient.

  Equation 2.5 Storativity $S = S_s b$
  Where S_s is the specific storage; b is the thickness of the aquifer
  (Freeze & Cherry, 1979)

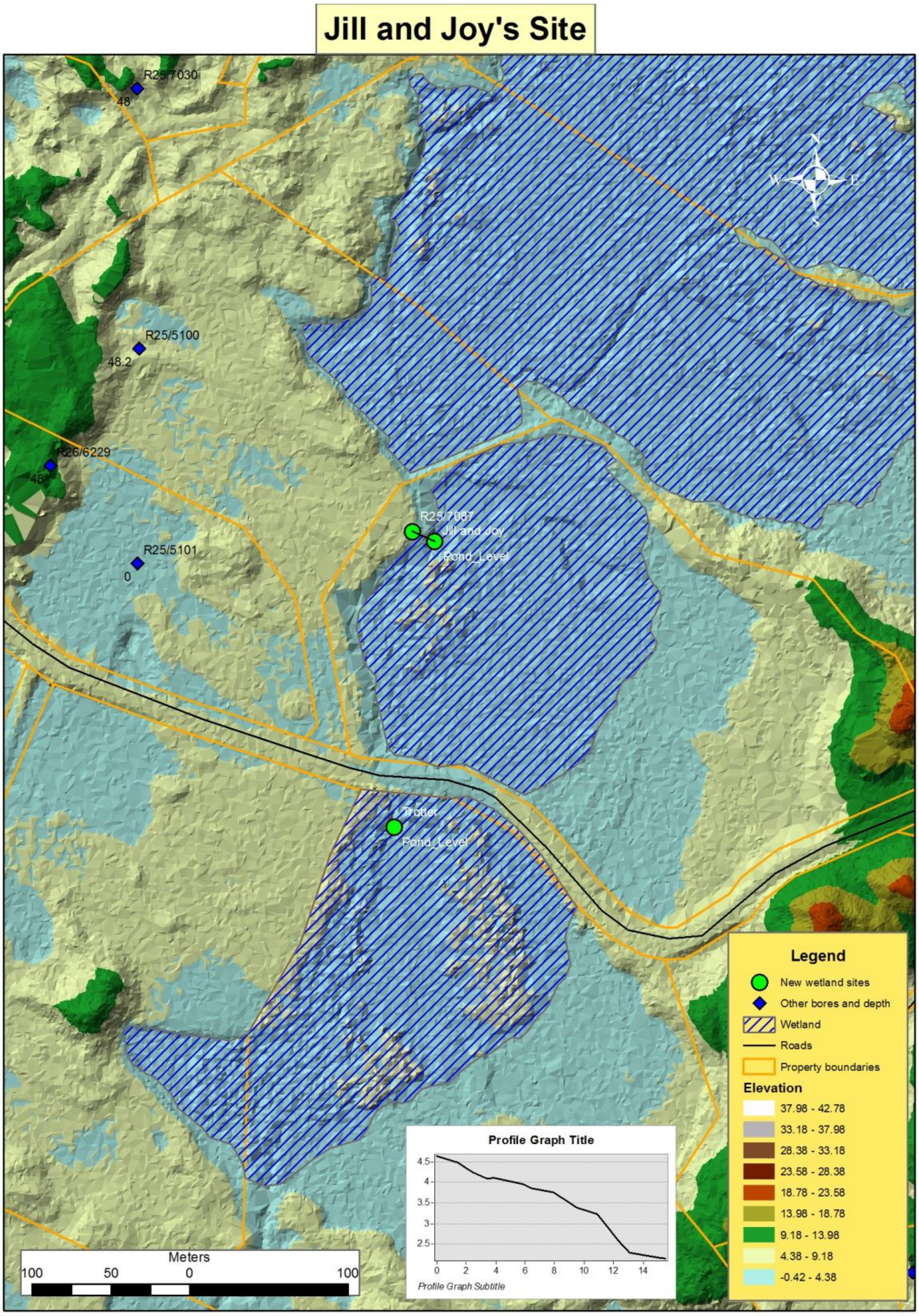
- *Transmissivity* (T) – a measure of how much water can flow from an aquifer – given the thickness of the aquifer and conductivity of the sediment (Freeze & Cherry, 1979; Singh, 1992)

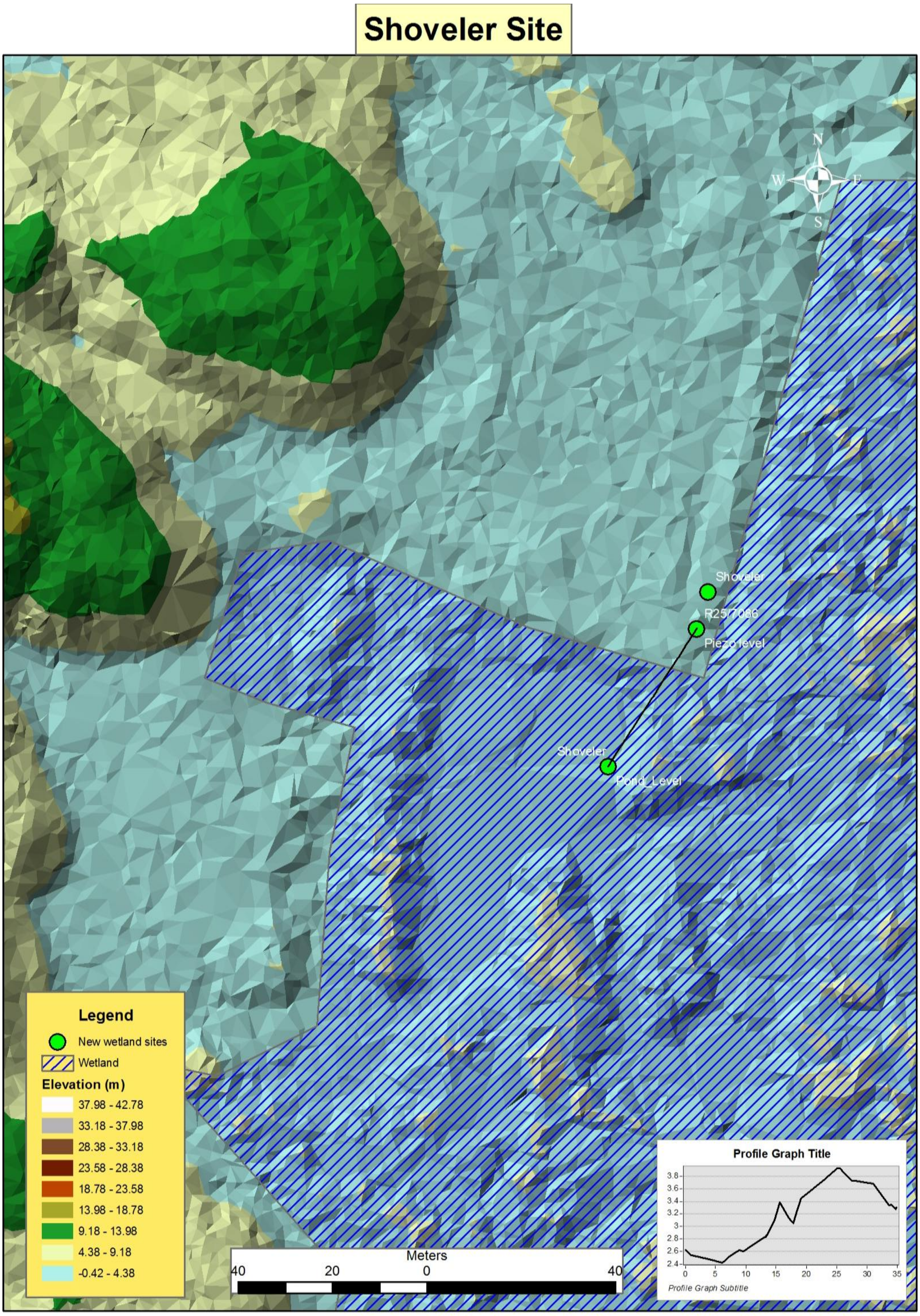
  Equation 2.6 Transmissivity $T = Kb$
  Where K is the hydraulic conductivity; b is the thickness of the aquifer
  (Freeze & Cherry, 1979; Singh, 1992)

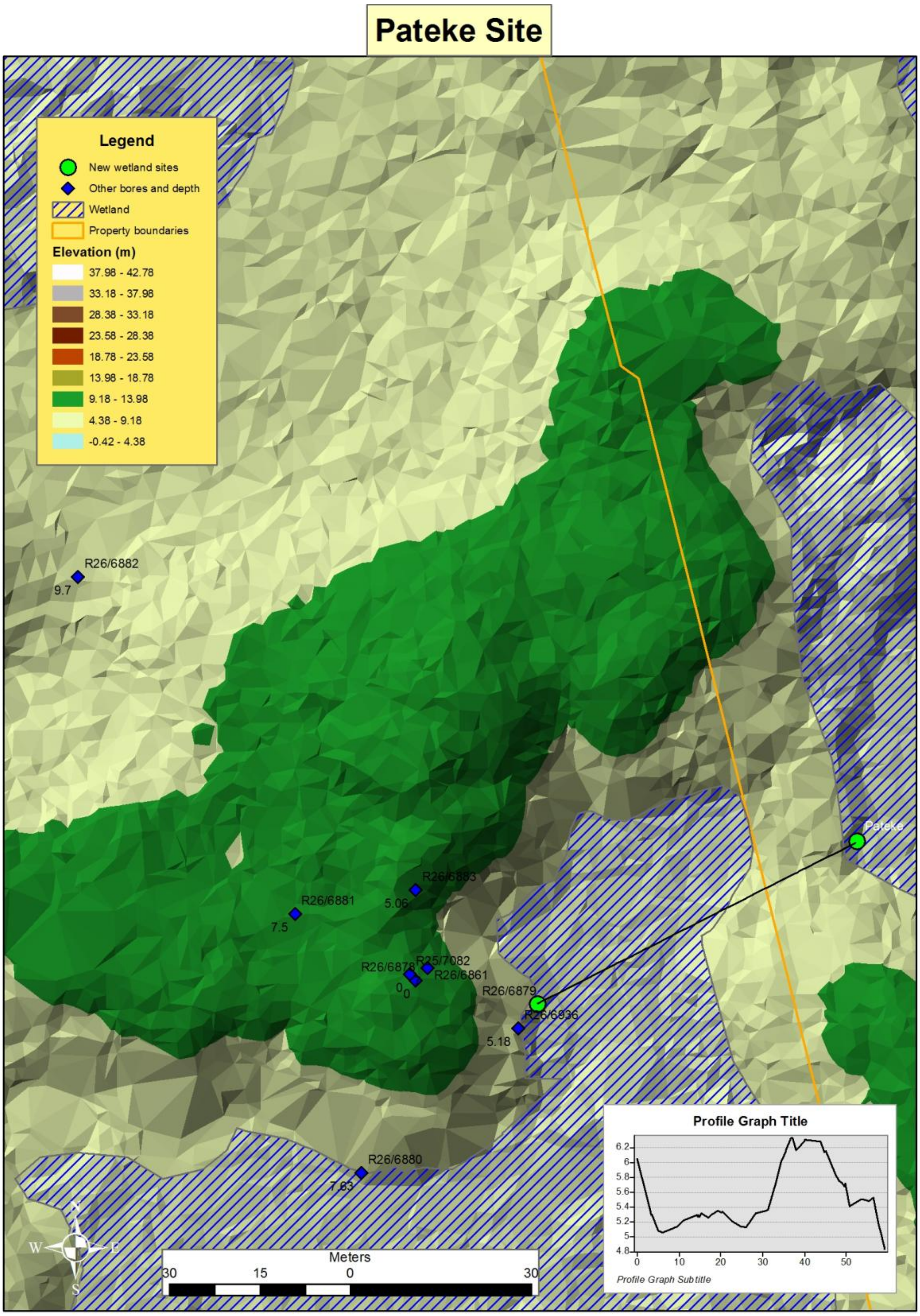
- *Specific yield* (S_y)– following saturation of an unconfined aquifer, the specific yield is the percentage of water an aquifer releases from storage via gravity, per unit surface area of aquifer, per unit drop in water table. (Freeze & Cherry, 1979; Singh, 1992).

- *Safe Yield* – The amount of water that can be taken from a groundwater basin annually without causing detrimental effects (Freeze & Cherry, 1979). Safe yield is used in water resource management to create limits of groundwater abstraction across a groundwater zone.

Appendix 8: Location and elevation TIN for the three sites




Shoveler Site
N
W
E
S
Shoveler
R25/7086
Piezo level
Shoveler
Pond_Level
Legend
New wetland sites
Wetland
Elevation (m)
37.98 - 42.78
33.18 - 37.98
28.38 - 33.18
23.58 - 28.38
18.78 - 23.58
13.98 - 18.78
9.18 - 13.98
4.38 - 9.18
-0.42 - 4.38
Meters
40 20 0 40
Profile Graph Title
Profile Graph Subtitle



Pateke Site
Legend
New wetland sites
Other bores and depth
Wetland
Property boundaries
Elevation (m)
37.98 - 42.78
33.18 - 37.98
28.38 - 33.18
23.58 - 28.38
18.78 - 23.58
13.98 - 18.78
9.18 - 13.98
4.38 - 9.18
-0.42 - 4.38
R26/6882
9.7
R26/6881
7.5
R26/6883
5.06
R26/6878
R25/7082
R26/6861
R26/6879
R26/6836
5.18
R26/6880
7.63
Pateke
Meters
30 15 0 30
N
W
E
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Profile Graph Subtitle