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Aupouri Aquifer Review

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EXECUTIVE SUMMARY

This report summarises and analyses the available hydrological and geological data for the Aupouri Aquifer. A conceptual model is proposed which is based on the available information, and this understanding forms the framework for a numerical model to quantify aquifer flow balances.

The Aupouri Aquifer covers a land area of 75,322 hectares, and extends along the whole length of Ninety Mile Beach on the west coast, and from Kokota (The Sandspit) to Waimanoni on the east coast. It also includes the low-lying land between Waimanoni and Ahipara. The aquifer is for the most part a deep sandy coastal system that has formed as a tombolo between islands of basement rock. Although it is a sandy aquifer, it also contains a significant proportion of clay and peat deposits that have formed between sand dunes. In particular, there is an extensive horizon of low permeability at approximately sea level, which acts as a confining layer to the deeper sediments. Most boreholes tap the more permeable shell-rich marine sands found at the base of the aquifer, although almost all of the water for these bores is provided by leakage from the overlying sands during pumping.

The shallow unconfined part of the aquifer is quite dynamic, and most of the rainfall recharge is routed towards the sea within this layer. The leaky-confined part of the aquifer that is found below sea level is relatively stagnant. Dating of groundwater samples from the top of the leaky-confined aquifer indicate a mean residence time of over 50 years, while deeper samples are over 200 years, which is older than the limits of the tritium dating method. Despite its age, the quality of the groundwater in the aquifer is very good.

A soil moisture balance model has been calculated for the whole Aupouri Aquifer. Annual rainfall over the study area ranges from 850 to 1,670 mm/year (average 1,280). Annual aquifer recharge ranges from 160 to 840 mm, averaging 500 mm, which is approximately 38% of mean annual rainfall. The average recharge volume for the entire aquifer is about 374 million m^3/year.

A numerical groundwater model was set up at a suitable grid resolution to cover the whole aquifer domain. The model calibration is adequate for making predictions at a regional scale, but would need refinement and additional data to make predictions at a sub-region scale. The model predicts that the current consented groundwater allocation of 7.44 million m^3/year is sustainable under current and projected future climatic conditions.

The model was also used to estimate a recommended safe yield of the entire aquifer for allocation purposes. To do this, sub-regions have been identified. Groundwater level thresholds have been proposed at key coastal locations in each sub-region to ensure seawater intrusion does not occur. The testing of this scenario in the model indicates that the aquifer is currently being managed sustainably. The only area of immediate concern is the Sweetwater sub-region, which is approaching its potential allocation limit. New coastal monitoring bores are recommended in the short term at Paparore, and Waihopo. It is also recommended that a groundwater level threshold be placed at Houhora to act as a precautionary measure for seawater intrusion from the east.

Sustainable management limits have been recommended for each sub-region to avoid seawater intrusion. These limits are provided in Table 8, and range from 10 to 35% of mean annual recharge. Higher allocation volumes are predicted to be sustainable in the Paparore and Sweetwater sub-regions where Holocene sand dunes hold a higher volume of water above sea level. The additional groundwater storage provided by the dunes creates a greater driving head for deeper groundwater, and maintains a steeper hydraulic gradient towards the coast. Low-lying areas such as Ahipara, Awanui, Waiparera and Motutangi have less groundwater storage above sea level and a relatively flat hydraulic gradient towards the coast. These areas are more vulnerable to seawater intrusion and have a sustainable management limit of 10-15% of mean annual recharge.

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INTRODUCTION

The Aupouri Aquifer system is located north of Kaitaia and covers approximately 788 square kilometres (78,808 ha) along the Aupouri Peninsula (Figure 1). The groundwater system is a valuable source of water for municipal, domestic, and stock supply, plus irrigation water for agriculture and horticulture.

The Northland Regional Council (NRC) has previously commissioned and undertaken various assessments to increase understanding of the Aupouri Aquifer. Since the most recent comprehensive report of the aquifer as a whole, by HydroGeo Solutions (2000), there has been on-going groundwater level and quality monitoring and an increase in consented allocation in some areas. This report presents updated conceptual and numerical models to assess sustainable yields and groundwater level thresholds on a sub-aquifer and sub-regional basis.

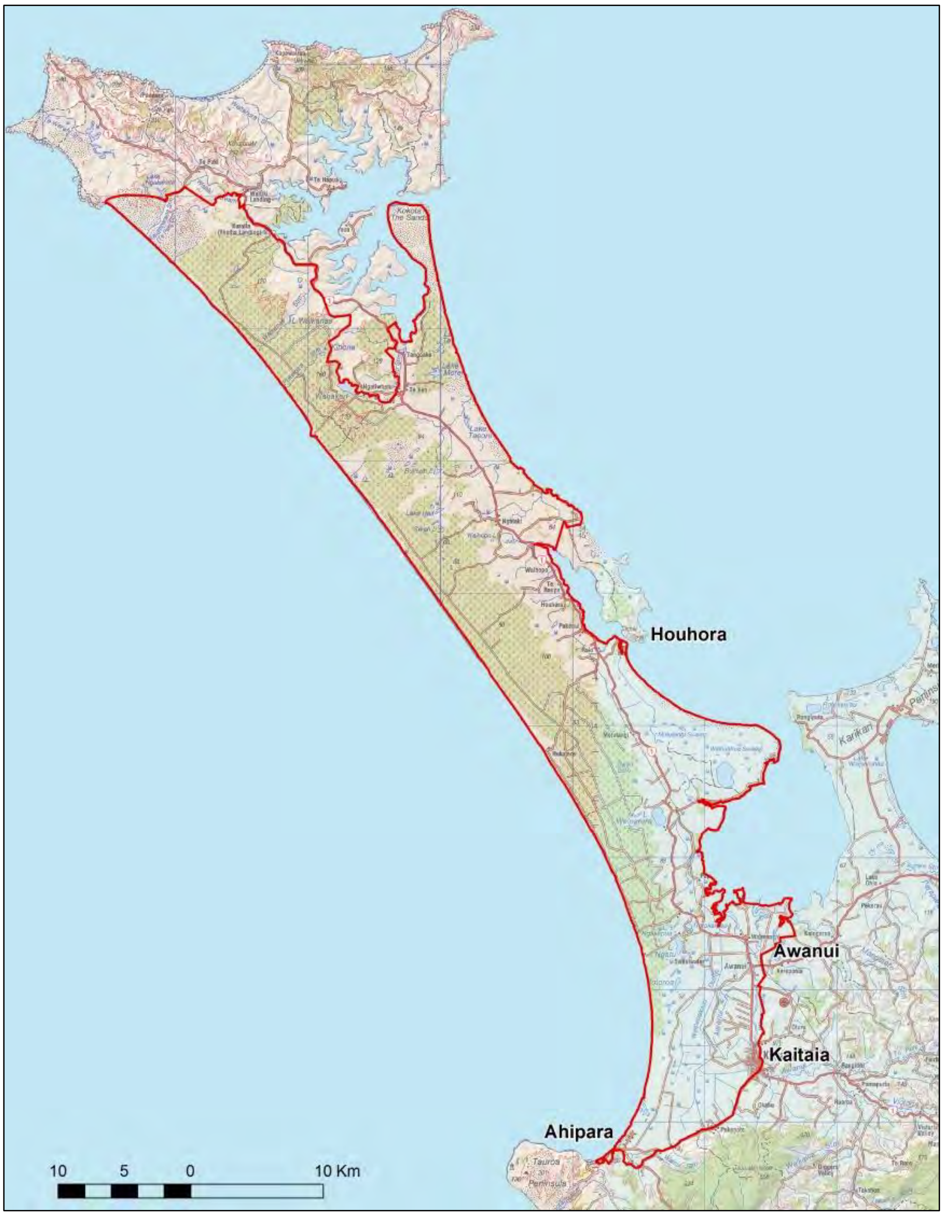


Figure 1 Map of the Far North showing the boundary of the study area in red

STUDY OBJECTIVES

The primary objective of this study is to:

Increase understanding of the aquifer to enable informed decisions on allocation limits and levels and ensure the future sustainable management of the aquifer

The secondary objectives are to:

- Increase the NRC's understanding of the aquifer with respect to groundwater recharge, discharge, storage and flow dynamics; and
- Identify information gaps and future actions required to enable the sustainable management of the aquifer

Fundamental to fulfilling the project objectives are the development of a robust conceptual model of the Aupouri Aquifer, and a numerical model that characterises the available knowledge of the system. The assessment and modelling are to be used by the NRC as decision support for establishing management units, sustainable water allocation limits and levels, and for future water resource management decisions.

SCOPE & NATURE OF THE SERVICES

The scope of this report consists of:

1. Initial review of existing reports and available data on the aquifer, including:
    a. regional geological structure;
    b. groundwater quality;
    c. groundwater levels / piezometric levels;
    d. aquifer hydraulic properties / pump test information;
    e. recharge, discharge and through flow information;
    f. bore log information (Approximately 590 bores of variable accuracy registered with the Council);
    g. current groundwater allocation (Approximately 60 consents with a total allocation of approximately 40,500 m^3/d, not including permitted takes)
2. Development of a conceptual model of the Aupouri Aquifer
3. Development of a land surface recharge model that includes the impact of forestry rotation through time
4. Development of a calibrated numerical model of the Aupouri Aquifer
5. Development of a sensitivity analysis of the optimised parameters in the numerical model
6. Document the results of predictive scenarios with associated uncertainty
7. Recommendations for aquifer management

REVIEW OF EXISTING DATA

This section of the report reviews the environmental data that is available and forms the basis for our conceptual understanding of how the Aupouri Aquifer system works. It also helps us to estimate a safe aquifer yield, which is a long-term measure of the natural replenishment rate of the aquifer, or zone within an aquifer. If groundwater abstraction is kept to within the safe yield there are unlikely to be undesirable environmental issues such as seawater intrusion.

HYDROGEOLOGY

The Geology of the far north is reviewed in the Kaitaia Q-map sheet (Isaac, 1996). This section will focus more on the basement structure and Quaternary sediments of the Aupouri Peninsula. At its simplest the peninsula can be considered as two main geological entities, Mesozoic basement and low permeability Cenozoic Era rocks, and the much younger water-rich sand and peat sequences.

BASEMENT ROCKS

Basement rocks are exposed around Mount Camel, and consist of Early Cretaceous volcanics. These rocks most likely extend across the subsurface of the Aupouri Peninsula together with greywacke, argillite and indurated conglomerate deposits of the same age.

The Cretaceous basement rocks are overlain by a complex series of Mid Cretaceous to Mid Miocene sandstone, mudstone and volcanic deposits. These deposits form the hills that lie to the east and south of Kaitaia. Limestone has also been logged at the base of some boreholes near Awanui (e.g. 209285, 209772), as has glauconitic sandstone (201375). However, most of the boreholes that reach the base of the Aupouri Aquifer tend to intercept mudstone or sandstone.

SEDIMENTS OF THE AUPOURI AQUIFER

The sandy landform that forms the peninsula between the basement rocks near Kaitaia and Awanui to the basement rocks at the end of Ninety Mile Beach is known as a tombolo. A tombolo is a sand bar that connects the mainland with an island, and is formed by longshore drift. Because of their formation by wave and current action, tombolos tend to manifest the shape of prevailing wave refraction, which is why Ninety Mile Beach forms such a fine sweeping curve.

The main sediment lithologies (sediment types) of the Aupouri Peninsula were entered into GIS in order to determine their spatial and depth distribution. Fine sand and silt are the dominant sediments, and there does not appear to be any obvious fining upwards or downwards in the sequence. The deeper sands were deposited in a shallow marine environment and can be identified by their blue-grey colour and the presence of shells which become more abundant towards the aquifer base. The local convention is to call the marine sands “shellbeds” when the concentration of shells exceeds about 30%.

The presence of shells in bore logs has been recorded as being from 0.2 to 32 m in thickness, with an average of 7 m. The thickness of the shell beds also seems to be greater in deeper bores. So far these shell-rich sands have only been found south of the northern end of Houhora Harbour (Waihopo Stream) where they appear to be ubiquitous in the marine sands deposited immediately above the basement. Thus, the success of intercepting the shell-rich sands depends on how deep one has to drill to intercept the basement.

The local practice is to call the coarser shell beds the ‘aquifer’, although there does not appear to be a distinct boundary between the “shell beds” and the overlying marine sands. The function of the shells is to create a macro-porosity within the sands, which increases its permeability. Thus, the shell beds effectively serve as a gallery for pumping to draw upon a wider area of storage from the overlying sands, and this access to vertical leakage effectively increases the bore transmissivity and hence yield considerably.

The boundary between the marine beds and overlying terrestrial dune sands is identified by a change in sand colour to yellow or brown due to the abundance of oxygen. These terrestrial sands are also marked by the presence of discrete peat and clay lenses formed by buried former wetlands between the sand dunes. These old wetland deposits are common throughout the upper sand sequence, and can be seen today on the surface, many of them being associated with inter-dune lakes. Perhaps the best known buried wetland is in the Sweetwater area, where a 2 to 5 m thick lignite deposit is present at about 20 m below sea level. This deposit is sufficiently extensive to form a potential economic resource (see Edbrooke, 1997).

From a hydrogeological perspective, the most significant wetland deposits are found at or around the elevation of the present day sea level. While they are not as thick as the Sweetwater lignite deposits, their significance is that they form a barrier to groundwater flow at around sea level, which is the main hydrological boundary for the aquifer. These wetlands were formed by the stabilisation of the sea level around 6,500 years ago following the last glacial period. In many places, these wetlands are still active, as evident in the Kaitaia, Motutangi, and Waihuahua swamps.

Bore logs for the Aupouri Aquifer indicate that clay and or peat deposits tend to be present beneath the sand dunes at around sea level. While these peat deposits are not laterally continuous, their widespread distribution suggests that wetlands once extended across most of the peninsula. The common occurrence of peat and clay at this elevation indicates that the stabilisation of the sea level had created a low energy depositional environment which, together with a low-lying topography, allowed a large area of wetland to form. The widespread occurrence of these low permeability deposits has implications for the flow of groundwater above and below this horizon.

The surface deposits of the Aupouri tombolo mostly consist of dune sands, interspersed with peat and clay deposits associated with wetlands. The youngest sand dunes are mobile, and are located along the west coast. The extent of these dunes is easy to identify because they were extensively planted with plantation pine trees, which has stabilised their movement. Older sand dunes (>100,000 years) form the lower lying sand country along the western margin of the tombolo (Isaac, 1996).

GEOPHYSICS

Low-level aerial geophysical surveys were carried out during 2011 (Stagpoole *et al.* 2012). The results of these surveys are useful for studying the basement structure beneath the Aupouri Aquifer, but do not provide much information about its internal structure.

Ground-based geophysical surveys have previously been applied in the Aupouri Aquifer by Groundwater Consultants NZ. Geophysical logging was carried out for piezometers drilled in some exploratory surveys (GCNZ, 1987a). The logs recorded were natural gamma, self potential, and resistivity. The resistivity response was particularly encouraging, indicating that EMI surveys may be a useful technique for distinguishing higher and lower permeability horizons. Seismic refraction surveys were carried out at Hukatere and Lake Heather (GCNZ, 1987b). The surveys were useful for detecting the depth of the basement and its slope.

Vertical electrical soundings were also carried out in the Ahipara and Awanui areas (GCNZ 1990). Interpretation of these soundings concluded that limestone forms the basement between Lake Heather and Awanui, and possibly southwards to Ahipara. The basement is found at about 75m below sea level at Lake Heather, and shallows rapidly towards Kaitaia and Awanui. This interpretation is consistent with the logging of limestone in boreholes from this area. The surveys also found that the sand content of the subsurface decreases towards Ahipara, which implies the presence of finer sediments in this area.

AQUIFER STRUCTURE

The structure of the basement is not well defined on the available geological maps, mainly because basement outcrop is sparse, being mostly hidden beneath Quaternary sediments. A number of inferred faults are shown on the Kaitaia Q-Map (Isaac, 1996), and these all strike to the southeast. What is clear from geological maps and bore logs is that the basement beneath the aquifer tends to dip generally in a westward direction, away from the hillsides that have been formed from basement rocks.

Interpretation of data from the Northland airborne magnetic survey (Stagpoole *et al.* 2012) provides insight into the basement structure. In particular, a regional-scale fault can be inferred from the Bouguer anomaly maps. The fault is shown on Figure 2 together with structure contours on the aquifer base. This follows a bearing of around 280^{o} from Waihuahua swamp and turns towards a bearing of 300^{o} near the start of Hukatere Road, and eventually goes offshore at Ninety Mile Beach about 20km northwest of Hukatere. This structure was interpreted by Stagpoole *et al.* 2012 to represent the northern boundary of Permian Caples Terrane basement rocks, and is therefore a major crustal feature.

The interpolation of basement intercepts on either side of this feature shows that the basement dips in different directions (Figure 2). In the southern domain, the basement dips quite steeply to the west-northwest, parallel to the strike of the fault. In the northern domain, the basement dip is considerably more shallow, and to the south-southwest. This means that the Aupouri Aquifer is thickest along Ninety Mile Beach to the north of Hukatere, where the basement may be over 200 m deep as the fault is approached. In the northern domain, the aquifer is much thinner, and is expected to be less than 40m along Ninety mile beach. The northern domain is thickest along the eastern edge of the fault at Waihuahua swamp, where the basement may be over 100m deep .

The fault is expected to pre-date deposition of the Quaternary sand sequence. From a water resources perspective, the main implications of the fault and its bearing on aquifer structure are the depth to the basal shellbeds for drilling purposes, and the spatial variability of storage in the aquifer.

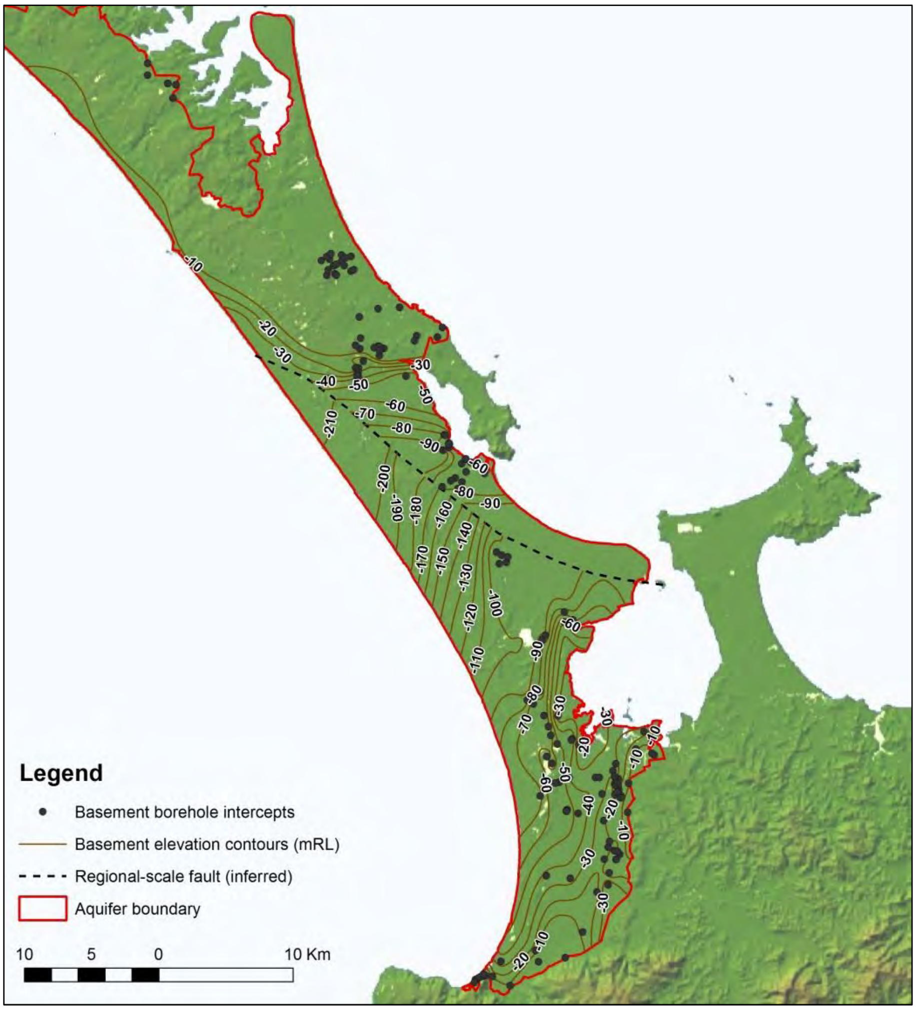


Figure 2 Map showing the structure of the Aupouri Aquifer base.

GROUNDWATER LEVELS

The Aupouri Aquifer is fortunate to have a network of multi-level piezometers for monitoring groundwater levels that have records dating back 30 years. These piezometers were drilled in two phase, firstly by the NZ Geological Survey in the early 70's (Petty, 1975) and later by the Northland Catchment Commission and Regional Water Board in the late 80's (GCNZ, 1987a). The multi-level piezometers are clustered in a number of areas, at Houhora, Paparore, Sweetwater, and Kaitaia (see Figure 3).

The Houhora piezometers have been drilled in a line between Hukatere and Houhora. This allows a dynamic cross section across the whole aquifer to be visualised. This was illustrated to good effect by Groundwater Consultants NZ (1987a), who drew a profile of potentiometric contours based on water levels in five multilevel piezometers. The profile (shown in Figure 4) shows a groundwater divide along the north eastern margin of the Aupouri Forest where the sand dunes reach their highest elevation. This flow divide follows the axis of the dune sands along the Aupouri Peninsula, so that the water table surface roughly mimics topography.

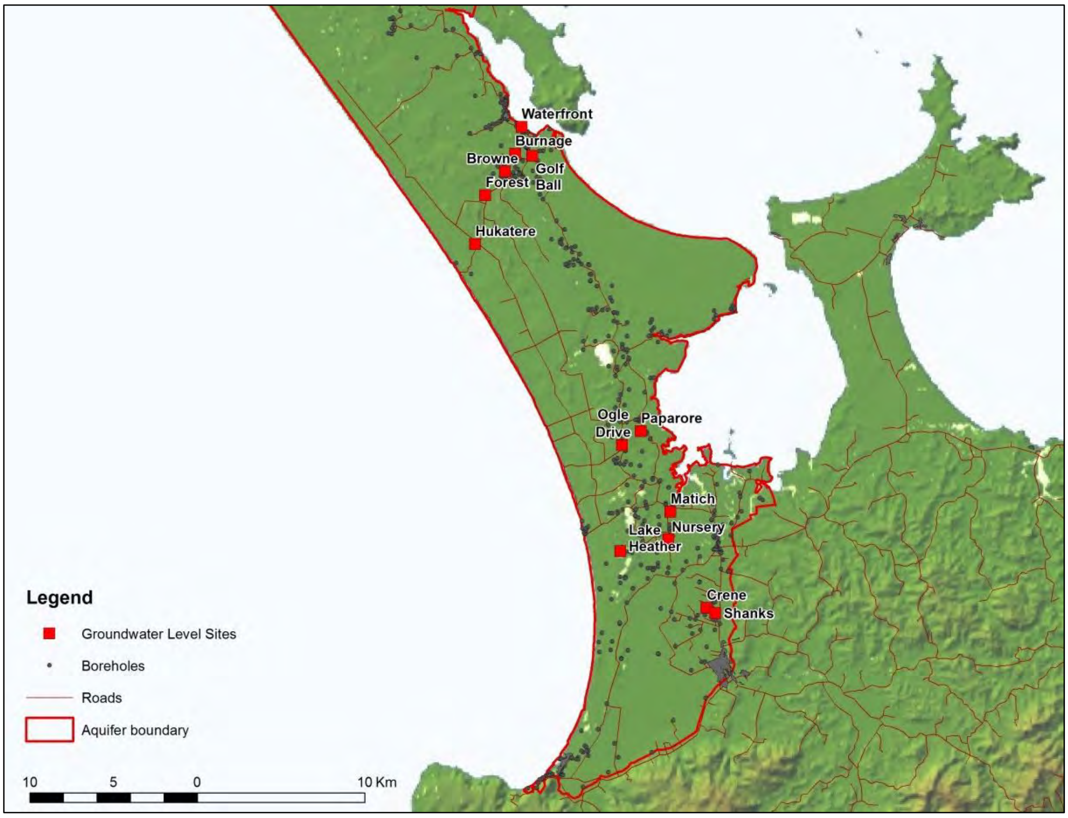


Figure 3 Map of groundwater level monitoring sites in the Aupouri Aquifer

The flow potential along the axis of the groundwater divide is vertically downwards. As we move away from this groundwater divide towards the coastline, the flow potential gradient becomes more horizontal with depth and distance from the divide. This pattern is consistent with groundwater recharge being received from rainfall, and discharge occurring along the coastline

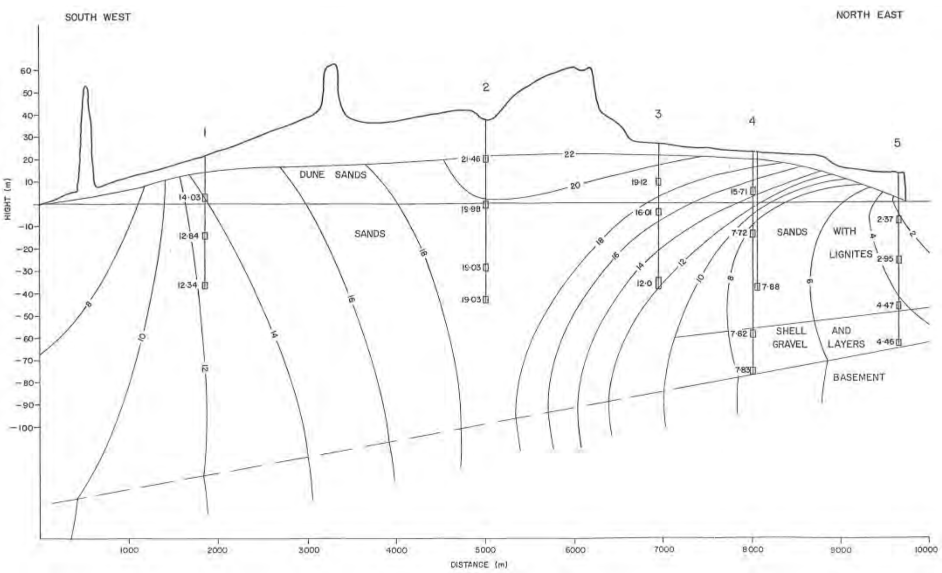


Figure 4 Profile from Hukatere to Houhora drawn by GCNZ

The flow potentials shown on the profile are also asymmetric, with a lower potential gradient occurring to the west. This asymmetry in the profile appears to be formed by the balance of two opposing factors:

1. the slope of the underlying basement, which dips to the west in this area. The dip of the basement favours discharge to the western coastline.
2. land surface recharge. Rainfall recharge is reduced over the forest (the western side of the profile) because of canopy interception and enhanced evapotranspiration. This results in relatively more recharge, and higher groundwater levels overall, on the eastern side of the groundwater divide compared to the more freely draining western side.

Despite the apparent asymmetry of the potential flow field, GCNZ (1987a) estimated very similar discharges to the two coastlines based on calculations using Darcy's law. The calculated discharges were 4.1 to 41 l/s/km length of aquifer and 4.8 to 48 l/s/km for eastward and westward flow respectively.

A summary of the active water level monitoring network is provided in Table 1, while Figure 3 shows the locations of NRC water level monitoring sites, both current and historical. The Aupouri Aquifer has a good coverage of monitoring sites overall.

It can be seen in Table 1 that the multi-level piezometers normally have three or four screen depths. The average water levels for different screen depths in the multi-level piezometers have been plotted in Figure 5 to illustrate how groundwater levels change with depth. The groundwater level seen at each site is largely governed by its proximity to the groundwater divide or the coastline. Four of the sites (Forest, Browne, Lake Heather and Hukatere) show a decrease in groundwater level with screen depth, indicating a downward flow potential. The Waterfront site shows an upwards flow potential, indicating discharge though the sea bed and perhaps increasing confinement with depth.

Table 1 Details of the active NRC monitoring network including top of screen and mean water level[1]

Bore	E	N	Name	Ground level	Piezometer	1	2	3	4
200208	1610722	6144033	Browne	26.6	Screen	-32.4	-2.5	11.1	
					Mean Water level	11.4	15.7	18.6	
200209	1611323	6145092	Burnage Road	23.5	Screen	-73.8	-57.0	-12.5	6.5
					Mean Water level	7.5	7.5	7.5	16.1
200207	1609541	6142603	Forest	37.3	Screen	-41.8	-27.2	0.8	21.3
					Mean Water level	17.9	17.9	19.2	20.2
200206	1608927	6139682	Hukatere	23.4	Screen	-34.8	-12.6	4.8	
					Mean Water level	12.0	12.4	13.5	
200226	1617605	6121325	Lake Heather 1	31.7	Screen	5.7	-27.4	-70.2	
					Mean Water level	11.7	8.6	7.9	
200227	1617258	6121482	Lake Heather 2	35.8	Screen	9.3			
					Mean Water level	10.3			
200228	1617682	6121552	Lake Heather 3	33.4	Screen	7.4			
					Mean Water level	11.4			
209581	1617702	6127677	Ogle Drive	35.7	Screen	5.7			
					Mean Water level	14.2			
200211	1618829	6128509	Paparore Road	9.1	Screen	-68.9	-54.9	-25.9	-8.9
					Mean Water level	6.8	6.8	6.5	6.4
200210	1611712	6146689	Waterfront	12.5	Screen	-60.9	-44.5	-24.2	-6.0
					Mean Water level	5.3	5.3	4.0	3.4
201025	1620470	6122039	Sweetwater Nursery	3.8	Screen	-23.2			
					Mean Water level	4.78			

For sites with a downward potential gradient, there appears to be very little change in groundwater levels below an elevation of about 10m below sea level. This indicates that the shallow groundwater is more dynamic than the deeper groundwater, which may be stabilised by sea level, and therefore relatively stagnant. The deeper Burnage piezometers show no change, and it is possible that this bore may be affected by leakage along the casing.

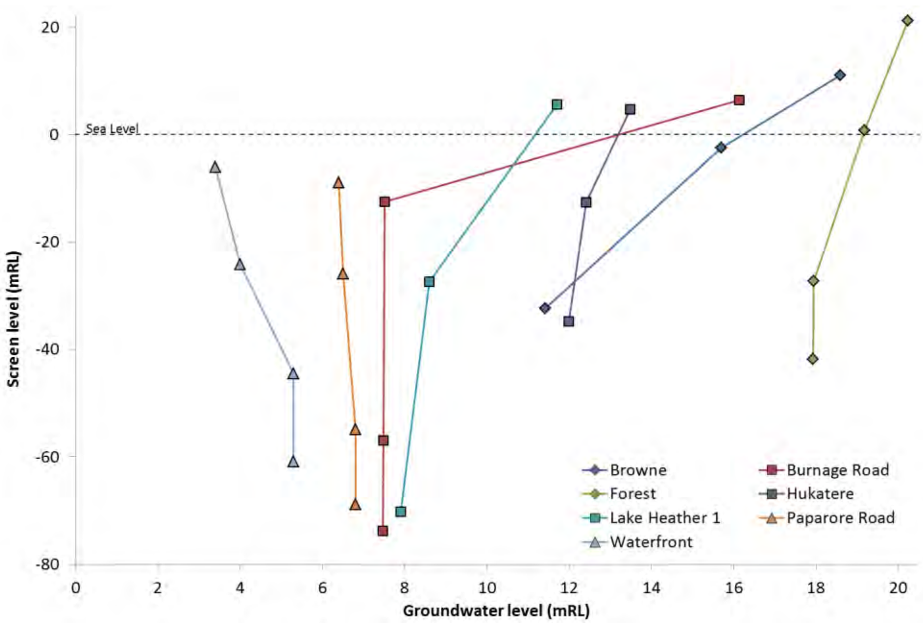


Figure 5 Graph comparing the of top of screen and water level for multi-level piezometers

[1] *All values are relative to sea level*

TRANSIENT RESPONSE

Groundwater levels in some bores have been monitored by NRC on a monthly basis since 1987. Graphs showing water levels in the piezometers are provided in Appendix 1. The groundwater elevation for each site has been coded according to screen depth, with shallow levels represented by dotted lines, mid levels represented by dashed lines, and the two deep levels represented by solid lines.

In general, bores with deeper screens are more responsive than the shallow bores. This is most likely due to lower storage coefficients at greater depths, although there is more pumping from the deeper aquifer also. Bores on the western side of the aquifer are much less responsive to individual recharge events than those in the east. A possible explanation for this is that land surface recharge is being attenuated by the unsaturated zone, which smooths the water table fluctuations. Certainly, the bores with more shallow water tables are more responsive, but not significantly so.

Multi-level piezometers with deeper screen depths respond strongly to summer pumping demand. This response is a combination of proximity to production bores and lowering of the storage coefficient with depth. The deeper bores also show more subdued long-term fluctuations than more shallow piezometers. It is interesting that this subdued response to recharge occurs despite the expected decrease in storage coefficient values with depth.

An example of delayed recharge response can be seen at Lake Heather, where the P1-3, P2, and P3 piezometers are all screened in the shallow unconfined dune sands (see Appendix 1). These piezometers show an almost identical response, the only significant difference between them being the actual groundwater level in each bore. The deeper P1-3 and P1-2 piezometers are screened in the shell-rich horizon and leaky-confined sand respectively. The Water levels in these two piezometers are very similar. The response of these piezometers is more subdued than the shallow piezometers, and also shows a relative delay of approximately 1-2 months.

HydroGeo Solutions (2000) have suggested that the observed attenuated and delayed recharge is derived from slow-release leakage from the lakes and the presence of significant peat deposits providing the attenuation. Our review of the Aupouri Aquifer hydrogeology agrees with this observation, and we have found the peat deposits to be a strong influence on the partitioning of groundwater flow vertically and laterally. However, the delayed response could also be caused by a fairly high degree of leaky confinement delaying the arrival of surface recharge at greater depths and hence subduing and delaying the pressure response

LAKES

There are a number of small lakes in the Aupouri Peninsula which have formed in the depressions between sand dunes. There are two hydraulic settings in which each of these lakes could be situated. Firstly, it is possible that a lake could be a “window lake”, essentially presenting an extension of the groundwater table. If this is the case, the lakes would have a direct hydraulically connection with the aquifer, and would be affected by pumping. The alternative possibility is that a lake could be perched above the aquifer, essentially being isolated from the main groundwater system by an underlying peaty clay or pan horizon. If this is the case, the lake would not be affected by groundwater pumping, but it may contribute to the aquifer via the percolation of water downwards to the main aquifer system, thereby providing a steady source of groundwater recharge. Note that the occurrence of a perched lake does not preclude the possibility that there is also some localised perched shallow groundwater that is in hydraulic connection with the lakes.

The possibility of window lakes has implications for aquifer management, since groundwater pumping could potentially affect water levels in these lakes. There is, however, little data available on which to base a conclusion. Monitoring data is only available for lakes Waiparera, Heather, Ngatu, and Rotoroa, and fortunately these lakes also have a record of groundwater levels nearby. The monitoring records clearly show that the groundwater level at each of these lakes is situated well below the water level of the lake. For example, shallow groundwater at the nearby Lake Heather piezometer is less than 10 m above mean sea level, while the water level of nearby lakes Heather and Rotoroa is 34 and 27.5m respectively. Groundwater levels from bore logs located near lakes Ngatu and Waiparera also indicate that the main aquifer is situated well below the lake surface. We can conclude that there is no evidence of a direct hydraulic connection between these four lakes the main aquifer system.

A preliminary assessment of the connection between groundwater and other lakes in the area can be made by using data from the NRC digital elevation model (DEM). Lake levels can be estimated from the DEM and compared with nearby groundwater depths from bore logs, also adjusted by the DEM to create groundwater levels. While this is not an accurate method, it does indicate which lakes that have a high likelihood of being connected to groundwater or not if a nearby groundwater level is available. The desktop exercise indicates that Salt Lake and Lake Waihopo possibly have a hydraulic connection, while Round Lake, West Coast Road, Rotokawau, and Gleesons lakes are almost certainly disconnected.

GROUNDWATER PROPERTIES

Aquifer tests were carried out and analysed for the exploratory bores that were drilled by the NZ Geological Survey (Petty, 1975) and NRC (GCNZ 1987a). Additional aquifer tests have been carried out in more recent years as supporting evidence for resource consent applications (e.g. SKM, 2007a). GCNZ (1987a) also estimated horizontal hydraulic conductivities for more permeable sediments in the aquifer using Darcy's Law. Values ranged from 1×10^{-5} to 1×10^{-4} m/s (1-10 m/d).

Hydrogeo Solutions (2000) provided a list of the aquifer test results that had been reported up to that time. The transmissivity values that were reported range from 12 m^2/d to 850 m^2/d. Storage coefficients ranged from 0.01 to 0.0001, indicating that leaky-confined to confined conditions are common throughout the aquifer.

For this study we have considered that it is important to consider hydraulic anisotropy in the aquifer. Anisotropy can form at a macro-scale by the overlaying of finer and coarser sedimentary units such as wetland deposits and sands. Anisotropy also occurs at a micro-scale due to imbrication (alignment of particles), compaction, or stratification. All of these macro and micro-scale features are expected to be present in the Aupouri Aquifer. It is clear from the geology that the aquifer consists dominantly of fine to medium sand, and this sand is expected to become more compact with depth. This means that the horizontal hydraulic conductivity will be significantly greater than vertical values. On a broader scale, we also know that the sand deposits contain significant lenses of silt, clay and peat. This will further increase the difference between the horizontal and vertical hydraulic conductivity values.

The effect of anisotropy is evident in the drawdown curves that have been previously reported, which depart from a classical Theis type-curve. This generates bulk values of hydraulic conductivity which may be higher than horizontal values once this anisotropy has been accounted for. For the purposes of groundwater modelling, it is important to try and describe this anisotropy because it can strongly influence the direction of vertical flow potential.

All of the tests that have been reviewed for this report show the influence of an external recharge source which causes the rate of drawdown in the observation bore to decrease over time. The late-time recharge phenomenon is so pronounced that it can only be sourced from the overlying saturated sediments, which are large potential source of groundwater storage (delayed yield).

Figure 6 shows a good example of the recharge effect at the Ogle Drive bore. The initial few minutes of the drawdown curve is dominated by storage in the vicinity of the pumped bore. After 10 minutes the drawdown curve is following a typical Theis type-curve, which forms a straight line on a semi-log plot. After an hour of pumping, the drawdown curve starts to deviate from the Theis type-curve. This is interpreted to be the consequence of vertical leakage, which effects drawdown at the point where the radius of potential drawdown is of sufficient extent to make the vertical component of flow a significant contribution discharge.

The aquifer test shown in Figure 6 has been modelled with the Boulton (1963) solution, which incorporates delayed yield from storage in an overlying aquitard, and allows a value of the leakage coefficient to be determined. To do this requires a test with an observation bore, and a test of sufficient duration and drawdown to provide a marked leakage effect. Table 2 shows the results of aquifer tests that we have re-analysed to account for aquifer leakage. Suitable aquifer test data for re-analysis required the availability of drawdown results for a constant discharge test with a drawdown response in an observation bore. This requirement limited the data available for re-analysis to seven sites, since most of the tests carried out in the aquifer have not included an observation bore.

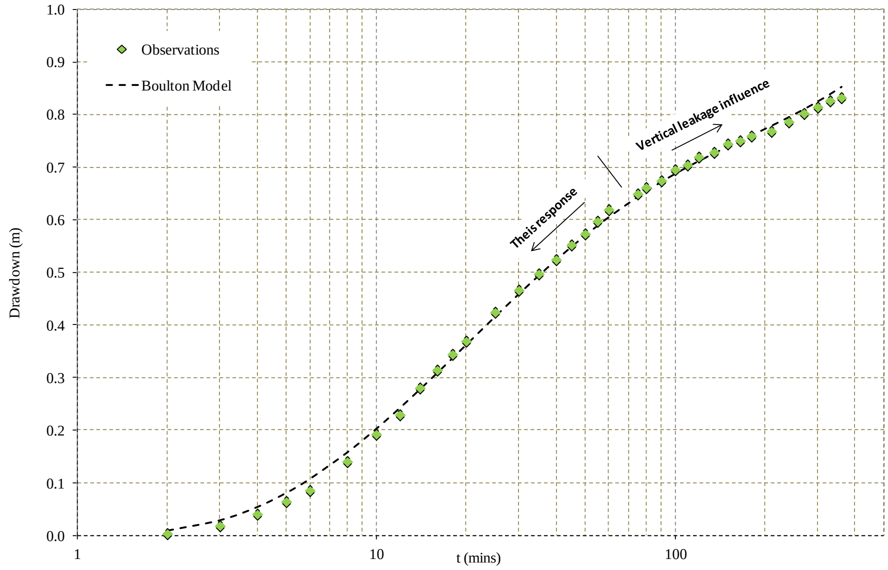


Figure 6 Time-drawdown curve plot for the Ogle Drive aquifer test

One of the difficulties in converting transmissivity (T) and leakage coefficients (K'/B') to hydraulic conductivity (Kx) and vertical leakage (Kz) components is the difficulty in characterising the aquifer (B) and overlying aquitard (B') thicknesses. These values have to be gauged from a drillers' well log, and it is not always apparent which depth to use for thickness calculations. Furthermore, the duration of the test determines how far the leakage effect will propagate through the overlying sediments. The tests carried out in the Aupouri Aquifer have typically consisted of less than a day of pumping, so it is unlikely that the well has drawn storage from the whole saturated sequence because of the large volume of storage available in the overlying sediments. Accordingly, the aquitard thickness has been interpreted here to represent the depth of more permeable sediments overlying the pumped bore until a low permeability layer such as a peat or clay is reached. Because of the uncertainty in the estimation of B', the leakage coefficients in particular (K'/B') are considered to be more reliable than the vertical hydraulic conductivity (Kz) values shown in Table 2.

Table 2 Results of re-analysis of aquifer test data

Pumped bore	Screen depth (m)	Test name	Obs piezo	Lithology	T (m^2/d)	B (m)	Kx (m/d)	S	K'/B' (d)	B' (m)	K'z (m/d)
200048	18.8	Hukatere 1	r1.5m	Sand	60	6.4	9.4	0.0017	0.1475	13.5	2.0
200048	18.8	Hukatere 1	r15m	Sand	60	6.4	9.4	0.0107	0.2927	13.5	4.0
200048	18.8	Hukatere 3	r1.5m	Sand	50	6.4	7.8	0.0022	0.1909	13.5	2.6
200048	18.8	Hukatere 3	r15m	Sand	62	6.4	9.7	0.0154	0.1909	13.5	2.6
200060	64	Browne	208 P1	Sand	400	10.4	38.5	0.0004	0.0014	21.2	0.03
200081	31.2	Ogle Drive	r1.5m	Sand	7.4	8.1	0.9	0.0467	0.8771	10.2	8.9
200229	73	Fitzwater	211 P1	Sand/shell	130	6	21.7	0.0002	0.0001	26	0.004
200229	73	Fitzwater	211 P2	Sand/shell	110	6	18.3	0.0004	0.0004	11	0.004
201025	27	Sweetwater	r17m	Sand	52	6.3	8.3	0.0004	0.0018	11	0.02
201037	27.2	Welch	r1.5m	Sand/shell	9	1.8	5	0.0005	0.0087	11.9	0.10
209606	110.5	King Avo	209607	Sand/shell	305	26	11.7	0.0007	0.0003	15.5	0.004
209606	110.5	King Avo	209608	Sand/shell	370	17	21.8	0.0011	0.0003	15.8	0.005
				Min	**7.4**	**1.8**	**0.9**	**0.0002**	**0.0001**	**10.2**	**0.004**
				Mean	**135**	**8.9**	**13.5**	**0.0067**	**0.14**	**14.7**	**1.7**
				Max	**400**	**26**	**38.5**	**0.0467**	**0.88**	**26.0**	**8.9**

Table 2 indicates that aquifer transmissivity ranges from about 5 to 400 m^2/d, and we can expect hydraulic conductivity values within the sand and shell beds to range from 1 to 40 m/d. The values we could expect for fine silt are less than 2 m/d, and for fine sand range from 0.02 to 20 m/d (Domenico and Schwartz, 1998). This suggests that the grain size within the "sandy" part of the aquifer may range from silt to medium sand, which is consistent with the driller's well logs.

The aquifer test results shown in Table 2 indicate that the leakage coefficient can vary from around 0.0001 to 1. When accounting for an estimated aquitard thickness, vertical hydraulic conductivity values in the sediments overlying the permeable pumped horizon can range from 0.004 to 9 m/d. These results indicate there is considerable aquifer anisotropy, with the estimated vertical hydraulic conductivity ranging from similar values to the horizontal, to a thousandth of the horizontal value depending on the overlying lithology. However, while the hydraulic conductivity of the overlying sediments may be small, there is a large volume of available storage for bores to draw on. Thus, a small leakage coefficient does not impose severe limits on the productivity of bores.

Values obtained for the storage coefficient range from 0.05 to 0.0002. Values of 0.3 to 0.01 are typical of unconfined conditions, while values less than 0.005 can be considered to represent confined conditions (Freeze & Cherry, 1979), although truly confined conditions aren't expected to occur until values of 0.00001 are approached. All of the tests that have been analysed can therefore be considered to represent confined (and leaky) conditions with the exception of Ogle Drive and perhaps Hukatere, which have values at the lower end of what may be considered to be unconfined conditions.

GROUNDWATER ALLOCATION

There are currently 64 consents to take groundwater from the Aupouri Aquifer. The total daily and annual allocation is around 41,100 m^3/d and 7.44 million m^3/y respectively.

Most of the consents are for irrigation of avocados, although there have recently been two large consents for public water supply (Far North District Council, 5000 m^3/d) and pasture irrigation (Landcorp, 15,525 m^3/d) which have not yet been exercised. There are also some minor takes for domestic and stock water supply, industrial use, and crop irrigation. Pumping bores are currently centred on three areas which constitute 87% of the consented total allocation volume:

Houhora: An area of concentrated avocado orchards. 5,256 m^3/d is allocated to twenty consents.

Pukenui: A more widespread area of avocado orchards. 8,046 m^3/d is allocated to fourteen consents.

Sweetwater: The Sweetwater area has more diverse water use than Houhora and Pukenui. 22,485 m^3/d is allocated to six consents. The majority of this water is allocated to the Far North District Council and Landcorp.

The Landcorp and Sweetwater consents together comprise 50% of the total volume of water that has been allocated from the Aupouri Aquifer. At the time of writing, these consents had not been exercised, so their impact on the aquifer has yet to be observed.

GROUNDWATER QUALITY

Groundwater quality sampling is currently undertaken at six sites throughout the Aupouri Aquifer by NRC. An additional site, West Coast Road, was monitored for a short period from 2007 to 2009. The only previous regional scale reporting of groundwater quality monitoring for the Aupouri Aquifer has been in national reviews of State of the Environment (SOE) and National Groundwater Monitoring Programme (NGMP) (e.g. Daughney & Randall, 2009; Daughney *et al.*, 2012).

The mean results of the NRC groundwater quality sampling are shown in Appendix 2. Overall, the quality of groundwater in the Aupouri Aquifer is very good. All of the sampled concentrations are less than half of the NZ Drinking Water Standards (Ministry of Health, 2008). Samples that exceed their respective guideline values are indicated in red in the Table on Appendix 2.

Exceptions to good water quality are found in some areas with iron, manganese and hardness exceeding half of the guideline values that have been set for aesthetic reasons. Iron and manganese can form a residue on white ware and linen in high concentrations. The guideline values for iron and manganese have been exceeded at Ahipara, Colville and Vinac sites, and the Fitzwater site exceeds the guideline value for manganese. These metals are often found in aquifers with reduced (anoxic) conditions, and their high concentrations are probably a consequence of the abundant peat deposits in the aquifer.

Hardness is a measure of the mineral content of water, with hard water having higher concentrations of calcium and magnesium. This makes it difficult for soap to form lather, and the formation of a lime crust in kettles can occur. Moderate to hard water has been sampled at the Fitzwater and Fish Club bores at Houhora. Both of these bores are screened within the shellbed layer at the base of the aquifer. The higher hardness content of these bores is most likely caused by dissolution of calcite from the shells. If this is the case, higher hardness contents can be expected from most bores screened within the shellbed layer.

Salinity is an important issue for the Aupouri Aquifer, which is bounded by the sea for most of its extent. Chloride and sodium concentrations are the best indicators of salinity. Figure 7 shows the results of chloride and sodium sampling, and it can be seen that concentrations are stable at most sites.

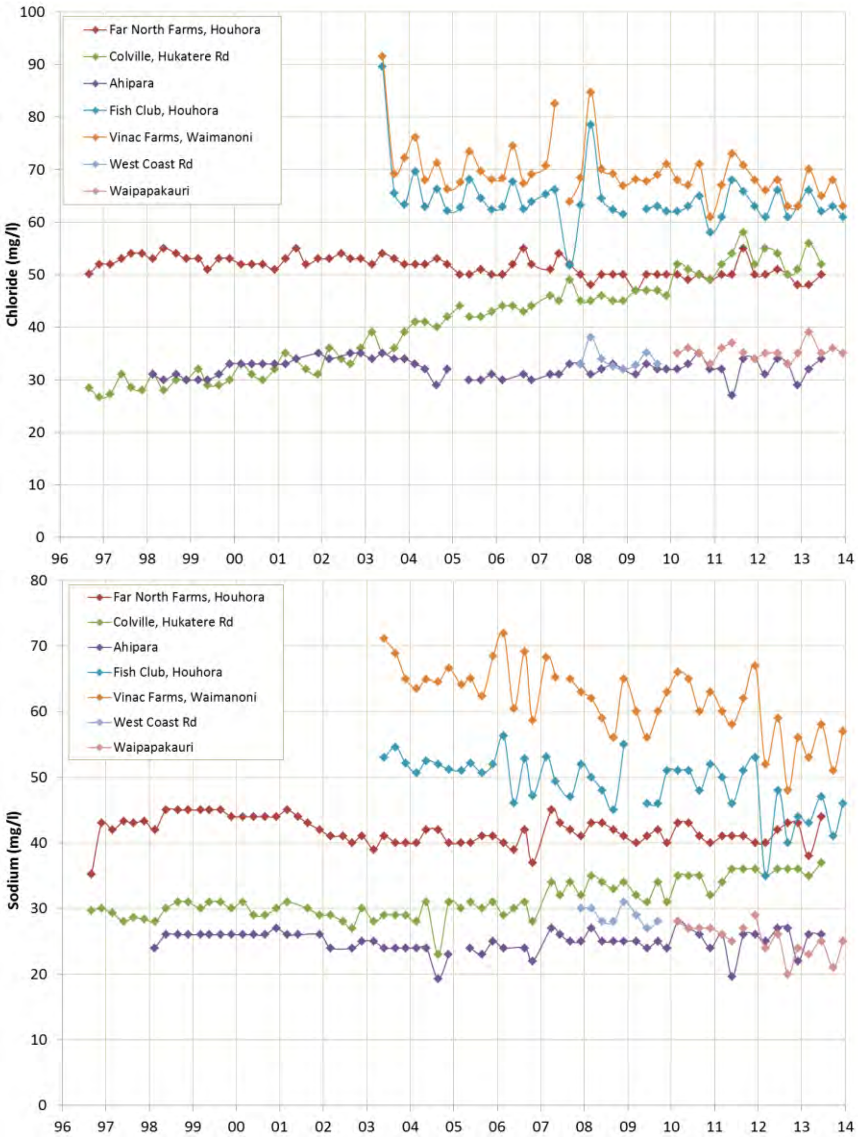


Figure 7 Time-series of chloride and sodium concentrations

Bores with higher concentrations are interpreted to represent greater mineral dissolution, and therefore represent older groundwater. The Vinac Farms and Houhora Fishing Club bores show the highest concentrations overall, and these sites show a slight decrease in both chloride and sodium over time. This suggests that younger, fresher water is being drawn into this bore in response to pumping. The nearby Waipapakauri Beach bore, which has been sampled since 2010 shows a stable response.

The Colville bore is the only site that shows an increase in chloride or sodium concentrations over time. There are a number of groundwater consents in this area, and the expected response in this bore is for decreasing concentrations over time as younger, fresher water is drawn down. The increase in concentrations in the Colville bore suggests the possibility that older water is being drawn in, perhaps from deeper sediments.

GROUNDWATER AGE

The mean residence time (MRT) of groundwater can be estimated using tritium, which is an unstable form or isotope of hydrogen. Unstable isotopes such as tritium change their atomic structure through time via radioactive decay. The decay rates for different radioactive isotopes are well known, and have been documented in numerous physics and chemistry textbooks. Tritium is a particularly useful isotope because it forms a part of the water molecule, and this enables the residence time for water to be determined.

Tritium is a radioactive form of hydrogen that has one proton and two neutrons, unlike the common form of hydrogen which has one proton and no neutrons. The decay of tritium to helium-3 has a half-life of 12.3 years and is naturally produced in the atmosphere by cosmic rays. Large amounts of tritium have released into the atmosphere by the testing of nuclear weapons since 1945. Concentrations peaked in 1965 due to the intensity of testing carried out in the early 1960's, and they are now close to background levels. A more detailed outline of the application of the tritium dating method to the NGMP is given in Morgenstern and Daughney (2012).

Table 3 shows the results of tritium analyses from the Aupouri Aquifer and the approximate elevation of the top of the bore screen relative to sea level. The analyses and interpretation have been made at the GNS isotope laboratory in Wellington. The results show consistently old MRT values of over 50 years, and four of the seven sites give values beyond the range of accurate tritium interpretation.

Table 3 Results of Aupouri Aquifer tritium analyses

Bore	Name	Screen top (m msl)	Groundwater level (m msl)	Lithology	Redox	Date	MRT (years)
210449	Long Bore, Ahipara	-28	?	Sand	Anox?	Apr-05	50
						Mar-09	52
						Dec-10	51
200059	Colville, Houhora	-28	?	Sand	Ox?	Apr-05	71
						Mar-09	53
						Dec-10	70
200211	Fitzwater, Paparore	-60	6.8	Shell bed	Ox	Apr-05	138
201563	Vinac Farms, Awanui	-31	12.7	Sand	Anox?	Jun-07	>200
209330	Waipapakauri Beach	-51	0.8	Sand/shell	Ox	Mar-12	>240
200250	Fish Club, Houhora	-68	1.4	Shell bed	Ox	Jun-13	>250
201025	Nursery, Sweetwater	-19	8.8	Alluvium	Anox	Jun-13	>250

The long mean residence times given by tritium analyses suggest that the aquifer is very sluggish, and may have very little shallow groundwater interaction under natural flow conditions at greater depths. The bores that were sampled have screen tops located below sea level, from 19m (Nursery) to 70m (Houhora Fish Club) and show upward flow gradients. The samples span a range of oxidation conditions, showing that even high quality oxidised water can be very old.

AUPOURI AQUIFER CONCEPTUAL MODEL

This section presents a conceptual model that is based on the observations made in the previous chapters.

At a regional scale the Aupouri Aquifer is best considered as a four-layer groundwater system:

1. **Unconfined dune sand and localised shallow water tables perched on peat beds**
   This upper layer is situated at or above sea level and groundwater is free to flow as gravity-driven drainage because of the high hydraulic conductivity of the sands and the ability to discharge to the coast. On a macro-scale, the sub-horizontal hydraulic conductivity is greater than vertical because of the presence of peat beds ($K_x>k_z$). This layer is the most dynamic part of the Aupouri Aquifer system.

2. **A widespread non-continuous aquitard of variable thickness situated approximately at sea level**
   The base of the unconfined layer is marked by a widespread Holocene peat, silt and clay horizon which is on average about 5-10 m thick. These sediments mark a low energy depositional environment that was established by the stabilisation of the sea at its present level about 6,500 years ago. The Waihuahua and 'Great Kaitaia' swamps are surface expressions of this horizon. Drillers' logs indicate that low permeability sediments at elevations similar to sea level are widely distributed beneath the dune sands.

3. **A confined-leaky sand interspersed with peat and clay and beds**
   This layer is situated below sea level and constitutes the bulk of the aquifer's storage. Sub-horizontal hydraulic conductivity is much greater than the vertical due to compaction, imbrication of particles, and the layering of silt, clay, and peat beds ($K_x>>k_z$). This anisotropy produces a groundwater system that can be highly stratified.

4. **Confined-leaky sand with high permeability shell beds**
   This is the deepest layer and is situated within the marine sands that overlie compacted Tertiary sediments. Sub-horizontal hydraulic conductivity is expected to be a little higher than the vertical due to compaction by the overlying sediments ($K_x>k_z$).

The groundwater system as a whole is referred to as the Aupouri Aquifer, but it is perhaps more accurate to think in terms of a stratified groundwater system, since sedimentary anisotropy and the localised peat bed aquitards play an important role in controlling groundwater flow paths and providing storage. A schematic profile through the groundwater system is shown in Figure 8.

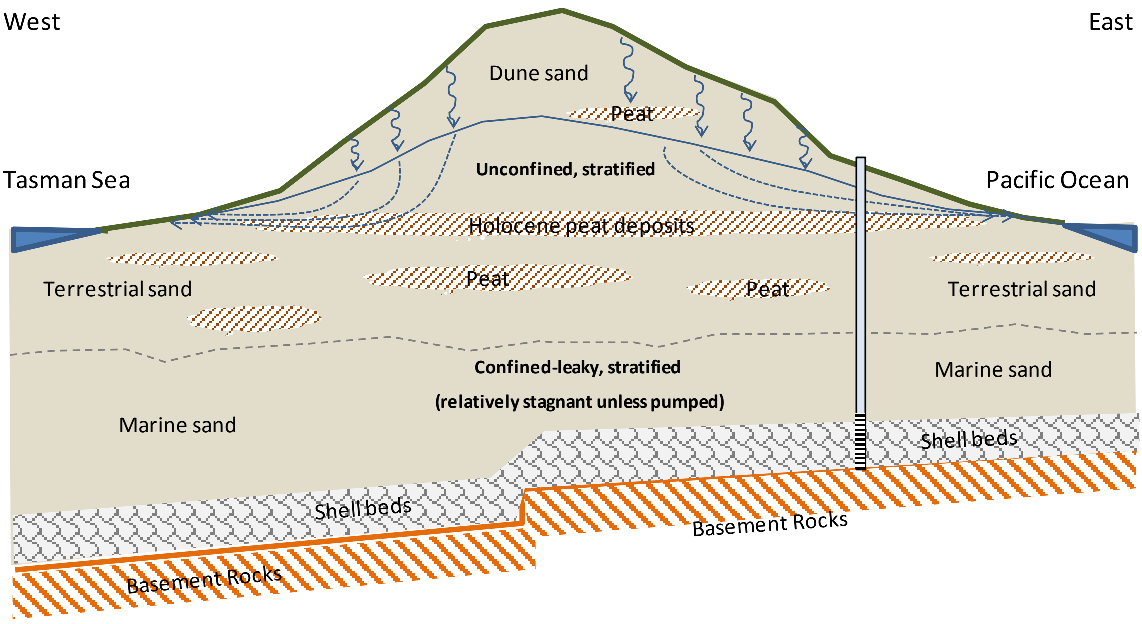


Figure 8 Schematic profile through the Aupouri Aquifer

THE UNCONFINED AQUIFER

Groundwater in the upper unconfined aquifer is recharged by rainfall and able to freely flow under gravity because it is situated above sea level. Localised perched water tables are found between sand dunes where rainfall recharge is impeded by isolated peat beds. Surface expressions of these localised water tables are the dune lakes. The underlying sands have a higher hydraulic conductivity and therefore a greater ability to drain. Most, if not all, of the dune lakes are expected to be perched above the regional water table.

The movement of groundwater in the unconfined aquifer is expected to be much greater in a lateral direction towards the coast than downwards into deeper parts of the system. The reason for this is the hydraulic anisotropy formed by the sand-wetland depositional sequence, together with imbrication and compaction of the sedimentary pile. The contrast between horizontal and vertical permeability favours a lateral groundwater movement, with drainage in the unconfined aquifer preferentially flowing towards the shoreline.

A particularly important geological horizon in the Aupouri Aquifer is the aquitard situated at sea level, which forms an important vertical hydraulic barrier over much of the Peninsula, particularly at Sweetwater. Flow above this aquitard is driven by the hydraulic gradient towards the sea, which sets the regional hydrological base level for the aquifer. The presence of low permeability sediments at sea level means that most of the recharge in the unconfined aquifer is preferentially forced out to sea rather than flowing downwards into the confined-leaky aquifer. Evidence of this discharge can be seen along Ninety Mile Beach at low tide. Ephemeral streams are also found along both coastlines, which act as a discharge mechanism when groundwater levels are high.

THE CONFINED-LEAKY SYSTEM

Flow in the confined-leaky groundwater system beneath sea level is most important to understand because this layer forms the bulk of the available storage within the aquifer, and is also the site of the most pumping.

Below sea level, flow potential is driven by the pressure of the overlying water column, including the unconfined aquifer. However, groundwater in the confined-leaky system also has a reduced ability to discharge upwards because of structural confinement by low permeability silt, clay and peat horizons. This reduced flow potential also applies to submarine discharge because of the way successive layers are draped over the gently-sloping sea floor. This is because passive coastal and marine sand deposition occurs by the successive mantling of newer sediments over older ones, and this process inherently forms a relatively low-permeability barrier between the Aupouri groundwater system and the sea.

The confined-leaky Aupouri Aquifer can be considered to be a discharge-driven system rather than a recharge-driven system. The reason for this emphasis is that groundwater recharge can only enter the deeper sediments if there is discharge to accommodate it. The rate of groundwater flow in its natural state is likely to be small because the low vertical permeability of overlying sediments limits the rate of aquifer discharge to the sea. The rate of groundwater flow in the confined-leaky system can be artificially and locally increased by discharge in the form of pumping, which induces groundwater downwards via leakage. The most influential aquifer property to understand is therefore its vertical leakage coefficient, since this regulates how the system responds to a change in pressure.

The preceding conceptual framework indicates that groundwater in the confined-leaky system will be quite old because anisotropy within the groundwater system results in a rapid decrease in natural flow velocity with depth. Tritium data supports this assumption. All of the available tritium data for the groundwater system is from bores with screens from 20 to 70m below sea level. Of these, the shallower bores have calculated mean residence times of 50 to 70 years, while residence times for deeper bores are beyond the range of tritium analysis (i.e. older than 100 years).

Special mention needs to be made of the function of the shellbed horizon at the base of the aquifer which many of the boreholes in the Aupouri system access. The shellbeds have a significantly higher overall hydraulic conductivity compared to the overlying sand sequence. However, the shellbeds are also a relatively thin layer, which limits the amount of storage available for pumping. Aquifer test responses show that the effect of pumping in this layer is to firstly draw on the highly permeable, porous shell bed sediments that surround the bore screen, since this water is most easily accessed. As pumping proceeds, the pressure in the shellbed layer drops, and additional water is progressively sourced from the overlying sandy sediments. In effect, the shell beds perform the role of a gallery, enabling the bore to access to a wider area of storage in the overlying leaky sands. Without the presence of the shellbeds, bore yields would be significantly lower and there would be more pronounced localised drawdown effects from pumping.

LAND SURFACE RECHARGE MODEL

There are three possible recharge sources to the Aupouri Aquifer: land surface recharge, peripheral aquifer boundary infiltration, and basement discharge. Volumetrically, recharge is expected to occur predominantly as land surface recharge. There may also be some additional infiltration along the edge of the hills that surround the sandy aquifer via the basement contact, and this could be a significant contribution at a local scale. For example, infiltration may occur as leakage from the Awanui River or Wainui Stream as they cross from a basement to a sandy substrate. Recharge to the Aupouri Aquifer may also occur as discharge from the basement rocks themselves, although this contribution is expected to be very small compared to the two potential surface water recharge sources because of the low permeability of the basement.

Of the three potential recharge sources there is only sufficient information available to estimate recharge over the land surface. The other two possible sources are assumed for the purpose of modelling to contribute negligible recharge to the aquifer, which is a conservative approach to an aquifer allocation assessment. However, we do recommend that surface-groundwater exchanges be characterised in the future by assessing groundwater responses in bore located close to the aquifer/bedrock boundary, and by conducting a series of concurrent flow gauging surveys on the main surface water bodies.

SOIL MOISTURE BALANCE MODEL

Land surface recharge was calculated using a daily soil moisture balance model, which has been modified from the Rushton model (Rushton *et al*., 2006; de Silva & Rushton 2007). This soil moisture balance model has been demonstrated to simulate lysimeter drainage rate data quite accurately in New Zealand if the soil hydraulic properties are known (Wilson & Lu, 2011).

A key assumption made in the recharge calculations is that water is able to freely drain from the soil profile into underlying permeable geology. An assumption is also made that recharge is not intercepted by artificial drainage before reaching the water table.

Spread-sheet calculations for soil moisture balance follow the algorithms provided in Rushton *et al.* (2006). The Rushton model consists of a two-stage process: calculation of near-surface storage and calculation of the moisture balance in the subsurface soil profile. The near-surface soil storage reservoir provides moisture to the soil profile once all the near-surface outputs have been accounted for. If there is no moisture deficit in the soil profile, recharge to groundwater occurs.

There are three steps to describe the soil moisture balance:

1. Calculation of infiltration to the soil zone (In), and near-surface soil storage for the end of the current day (SOILSTOR). Note that infiltration (In), as specified by the Rushton algorithms, is not just infiltration (rainfall-runoff), it also includes SOILSTOR from the previous day.
2. Estimation of actual evapotranspiration (AET). PET is derived by the Penman-Monteith equation (Allen *et al.*, 1998). For most of the peninsula, a crop coefficient is not applied since the crop is assumed to be pasture, which is the reference crop for the Penman-Monteith equation. Most pastures in New Zealand behave like the reference crop for most of the year (Scotter and Heng, 2003). The Aupouri peninsula also has extensive areas of forestry and native scrubland. Crop coefficients have been applied for different land uses by altering the profile readily available water value.
3. Calculation of soil moisture deficit and groundwater recharge. Recharge occurs only when the soil moisture deficit is negative, i.e. when there is surplus water in the soil moisture reservoir.

The three steps outlined above partition near-surface soil storage between near-surface soil storage for the following day, AET, and the soil moisture deficit/reservoir respectively. The Rushton model is usually started in winter when the initial soil moisture deficit can be safely assumed to be nil. This also allows a lead-in time for the model to give a satisfactory water balance for the following calendar year.

MODEL INPUTS

Rainfall and potential evapotranspiration (PET) data for the soil moisture balance model have been sourced from the NIWA Cliflo database. The virtual climate station data was used, which is available for Northland over an approximately 5km grid. In addition to rainfall and PET data, the soil moisture balance model requires input values for three soil hydraulic properties to calculate the daily water balance:

Profile Available Water (mm): PAW or TAW is calculated from field capacity, wilting point and rooting depth data. Typical values for field capacity and wilting point are given in Table 19 of Allen *et al.* (1998), and many values for New Zealand soils can be found in the literature (e.g. McLaren and Cameron, 1996). It is more difficult to determine appropriate values for rooting depth. Values quoted in the literature are usually for uninhibited root penetration. Some knowledge of the soil profile is required to estimate rooting depth, because root penetration at a particular site may be limited by the presence of a resistive layer such as a loess or clay pan. If rooting depth is not known, it may be estimated from the profile thickness for thicker soil units. However, because rooting depth is also a function of water capacity and soil aeration, some caution is needed in using profile thickness as a proxy.

Profile Readily Available Water (mm): PRAW or RAW is related to PAW by a depletion factor, *p*. The depletion factor is the average fraction of RAW that can be depleted from the root zone before moisture stress (Allen *et al.* 1998). For New Zealand conditions, *p* should be around 0.4 to 0.6, typically 0.5 for pasture.

Fracstor: This is the near-surface soil moisture retention. The contribution of Fracstor to the soil moisture balance is small, so errors resulting from estimations are considered to be negligible. Typical values are 0 for a coarse sandy soil, 0.4 for a sandy loam and 0.75 for a clay loam (Rushton, 2006, p. 388). Appropriate values can be estimated from field observations (de Silva and Rushton, 2007). If the soil dries quickly, then Fracstor will be less than 0.3. If the soil surface remains wet after heavy rainfall, so that it is not possible to work the soil for several days, then Fracstor is likely to be in the range 0.6–0.8.

Modal values for PAW and PRAW were taken from the Landcare Research FSL New Zealand Soil Classification database. Values for Fracstor were estimated based on the soil textural descriptions in this database.

MODIFICATIONS

Some modifications have been made to the Rushton model to account for runoff, avocado irrigation, and forestry harvest and growth cycle.

RUNOFF

The Rushton model has been adapted for this report to incorporate runoff, which is removed from the soil moisture balance. This was calculated using the US Department of Agriculture, Soil Conservation Service (SCS) runoff curve number model (SCS, 1972). The SCS runoff model is a commonly adopted empirical method for predicting direct runoff or infiltration from excess rainfall (Ward & Elliot, 1995), and is comprehensively described in Rawls *et al.* (1992).

The SCS runoff method involves an attribution of a hydrological soil group for each soil (A to D). Soil group data for Northland soils are available from the Landcare S-Map database. A curve number is then estimated for each soil based on its hydrological soil group, which is used to calculate maximum soil retention for the calculation of runoff. Lower curve numbers give more water soil retention, and therefore less runoff. Pasture in good condition on free-draining soil has a low curve number, whereas pasture in poor condition on a poorly drained soil has a high curve number. A list of curve numbers for different soil conditions and land covers is given in Table 5.5.1 of Rawls *et al.* (1992). Curve numbers have also been adjusted within the soil moisture balance model to account for wet or dry antecedent conditions using the method of Ward and Elliot (1995).

IRRIGATION

Irrigation increases land surface recharge because it artificially raises the soil moisture content of the soil. This means that when rain occurs, more of that rain can potentially be drained through the soil profile.

Irrigation is estimated in the soil moisture balance model according to the antecedent soil conditions. This demand-driven approach assumes that irrigators are fully efficient, and apply a pre-defined depth of water when the soil moisture falls below a certain point during the irrigation season. A pre-defined depth is used because it is assumed that the amount of water applied is usually constrained by a combination of the consent conditions and the infrastructure on the orchard. The consent details for irrigation of avocados indicate that a daily demand of 3 mm is a representative value for Northland.

Irrigation is accommodated in the soil moisture balance model with an application of 3 mm when the soil moisture at the end of the previous day reaches 85% of the TAW during December to April. Running the soil moisture balance model for these constraints gives comparable results to those provided by NRC's SPASMO calculator (Green, 2010).

FORESTRY

Forestry is expected to reduce the amount of recharge to the Aupouri Aquifer. Approximately 40% of the aquifer area is covered in exotic forestry, so there is the potential for forestry to have a significant impact of the aquifer water balance. Unfortunately there have been few studies on the affect that pine forests have on groundwater recharge. The few studies that have been undertaken have applied quite different approaches because of the difficulty measuring observations (see Rowe *et al.* 2002).

There are a number of ways that forestry reduces recharge, the main factors being interception by the forest canopy, and increased evapotranspiration. The approach we have taken is to simply remove a fixed depth of each rainfall event. Previous studies have indicated that approximately the first 2 mm of rainfall is intercepted by a full forestry canopy (Rowe *et al.* 2002).

To account for the forestry growth cycle we have included a canopy factor within the soil moisture balance. This provides a linear change in canopy interception from the time of planting (no interception), to the development of a full forestry canopy after eight years of growth (2mm of interception). Forestry was given a thirty year growth cycle from planting to harvesting if the year of planting was known. The year of planting was only available for forestry blocks located within the Aupouri Forest. Forestry located outside of this area has been assumed to have a full canopy.

For consistency, a full canopy adjustment of 1.5 was also applied to indigenous forest and scrub, and avocado orchards were given an adjustment of 0.5. No interception loss has been assumed for pasture.

LAND SURFACE RECHARGE MODEL RESULTS

Annual rainfall over the Aupouri Aquifer from 1987 to 2013 varies from 580 to 1,670 mm in a calendar year (average 1,280 mm). Figure 9 shows the results of the soil moisture balance model, which predicts recharge values of 160 to 840 mm per year (average 500 mm). In terms of volume, this is an annual average of 374.2 million m^3/year for the whole aquifer, which is equivalent to 4,968 m^3/ha/year.

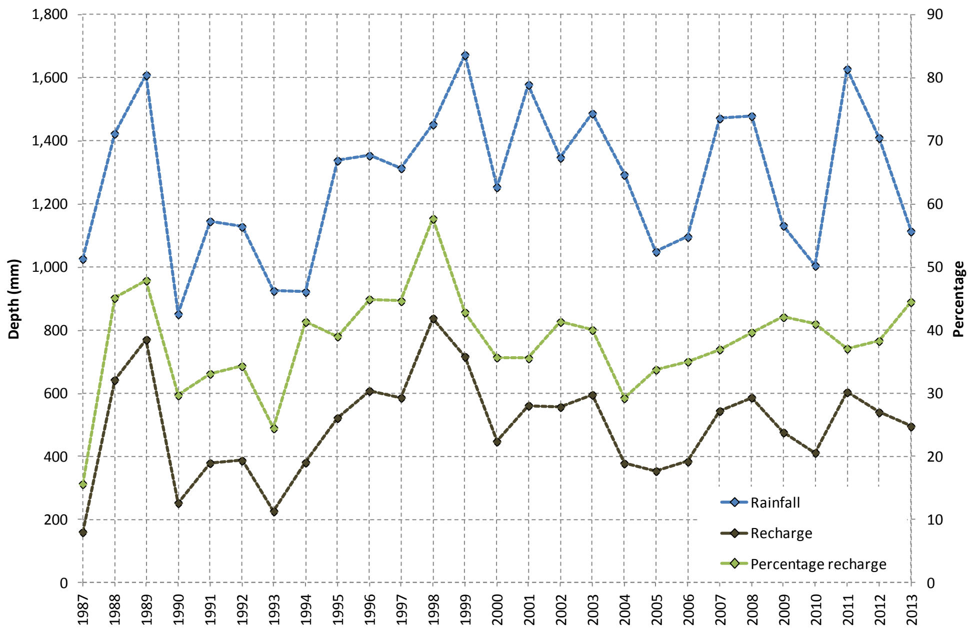


Figure 9 Annual rainfall and recharge results for the soil moisture balance model

On average 38%, of annual rainfall is infiltrated, which is high for New Zealand. Recharge is a high percentage of rainfall because of the light nature of the soils associated with sand deposits. A comparable recharge rate was reported by SKM (2007), who calculated a recharge rate in dune sand of 44% of mean annual rainfall using a soil moisture balance. The Rushton model gives an annual recharge rate around 540 mm for the dune sand beneath Aupori Forest, which is 43% of annual rainfall. The wetland areas, like Kaitaia Swamp, have a potential recharge of around 30%, although the actual recharge rate is likely to be somewhat less because of near-surface drainage.

About 21% of the area has a PAW less than 60 mm, and nearly 90% has a PAW of 75 mm or less. Heavier soils with a moderate to high PAW have a higher water holding capacity, but they also have larger moisture deficits in the summer because they are subject to more evapotranspiration (lighter soils have a limited water reserve). These factors result in much larger recharge rates over lighter soils compared to heavier soils. Consequently, the largest recharge rates are predicted to occur on the sand dunes, despite the presence of the forest plantations.

Figure 9 shows that the lowest estimate of annual recharge (16%) occurred in 1987, and the highest (58%) occurred in 1998. It is interesting that these years do not coincide with the years of lowest and highest rainfall. This illustrates that it is the timing and intensity of the events, rather than the annual amount that determine the amount of annual recharge.

Figure 10 shows the average monthly values for rainfall and recharge. Northland has a relatively high annual rainfall total for New Zealand, and it can be seen that the majority of this rainfall occurs during the winter months when PET values are low. The calculation of recharge follows a bell-shaped curve throughout the year with a peak occurring in June-July, and very little recharge occurring during summer.

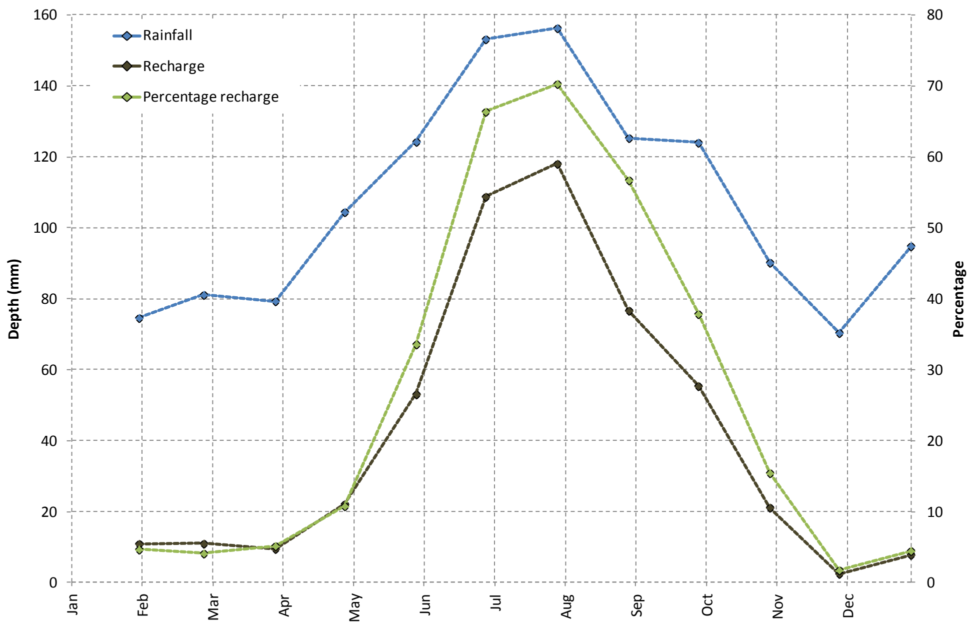


Figure 10 Average monthly variation in rainfall and recharge for the soil moisture balance model

VALIDATION OF THE SOIL MOISTURE BALANCE MODEL

The recharge values calculated by the soil moisture balance model were compared with estimates of recharge from groundwater level fluctuations. The groundwater level fluctuation method we have applied is outlined in Cuthbert (2010). Recharge is calculated from the change in water level over time, the specific yield, and an aquifer drainage term. The aquifer drainage term is a function of the distance to the aquifer boundaries and the hydraulic conductivity.

The Cuthbert method was applied to the two most responsive monitoring records in the unconfined aquifer, Browne (200208), Burnage (200209). These two sites have a relatively shallow water table (8 and 7m respectively) and are outside of the forestry plantation. These two characteristics mean that these sites are less affected by water retention in the unsaturated zone, which appears to make other sites in the aquifer less responsive to individual recharge events.

The aquifer dimensions were determined for the two sites by estimating the distance to the groundwater divide and the sea. An estimate of the specific yield needs to be made because there are no suitable aquifer test results available for the shallow sands. Johnson (1967) reported average specific yield values of 0.28 to 0.32 for fine and medium sands respectively. Domenico and Schwartz (1998) note that dune sand could have a higher value of 0.35, presumably because of its better sorting. A value of 0.3 has been used for application in the Cuthbert solution, and this value gives the best comparison overall with results from the soil moisture balance model.

Resolution of the Cuthbert solution does rely on knowledge of the aquifer transmissivity, and this is the value for which we have the least information. An aquifer test result undertaken at a deeper screen depth at Browne gave a transmissivity result of 400 m^2/d (Table 2). If this value is applied to the Cuthbert solution, we do get a close match with the soil moisture balance results (Figure 11). The results show that the soil moisture balance model estimates 70 mm more recharge than the Cuthbert method over a 27 year period, a 14% error. The error can be reduced by estimating the transmissivity value that gives the lowest sum of squares error between the two models (on the assumption that transmissivity is the parameter of least confidence). The optimised transmissivity estimate for Browne is 460 m^2/d for Browne, which reduces the discrepancy between models to 4%.

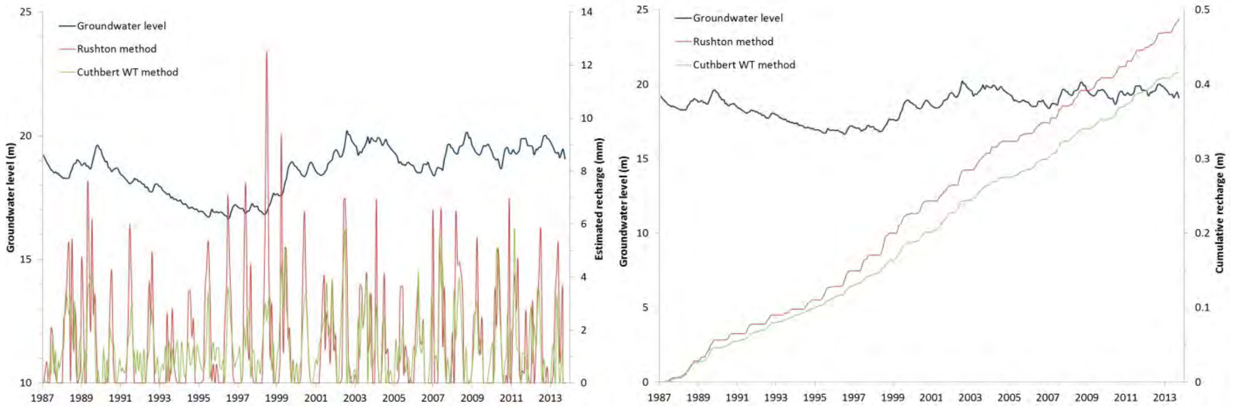


Figure 11 Land surface recharge validation at Browne

Figure 12 shows the results for recharge modelling at Burnage. In this case the soil moisture balance model underestimates recharge by 56mm over 27 years, a 12% error. The optimised transmissivity estimate for Burnage is 280 m^2/d, which reduces the discrepancy between the two models to 11%. The error at Burnage can be reduced further to just 1% by lowering the specific yield to 0.15, although there is little information to support the attribution of a different storage coefficient between the two sites.

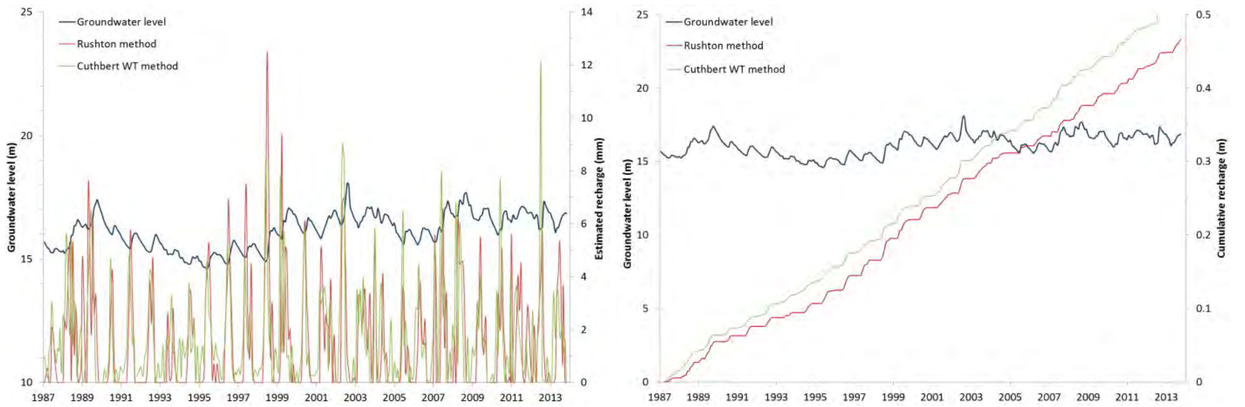


Figure 12 Land surface recharge validation at Burnage

In general, the validation has shown that the two models give comparable results over a long period of modelling. Both of the monitoring records are affected by pumping in later years, which can explain much of the error between the two models. Another source of error is the temporal resolution of groundwater level observations, since monthly measurements will miss many of the smaller recharge events that are calculated by the soil moisture balance model.

In conclusion, the validation exercise is limited by a paucity of suitable shallow groundwater level monitoring sites to use as "lysimeters", together with a lack of transmissivity and storage coefficient observations. The soil moisture balance approach is favoured over the groundwater level fluctuation method because there is better knowledge of hydraulic properties for use in the model, particularly their spatial variability. It is recommended that NRC carry out a program of soil moisture or lysimeter monitoring in the predominant sandy soil units. This information would greatly assist the validation of land surface recharge estimations.

NUMERICAL GROUNDWATER MODEL

MODEL STRUCTURE

Our approach to the modelling process has been to start with a simple model and increase complexity as required. A Modflow2005 (Harbaugh, 2005) model was constructed in Groundwater Vistas 6.68 with three layers to represent the four-layered system identified in the conceptual model. The three layers are as follows:

1. Unconfined, mostly sandy aquifer (Layer Type 3 - Unconfined (T Varies)
2. Leaky confined sandy aquifer situated below sea level (Layer Type 0 - Confined)
3. The more permeable shell-rich horizon at the aquifer base (Layer Type 0 - Confined)

The elevation of the ground surface was taken from the NZSoSDEM v1.0, digital elevation model which has a 15 m spatial resolution. Intercepts for the bottom of each layer were identified in bore logs and subtracted from this DEM. These values were then interpolated to generate surfaces for importing into MODFLOW. The underlying basement rocks were assumed to be impermeable and therefore the base of the model represents the basement unconformity.

The structure of the model domain is shown graphically in Appendix 3. The model finite difference grid consists of 75 rows and 60 columns, with 4,755 active cells in the three layers (no-flow cells are greyed out). Grid spacing ranges from 500 m to 2,250 m, with the majority of the domain being 1km or less. The finer spacing is centred on clusters of pumping wells, and also the NRC monitoring bores (labelled), whereas the coarser spacing is situated north of Te Kao where there is little information on the aquifer. Modflow calculates groundwater levels for each cell based on the levels in neighbouring cells, so the grid resolution can affect the accuracy of the model's simulations. We consider the selected grid spacing to be a good balance between the regional scale of the model, the level of detail available for the aquifer, and computational limitations for transient modelling.

Pumping wells and observation targets were included in the model as analytic elements. Constant head boundaries (light blue squares in Appendix 3) were set around the coast in layer 1 to represent sea level. No-flow cells have been added to represent pre-Quaternary basement rocks, and have also been set offshore outside of the influence of constant head cells. Drain boundaries (dark blue) were added to remove water in wetland areas and to represent streams. Levels for the drains were set at a nominal metre depth below the DEM, and were given a high bed conductance value. Because there is little information available on these surface waterways, they were not optimised during the calibration process. Instead, vertical flows are constrained by vertical hydraulic conductivity (Kz) values. Similarly, leakage from leaky artesian bores is considered to be catered for by Kz values.

An assumption made in our modelling is that the recharge rate as calculated by the Rushton model is considered to be correct. We have not included recharge as a parameter for optimisation.

STEADY STATE CALIBRATION

The PEST routine with singular value decomposition (SVD) (Doherty and Randall, 2010) was used to automate the model calibration process. Initial calibration runs were focussed on optimising preliminary horizontal (Kx) and vertical (Kz) hydraulic conductivity values. The purpose of this optimisation was to characterise the overall vertical anisotropy of each layer caused by the clay and peat aquitards, and to generate preliminary initial heads for the transient calibration. This was done in two phases:

1. Mean water levels from 18 NRC monitoring bores were used for were used for steady state targets. Static water levels from an additional 60 bores were used to guide conductivity values in regions of the model where no monitoring data were available. These targets were given a weighting of half that given to the monitoring sites.
   Constant values of Kx and Kz were used for each layer. Under this model structure, Kx is highly correlated to its corresponding Kz value for layers 2 and 3, and the objective function is most sensitive to Kx_2, Kz_2,

and Kx_3. This preliminary model run produced significant scatter in the calculated residuals, with a sum of squares error of 1,050 m, and a residual mean of 0.4 m. The largest residuals in the monitoring bores were from layer 3. It is clear from this preliminary model run that assuming constant Kx and Kz values is inadequate for simulating the observed groundwater levels, and that a variable hydraulic conductivity field is required to fit the modelled heads to the observations.

2. Complexity was included in the model by adding prior information and regularisation with pilot points. Kx and Kz targets were added to incorporate the revised aquifer test analyses. Pilot points for Kx were added to all three layers on a grid to generate a hydraulic conductivity field. Similarly, pilot points for Kz were added to layers 1 and 2, which were expected to be the layers most sensitive to vertical conductance.

TRANSIENT CALIBRATION

The preliminary steady state head and hydraulic conductivity distributions were used to establish the initial condition for transient model calibration. The transient numerical model was set up to cover the 27 year period of available groundwater level records, from January 1987 to December 2013.

Monthly stress periods were used to provide a good balance between temporal resolution and computational demands. Monthly stress periods do result in convergence issues within the model because of large changes in flux. To improve convergence the stress periods were divided into three time steps with a multiplier of 1.3 to improve stability and provide a good mass balance. This produces model outputs for the 1st, 8th and 18th of each month. Some difficulty was found establishing a suitable initial head distribution for the transient model, so the first year of the simulation is considered to give a lead in time for the model to reach equilibrium.

All of the available time series data were used for transient calibration. The approach taken has been to use all of the available data for PEST, which is a stochastic approach to modelling. It therefore makes more sense to use the entire dataset rather than split the data into calibration and validation datasets. SVD-assist was used to streamline the parameter optimisation process.

UNSATURATED FLOW

During transient calibration it was found that water levels could not be adequately simulated with saturated flow properties alone. Water level response to recharge is both delayed, and attenuated beneath the Holocene sand dunes, which suggests that the unsaturated zone is buffering the effect that land surface recharge has on groundwater levels.

To accommodate the effect of the unsaturated zone on mediating recharge, the UZF-1 package (Niswonger *et al.*, 2006) was employed within Modflow2005. The use of the UZF-1 package does mean that some recharge is lost from the unsaturated zone to shallow drainage and does not reach the aquifer water table. A comparison between the calibrated numerical model with the input recharge rates showed that average annual recharge was reduced by approximately one third in the UZF-1 package.

The spatial distribution of zones for unsaturated properties and also the specific yield of layer 1 were based on the main Quaternary units as shown on the Kaitaia Q-map sheet (Isaac, 1996).

Vertical hydraulic conductivity in the unsaturated zone was given the same value as that of the top saturated layer (Kz1), which enabled a partial incorporation of the unsaturated zone properties into PEST. The remaining parameters for the unsaturated zone were given properties suitable for the main surficial deposits, and altered on a trial and error basis. Table 4 shows the parameter values that were considered to give the best response in the model.

The Brooks-Corey exponent characterises pore-size distribution of the sediments. Typical values for sand are 3.5 to 4, and values are higher for fine-grained and more heterogeneous sediments. Evapotranspiration was only used in the soil moisture balance model, so a soil extinction depth was not required as an input for the UZF-1 package. Additional options used were an undulation depth of 2m and total of 10 trailing-wave and trailing-wave sets.

Table 4 Unsaturated zone properties used in the model

	Zone	Residual water content (ϑr)	Brooks-Corey exponent (ε)	Specific Yield
Loose dune sands	1	0.08	4	0.33
Consolidated dune sands	2	0.1	4.5	0.23
Clay and peat wetlands	3	0.25	6	0.001

CALIBRATION RESULTS

The model calibration results for the whole domain have a residual mean and absolute residual mean of 0.02m and 0.41m respectively, with a standard deviation of 0.54m. The model error could be improved with further parameter optimisation runs. However, a PEST optimisation run on the model's hydraulic conductivity values takes approximately one week to perform, so a balance has been made between model performance and timely reporting.

No groundwater model can perfectly predict water table responses, which results in a predictive error at any point in the model. For this reason, a margin of error is required to act as a safety buffer for any model scenario testing. Table 5 shows the predictive error at each site that was used as a target for model calibration. The standard deviations tend to be greater close to the flow divide, and decrease towards the coast. We suggest that the standard deviation of the predictive error would be a good safety margin for the prediction of water levels during scenario testing. For predictions at coastal locations where no observation data are available, 0.5m would be an appropriate, albeit conservative safety margin.

Table 5 Summary of the model predictive error for each site

Monitoring Site		Model Site		Predictive Error				
Bore Number	Bore	Target Name	Layer	Mean	Std Dev	Min	Max	SSE
200206	Hukatere 3	P4_Hukatere	1	-0.06	0.41	-1.07	0.95	17.2
200206	Hukatere 2	P13_Hukatere	2	0.06	0.35	-0.82	0.80	12.6
200207	Forest 3	P3_Forest	1	0.06	0.47	-0.72	1.55	22.8
200207	Forest 1-2	P11_Forest	2	0.11	0.33	-0.50	0.96	12.6
200208	Browne 3	P1_Browne	1	0.02	0.42	-0.63	1.61	17.8
200208	Browne 2	P9_Browne	2	0.05	0.29	-0.70	0.71	8.8
200208	Browne 1	P8_Browne	3	0.12	0.66	-1.62	1.90	45.3
200209	Burnage 4	P2_Burnage	1	0.01	0.37	-0.71	1.12	13.7
200209	Burnage 1-3	P10_Burnage	3	0.05	0.39	-0.97	1.24	16.3
200210	Waterfront 1	P17_Waterfront	3	-0.01	0.32	-0.81	0.68	10.6
200211	Paparore 3	P7_Paparore	2	-0.36	0.36	-1.17	0.70	27.0
200211	Paparore 1-2	P16_Paparore	3	0.35	0.69	-0.82	2.23	59.8
200214	Golf Ball	P18_Golf Ball	1	1.08	0.38	0.37	1.98	23.6
200226	Lake Heather P1-1	P5_Heather	1	0.22	0.73	-0.91	2.33	59.6
200227	Lake Heather P1-3	P6_Heather	3	-0.70	0.63	-2.08	0.67	87.1
201025	Sweetwater Nursery	P14_Nursery	2	-0.01	0.79	-1.15	3.27	118.8
201037	Crene	P12_Crene	3	0.23	0.49	-1.38	1.39	15.7
209581	Ogle Drive	P15_Ogle	1	-0.79	0.34	-1.41	-0.07	22.0

Plots of observed and predicted water levels are shown in Appendix 4, and the calculated water levels at August 2003 are shown in Appendix 3 for each layer. This date was chosen to be drawn because the predictive error is negligible for this date and groundwater levels were quite high so we can see more spatial definition. The dynamics of most sites has been captured quite well by the model, although there are obvious exceptions at the Lake Heather and Forest sites. The deep Burnage piezometers (1-3) did also not calibrate well, although as previously mentioned it is possible that this bore is leaky and is not providing true head measurements in the deeper piezometers.

The numerical model is constructed as a regional scale model. Because of its scale and the coarseness of the grid, the model is not expected to exactly simulate local changes in groundwater levels, but is intended to simulate the flow field as a whole. However, despite its scale, the calibrated model does characterise the dynamics of the system quite well. In particular, very good model fits are found in the northern well array at Houhora.

Poorer fits are found further south at the Paparore and Lake Heather sites, and to a large extent these misfits are caused by the use of uniform storage coefficients to represent the main geological units. In the case of Paparore, uncertainty in the storage coefficient may be compounded by an overestimation of the pumping demand in this area. In the case of Lake Heather, the model has difficulty simulating the dynamics of the long-term drainage and recharge response, particularly the observed lag time in the recharge response.

Scrutiny of the observed shallow groundwater levels shows that there is a diverse range of responses to recharge, indicating that shallow vertical flow can be quite variable at a local scale. It has been difficult to simulate this variability consistently for every site with the unsaturated flow package, which requires zones of constant value to be set for residual water content and the Brooks-Corey exponent. There appears to be more variability within the shallow sands than can be accounted for by the three zones that were used for the model UFZ-1 package.

The model is suitable for its intended purpose of assessing the impact of the current allocation at a regional scale, and the setting of provisional management limits within proposed allocation zones. The model does not have sufficient detail to enable an assessment of the impact of individual abstractions, or to derive more refined allocation limits for specific zones. We recommend that individual zones be reviewed in the future if the demand approaches the provisional groundwater management limits. This can be done with more detailed modelling of the zone in question, perhaps by telescopic mesh refinement and by extracting boundary conditions from the regional scale model.

Areas where the model is less reliable are on the periphery, where there is inadequate data to constrain the aquifer structure, groundwater levels, and hydraulic properties. These areas are north of Houhora, and in the southern Awanui and Ahipara areas. Further field investigations are required to better constrain the model in these areas.

OPTIMISED AQUIFER PROPERTIES

In addition to the specific yield values for layer 1 shown in Table 4, uniform storage coefficients were applied to layers 2 and 3. The specific storage for layer 2 (leaky-confined sand) was optimised to a value of 0.0005. This value is consistent with values observed in deeper aquifer tests. The storage coefficient was not found to be very sensitive in layer 3 (shellbeds). This is consistent with our conceptual model, which predicts that most of the storage from pumping is derived from the overlying sands. Layer 3 was given a storage coefficient of 0.0007 to ensure consistency with layer 2.

Hydraulic conductivity values changed significantly from their steady state values during transient calibration due to the influence of the UZF-1 package. As previously mentioned, hydraulic conductivity values were optimised as a hydraulic conductivity field using PEST with pilot points. Pilot point bounds were given a large range so as not to overly constrain the parameter optimisation, and to incorporate the effects of heterogeneity.

A cumulative percentage of optimised hydraulic conductivity values are shown in Figure 13. The resulting curves portray what we would expect for the proposed conceptual model. Vertical hydraulic conductivity values have a much larger spread than the horizontal, and values in the deeper sandy sediments (layer 2) are the most consistent (the smallest range). Values in the shellbed horizon are considerably larger overall, as we would expect for the main productive sediments in the aquifer. The extreme values have tended to settle on hydraulic conductivities set by the pilot point bounds. However, the mean values are very similar to values determined by aquifer tests (Table 2), with an overall anisotropy ratio of about 10:1.

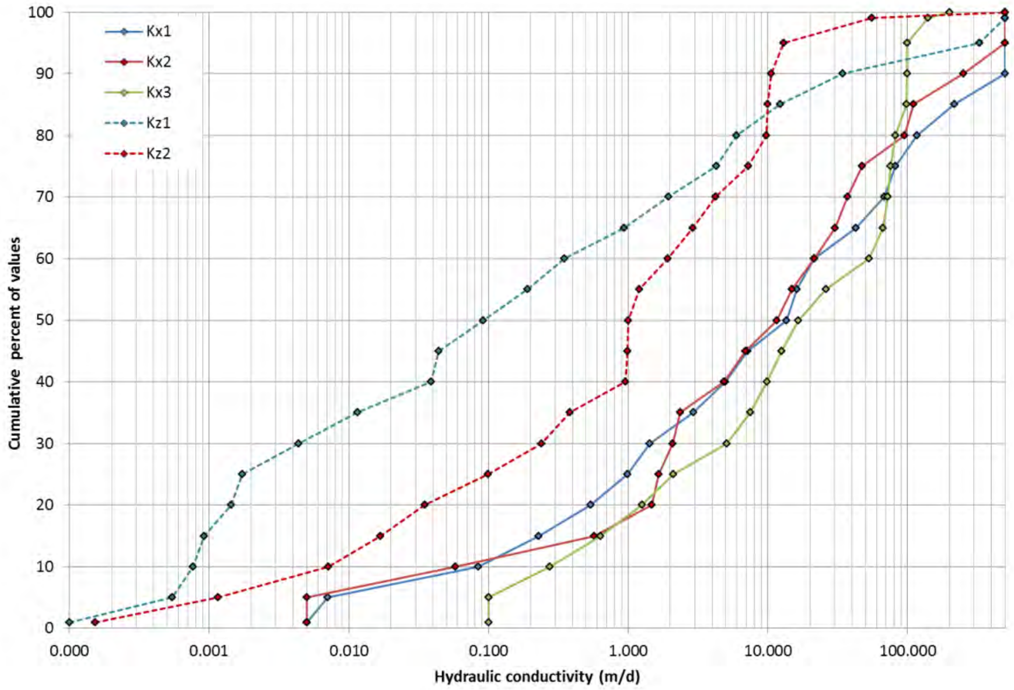


Figure 13 Cumulative percentage frequency plot of optimised hydraulic conductivity values

PARAMETER SENSITIVITY

Parameter sensitivity forms a part of the PEST optimisation routine, so the sensitivity of each parameter can easily be drawn from the PEST output file. This was done in two phases, one PEST run to determine values from the variable hydraulic conductivity fields, and a second run to determine sensitivities of the uniform values attributed to storage coefficients.

Figure 14 shows the sensitivity distribution for the optimised parameter values. The model is most sensitive to the specific yield of the dune and cemented sands of layer 1. The model is fairly insensitive to the specific yield of the unconfined clay sediments, and also the storage coefficients of the confined system. Surprisingly the model is more sensitive to horizontal hydraulic conductivity in the shellbed layer, and is less sensitive to the vertical hydraulic conductivities.

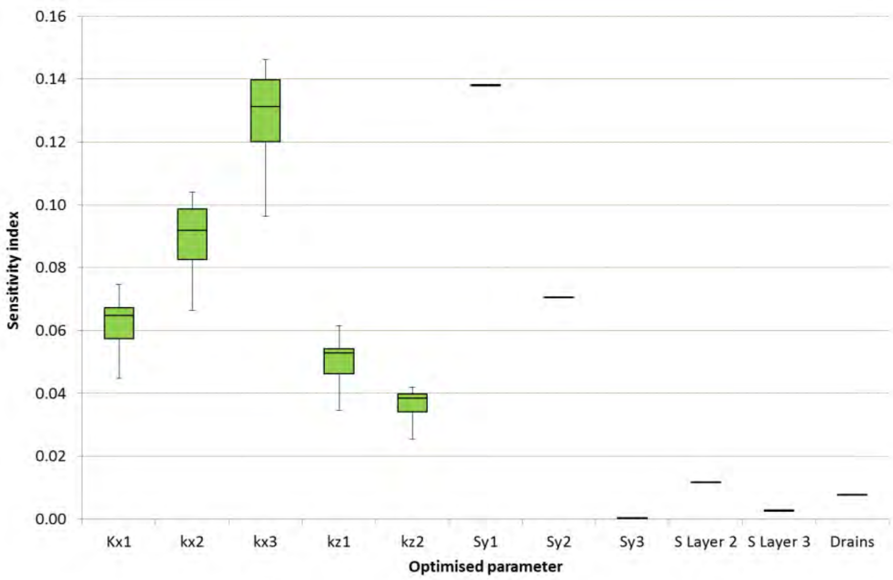


Figure 14 Optimised parameter sensitivity for the calibrated model

MODEL MASS BALANCE

The transient mass balance predicted by the numerical model is shown in Figure 15. Because the mass balance in Figure 15 is for the entire Aupouri Aquifer it deals with very large values, so the fluxes are expressed in units of million m^3/day (Mm^3/d). The annual average land surface recharge to the water table for the whole model domain is 262 Mm^3, while the annual pumping volume is 8.67 Mm^3, which is 3.3% of total recharge.

The mass balance is overwhelmingly dominated by land surface recharge, changes in aquifer storage, and offshore discharge. The pumping component is minor, although this does not preclude that it may be a significant component of the mass balance at a local scale. The model error is very small for each time-step, the largest error being 0.02% of the total inflow.

During dry periods the aquifer relies on aquifer storage and delayed recharge to supply well abstraction demand and maintain coastal discharge. The response to the prolonged dry period during the 1990s is particularly evident in the modelled land surface recharge predictions. This dry period resulted in markedly less offshore discharge than at other times.

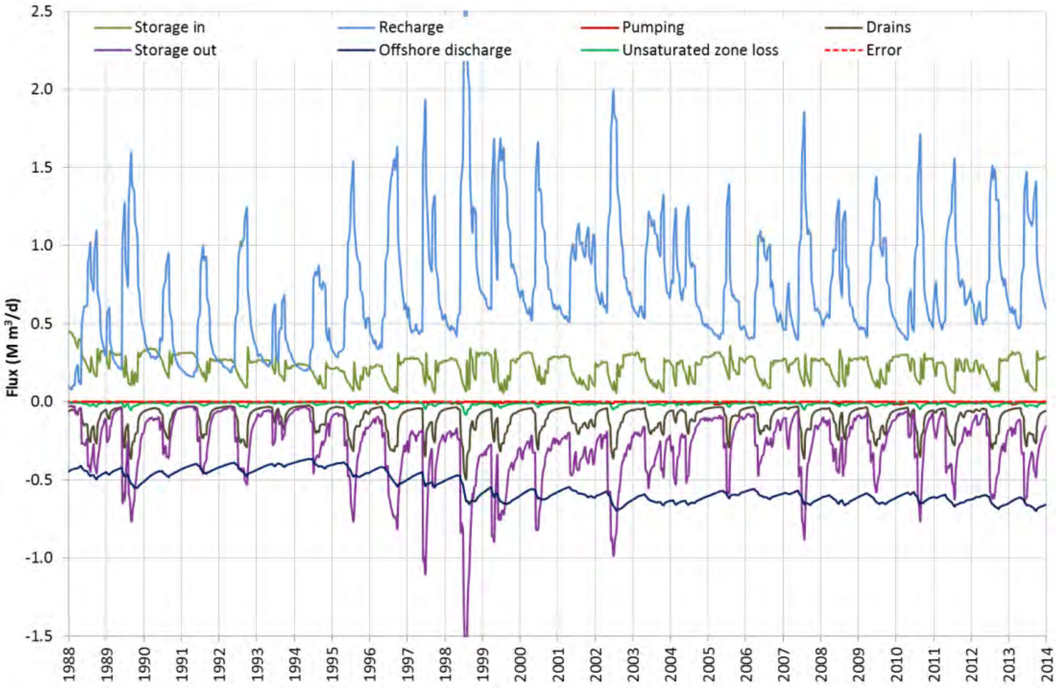


Figure 15 Daily Mass-balance of the Aupouri Aquifer as calculated by the numerical model (Mm^3/day)

PREDICTIVE SCENARIOS

A number of predictive scenarios were agreed upon in the scope and nature of services for this project. Some of these can be addressed in a quantitative manner by using the numerical model for scenario testing. Other environmental concerns can only be addressed qualitatively at this stage because data is not available for an adequate quantitative assessment to be made.

AQUIFER SUB-REGIONS

This section assesses the effect of the distribution of existing groundwater allocation on the freshwater resource. The aquifer has been divided into allocation sub-zones to assist in accounting. A number of factors were considered in developing these aquifer sub-region zone boundaries, including:

- Confined aquifer flow divide as calculated by the numerical model
- Cross-boundary flows between zones
- Location of existing coastal monitoring sites (Houhora and Waipapakauri Beach)
- Location of proposed coastal monitoring sites
- Clustering of groundwater consents
- Clustering of coastal domestic bores
- Locations of dunes and wetlands (local surface flow divides)
- Presence of forest or native scrubland (areas of little potential groundwater demand)

The existing distribution of groundwater consents shows that they tend to be clustered in a number of distinct zones. Figure 16 is a map showing the locations of existing consents, the existing monitoring network, as well as the recommended sub-regions and coastal monitoring sites used for scenario testing in the numerical model. The recommended zones have been placed into the numerical model for the purpose of calculating the approximate mass balance within each zone.

A monitoring threshold has been placed within each sub-region or zone for the purpose of observing drawdown at the coast during scenario-testing. It is recommended that these monitoring positions and thresholds be adopted for management and monitoring of the effects of pumping on the aquifer.

Proposed monitoring sites have been located where potential movement of the seawater interface may cause problems. For example, in the Houhora area there is a concentrated cluster of groundwater consents, mostly for the irrigation of avocados. This area of high groundwater demand is located up-gradient of the coastal Houhora community, which relies on groundwater for its drinking water supplies. It is important in this area that the allocation of groundwater consents does not induce saline water inwards towards these coastal water supplies.

The current NRC monitoring network as outlined in Table 6 shows that four of the nine groundwater zones have an NRC monitoring bore of some kind. This network could be greatly improved upon, since water quality samples are only taken on a quarterly basis. The installation of conductivity sensors in areas of high pumping demand would provide considerably more information about changes in salinity. Water levels could also be measured in water quality monitoring sites prior to sampling where this is possible.

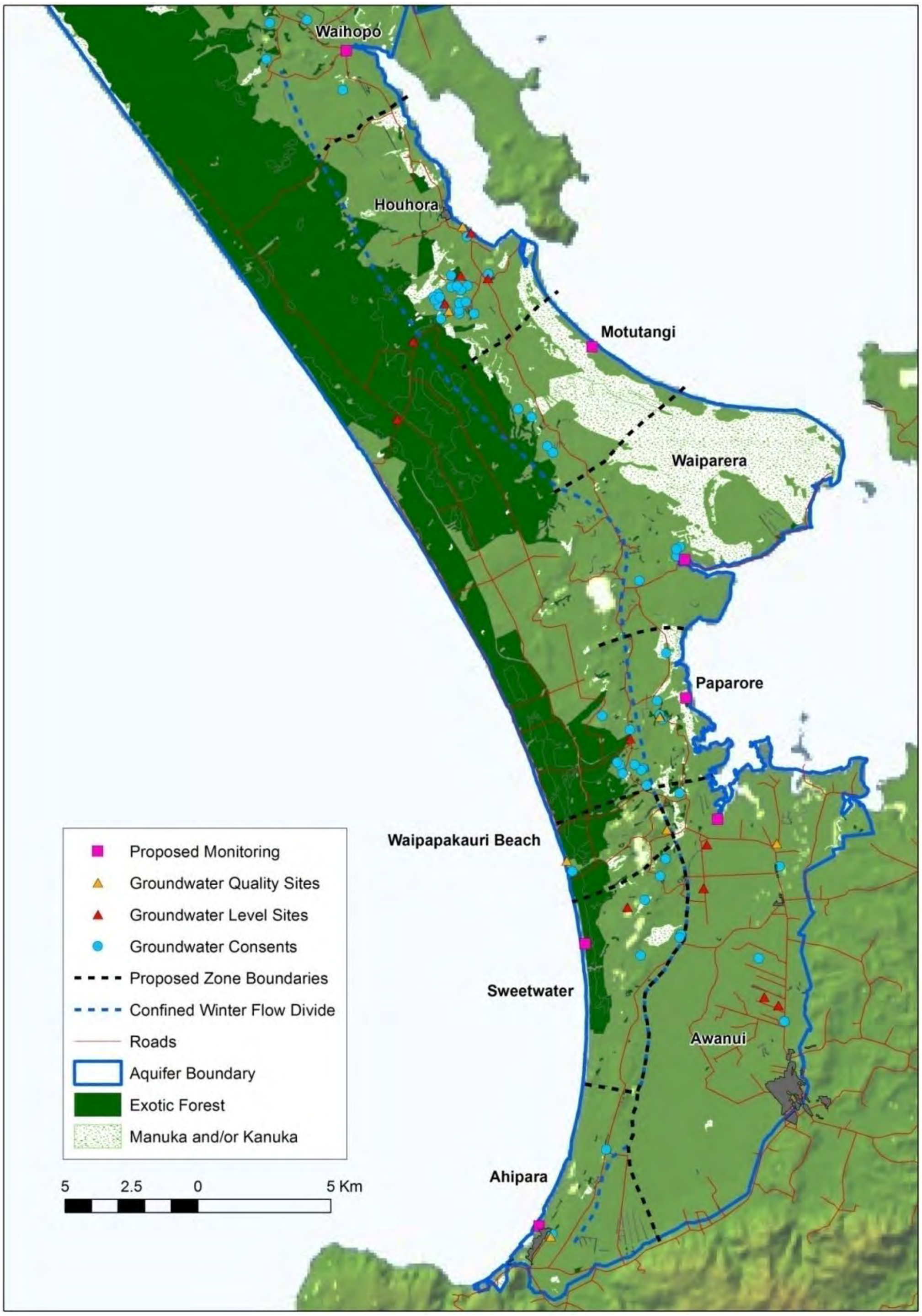


Figure 16 Location of existing groundwater consents, monitoring network, proposed monitoring, and proposed aquifer sub-regions

There is a tendency for water quality monitoring to focus on the shell-rich marine sands found at the base of the aquifer. These sediments are where the majority of production wells are screened. However, some domestic supply wells are drilled to shallow depths because they do not require the high yields that the shellbeds provide. It would be prudent to have some monitoring within these shallow dune sands at Houhora for the purpose of ensuring domestic supplies are not affected by seawater intrusion. Table 6 also summarises the existing groundwater consents, which have been sorted according to these identified aquifer sub-regions. Existing NRC monitoring bores have been identified where they exist in a zone (WL= groundwater level monitoring, WQ=groundwater quality monitoring).

Table 6 Current consented groundwater allocation by aquifer sub-region, and approximate land surface recharge volumes

Zone	Area (ha)	Consents	Allocation (m^3/d)	Allocation (m^3/year)	Monitoring Bore	Recharge (m^3/year)	% recharge allocated
Waihopo	5,307	5	710	148,320	-	8,521,629	1.7
Houhora	4,054	20	5,106	783,448	200210 (WL), 200250 (WQ)	19,946,675	3.9
Motutangi	3,017	4	1,036	161,120	-	10,696,583	1.5
Waiparera	5,403	5	1,800	226,600	-	23,122,982	1
Paparore	2,123	14	8,046	1,066,420	200211 (WL,WQ)	10,821,694	9.9
Waipapakauri	1,160	1	30	10,950	209330 (WQ)	5,964,031	0.2
Awanui	9,349	4	944	106,010	201563 (WQ)	38,670,081	0.3
Sweetwater	2,433	5	20,751	4,069,633	-	13,357,410	30.5
Ahipara	2,335	2	303	98,567	-	7,687,883	1.3
Total	**43,655**	**60**	**38,726**	**6,671,068**		**138,788,968**	**4.8**

EXISTING ALLOCATION

ENVIRONMENTAL CONSTRAINTS

From a mass balance point of view, the main constraint on water abstraction is volume of land surface recharge, which is the only source of inflow to the Aupouri Aquifer. This determines the volume of water that is available for each of the discharge components of the system, including pumping. However, it is also important to consider local environmental constraints, because pumping effects can cause nearby issues regardless of the proportion of recharge that is allocated for pumping (e.g. saline intrusion, land subsidence). Therefore, an appropriate, allocation for the Aupouri Aquifer involves setting a limit that considers both the available recharge, and the environmental effects that pumping may have.

The main environmental constraint on groundwater allocation in the Aupouri Aquifer is the presence of the sea. If bores are pumped beyond an aquifer's safe yield, seawater can be drawn into the pumped bores, or other bores located along the coastline.

SEAWATER INTRUSION

Groundwater from coastal aquifers discharge offshore, either as seepage along the coastline or as submarine springs. Fresh water is less dense than seawater, and because of this characteristic, it naturally forms a fresh water lens or layer on top of the heavier saline groundwater derived from the sea. The zone in which the salt and freshwater layers meet is known as the seawater interface. The interface is usually not a sharp boundary, but consists of a mixing zone.

The density difference between the two layers means that the underlying saltwater lens can naturally extend inland of the coastline along the base of a coastal aquifer. The lateral position of the interface depends on a number of factors, including the density, viscosity, and temperature differences between salt and freshwater, coastal groundwater levels, aquifer depth and layering, and the rate of offshore groundwater flow. If coastal groundwater levels are lowered too far, or if offshore flow is overly-reduced, the position of the seawater interface will respond by moving inland and upwards. This phenomenon is known as seawater intrusion, and is extremely undesirable because it is so difficult to reverse the saline contamination of water supplies. The salinity of sea water is 35,000 mg/l, whereas groundwater in the Aupouri Aquifer has salinities less than 250 mg/l. A mixing of just 1.2% sea water would be enough to render groundwater unpalatable. For this reason, a conservative approach to assessing the potential for seawater intrusion is advised.

This position of the seawater interface has not been observed along the coast of the Aupouri Aquifer. Data from monitoring bores indicate show that chloride concentrations are low, and quite stable (Figure 7). This is evidence that the freshwater lens may extend for some distance offshore under existing pumping conditions.

The objective of a sustainable groundwater allocation in a coastal aquifer is to ensure that saltwater intrusion does not result in reduced groundwater quality. In Northland, consent conditions are usually placed on groundwater abstractions near the coast that might contribute to seawater intrusions. These conditions are normally stated as "To prevent saline contamination, the Regional Council reserves the right to require the Consent Holder to cease the taking of groundwater from any or all the bore/s at such times as the chloride concentration in water delivered by any of the bores is measured by standard methods to be greater than x mg/l." Where 'x' in this condition is either 200, 220 or 250 mg/l, depending on the location if the abstraction point (Callander *et al*. 2011).

The placement of salinity conditions on consents holders is a good practice. It is also important to consider that this type of approach is not 'self-regulating' because the consent holder may not be the only party affected by their pumping. We therefore recommend that individual consent conditions be supplemented with conditions that relate to strategically placed coastal monitoring bores within identified groundwater management zones. This approach has been adopted in other coastal aquifers in Northland.eg Russell.

FULL ALLOCATION ASSESSMENT

To date there have been no recorded occurrences of seawater intrusion in the Aupouri Aquifer. While this is reassuring, it is also expected that many water users are not currently using their entire allocation. Meter data of water use are not available, so estimates of abstraction demand have been made with the soil moisture balance model. The results indicate that the average annual demand is approximately 56% of the consented total for pasture, and 48% for avocados. This proportion varies between seasons and water users, however it is fair to say that there is potential for increased water demand amongst existing consent holders, particularly during prolonged dry periods.

This scenario tests whether the current total allocation can be sustained if it all consented and permitted takes were to be fully exercised. The assumption made for this assessment is that the historical aquifer recharge rates will be similar to the future. In making this assumption we can use the historical record, as characterised by the calibrated model, to simulate future increases in demand.

Our original intention was to predict movement of the seawater interface in response to pumping demand using the SEAWAT Version 4 package (Langevin *et al.* 2008) within our Modflow model. However, during our model calibration it became apparent that the flow in the unsaturated zone above the aquifer plays a large role in aquifer recharge dynamics. Unfortunately, the UZF-1 pacakge is not currently compatible with the contaminant transport package MT3DMS, which is required to run SEAWAT. We have therefore changed our approach to assessment of the groundwater resource by considering that sustainable aquifer use should meet two key environmental criteria:

1. Groundwater levels should be maintained above the critical thresholds predicted by the Ghyben-Herzberg principle to ensure there is no seawater intrusion
2. Groundwater flows should not be reversed across the coastal boundary (there should be no positive constant head boundary fluxes)

The Ghyben-Herzberg principle is a simple relationship that predicts the position of the seawater interface, assuming a static groundwater system that is in hydraulic connection with the aquifer. The assumption of a static aquifer is a reasonable assumption for the Aupouri Aquifer because recharge pulses are attenuated with depth, so the small volume of offshore flux which does travel through the confined sediments will be fairly constant. The assumption of a hydraulic connection is perhaps less tenable because the aquifer is layered and strongly anisotropic, having a vertical hydraulic conductivity which is considerably lower than its horizontal value. However, the Ghyben-Herzberg approximation will provide a conservative estimate for a suitable aquifer level at the coastline, and a conservative approach is recommended for ensuring saline intrusion does not occur.

The Ghyben-Herzberg principle states that the position of the seawater interface is determined by the density ratio between salt water and fresh water. Densities for these two waters are commonly reported as 1,250 Kg/m^3

and 1,000 Kg/m^3 respectively. Using these densities in the Ghyben-Herzberg equation calculates that if the freshwater table is 1 metre above mean sea level the fresh/saltwater interface will be 40 metres below sea level. The minimum groundwater level required to maintain the interface offshore can be calculated if the depth to the base of the aquifer is known.

Table 7 shows the calculated thresholds made at key coastal locations within each of the proposed groundwater zones. These are the minimum groundwater levels required to ensure the seawater interface does not move inland of the coastline. Model threshold values have also been shown, and these values include the standard deviation of the model predictive error from Table 5. The threshold locations shown in Table 7 were determined by increasing pumping rates in the model, and identifying where the onset of saline intrusion is most likely to occur. It is recommended that coastal monitoring be carried out at these sites if the allocation starts to approach its proposed safe yield.

It is important to recognise that we can only have confidence in the model's predictions in areas where data is available to constrain the calibration. For five of the groundwater zones we consider the model to be poorly constrained due to a lack of available data, and we do not recommend that the model be used for predictive purposes within these zones. The level of confidence in the predictive ability of the model has been indicated in Table 7.

Table 7 also shows predictions of groundwater levels at the key threshold locations for the sub-regions where there is sufficient information to have some confidence in the model predictions. These predictions were made using the numerical model under a full allocation scenario, which consisted of all irrigation consents pumping at their maximum rate from Nov-April (six months), and industrial, stock and water supply consents pumping at their maximum all year. Stock and domestic supply bores were pumped at 5 and 1 m^3/d respectively throughout the year. This gives an additional permitted activity use of 289,460 m^3/y for the whole aquifer.

The predicted groundwater levels are shown as a map in Appendix 5. All groundwater levels remain above sea level for this scenario, and there is no reversal of groundwater flow across the coastline boundary (no constant head inflow).

Table 7 Coastal thresholds at key points within each groundwater zone, and the predicted level at full allocation

Location	E	N	Aquifer base	Threshold (m)	Model threshold (m)	Confidence	Full allocation level (mamsl)	Freeboard (m)
Waihopo	1606830	6153780	-30	0.75	1.25?	Low	2.2	-
Houhora (200210)	1611712	6146689	-76.4	1.91	2.2	High	3.8	1.6
Motutangi	1616290	6142240	-99	2.47	3.0?	Low	0.2	-
Waiparera	1619720	6134490	-66.7	1.66	2.2?	Low	4.7	-
Paparore	1619720	6129430	-28.6	0.71	1.1	Mod	2.0	0.9
Waipapakauri (209330)	1615319	6123074	-75.4	1.88	2.4?	Low	4.4	-
Sweetwater (210527)	1616374	6119055	-72.5	1.81	2.3	Low-Mod	3.9	1.6
Awanui	1621400	6124500	-25.3	0.63	1.1	Mod	2.4	1.3
Ahipara	1613260	6108310	-35	0.87	1.4?	Low	1.5	-

Groundwater levels also remain above the thresholds calculated by the Ghyben-Herzberg approximation with the exception of Motutangi. This area has a low hydraulic gradient, and the projected deep aquifer base in this area gives a high sea water intrusion threshold level using the Ghyben-Herzberg approximation. As a result, groundwater levels at the recommended Motutangi monitoring site do not meet the threshold groundwater water levels during model calibration. We interpret this to be an artefact of the model since there is insufficient information to constrain the aquifer structure and hydraulic properties, or to characterise groundwater levels in this area. While the low predicted water levels are not a cause for immediate concern, the relatively flat hydraulic gradient and deep aquifer base do indicate that the Motutangi area is an area of potential risk for seawater intrusion. It is recommended that further investigations be carried out prior to further allocation in the Motutangi sub-region.

RECOMMENDED AQUIFER MANAGMENT LIMITS

MANAGEMENT LIMITS FOR AVOIDING SEAWATER INTRUSION

We have used the numerical groundwater model to estimate the aquifer management limits for sub-regions where we have confidence in the model's predictive capability based on the existing arrangement of abstraction bores. It is considered that this approach is more sensible than trying to guess the locations of future abstractions. The maximum safe pumping rate is calculated by increasing the allocation in the model by a factor until either the sea water intrusion threshold shown in Table 7 has been reached (potential limit), or sea water is drawn into the model (reversal of constant head flux).

The model can also be used to give an indication for suitable management limits in areas where there is little information, or where the model is less well constrained. In areas where there is little information, some guidance for setting allocation limits is currently given by Section 5.1.1 of the National Environmental Standard (NES) on ecological flows and water levels (MFE, 2008b). The proposed allocation limits in these guidelines are:

- For shallow, coastal aquifers (predominantly sand): 15% of the average annual recharge as calculated by the regional council
- For all other aquifers: 35% of the average annual recharge as calculated by the regional council

These two land surface recharge thresholds of 15% and 35% are useful measures for comparing the modelled limits, particularly in areas where there is little information to constrain the model.

Table 8 shows the results of the aquifer sub-region safe yield assessment as annual volumes (m^3/y) and as a percentage of average annual land surface recharge (%LSR). The modelled limits shown in Table 8 are the most that each sub-region could be pumped without drawing groundwater levels below the suggested threshold values, or inducing seawater into the aquifer. A map of the resulting groundwater levels is shown in Appendix 6.

Table 8 Modelled and recommended management limits for proposed sub-regions of the Aupouri Aquifer

Zone	Current allocation (consented & permitted)		Modelled limit		Recommended limit		Comments
	m^3/y	% LSR	m^3/y	% LSR	m^3/y	% LSR	
Waihopo	166,435	2.0	2,799,766	33	1,278,200	**15?**	Water level threshold reached at 33%, little information for area
Houhora	827,310	4.1	2,141,278	11	2,141,300	**11**	Water level threshold reached at 11%, model well constrained
Motutangi	176,758	1.7	1,606,613	15	1,069,600	**10**	Low lying area, little information for area
Waiparera	266,124	1.2	712,961	3.1	2,312,200	**10?**	Low lying area, little information for area
Paparore	1,025,727	9.5	3,845,640	36	3,787,500	**35**	Water level threshold reached at 36%, model well constrained
Waipapakauri	17,119	0.3	1,261,281	21	1,192,800	**20?**	Seawater drawn in above 21%, model not well constrained
Awanui	209,922	0.5	4,640,978	12	4,640,400	**12**	Threshold unresponsive, seawater drawn into Ahipara at higher allocation
Sweetwater	4,054,527	30.4	4,658,983	35	4,675,000	**35**	Limit to 35%, model not well constrained at Lake Heather
Ahipara	112,721	1.5	922,218	12	922,500	**12**	Vulnerable to seawater intrusion, little information for area

The results of the modelling indicate that overall, the aquifer is currently not being utilised to its full potential. The sub-region or zone with the highest allocation as a percentage of recharge is Sweetwater, which is close to the 35% guideline of the NES. Aquifer properties are constrained with less confidence in this area due to the difficulty in simulating groundwater levels at the Lake Heather monitoring bores. This has resulted in rising groundwater levels in the Sweetwater and Waipapakauri Beach sub-regions of the numerical model. The most likely reason for this is that the unsaturated zone hydraulic properties and also the aquifer storage coefficients in these areas differ from those in the rest of the Aupouri Aquifer. The values shown in Table 8 for these two areas should be treated with caution.

The pattern of drawdown caused by pumping in the model is influenced by the arrangement of existing wells, and local aquifer structure and properties. Perhaps the most influential factor is the distribution of sand dunes, since groundwater storage in these dunes provides the driving head to maintain higher groundwater levels and a steeper hydraulic gradient towards the coast. Scrutiny of the modelled limits shown in Table 8 indicates that areas with fewer sand dunes (e.g. Motutangi, Waiparera, Awanui and Ahipara) have a lower ability to sustain higher pumping demand. These areas have sustainable allocations that are less than the 15% of annual recharge recommended by the NES. Areas with more sand dunes (e.g. Paparore and Sweetwater) have a greater volume of groundwater storage above sea level, and these areas have the potential to sustain more pumping demand, perhaps up to the 35% guideline value recommended by the NES.

The model does show that the southern sub-regions of the Aupouri Aquifer show strong evidence of cross-boundary pumping effects. The main reason for this is that the Waipapakauri Beach, Awanui, Sweetwater and Ahipara zones collectively straddled the groundwater flow divide that runs through the middle of the aquifer. This means that an increase in pumping within one of these zones tends to affect groundwater levels in the adjacent zones. For example, it was found that an allocation of 15% of land surface recharge was not feasible for both the Awanui and Ahipara sub-regions without drawing seawater into the Ahipara coastline.

The management limits proposed here are intended to be interim limits for the purpose of avoiding saline intrusion. If allocation beyond these interim limits is made in any the proposed sub-regions, we recommended that additional work in the form of more detailed modelling be carried out. More refined modelling is particularly important in areas where there is less information, or where our model is poorly constrained. Given the severity of seawater intrusion as a threat to water quality, it is also prudent to be conservative, and the recommended management limits shown in Table 8 should be considered as maximum values until better information becomes available, and should be paired with coastal monitoring sites.

LAND SUBSIDENCE

Land subsidence resulting from groundwater abstraction could potentially occur in two ways:

1. If organic soils or peat deposits are drained, they can become oxidised, lose buoyancy, and shrink. Of these three processes, oxidation is of most concern for subsidence because the loss of organic material is irreversible.
2. When water is withdrawn from a confined aquifer, some of the water is provided by the elastic expansion of water, which is very slightly compressible. This is known as elastic storage. Any loss in pressure is compensated for by a reduction of the aquifer porosity by compaction. The compressibility of fine-grained sediments such as clay or silt is greater than that of coarser sediments such as sand. The sediments that host the Aupouri Aquifer are an alternating mix of silt and clay with low storage coefficients and coarser grained sand and shellbeds, with higher storage coefficients. This combination may result in some compaction of the aquifer matrix, particularly in areas where there are thicker deposits of clay and peats coincide with areas of significant depressurisation.

Compression resulting from the drainage of organic material only applies to sediments located above or near to sea level. Most of these areas are already low-lying, because they constitute the wetland areas that formed when the sea level stabilised to its present position around 6,500 years ago. Consequently, many of these areas such as the Kaitaia swamp are already drained because of their high water table. If subsidence is significant in these organic horizons, it would most likely have already occurred due to the existing drainage networks.

Perhaps of more concern because of its uncertainty is subsidence resulting from depressurisation and compaction. At this stage, we have little knowledge about the compressibility and abundance of different materials within the aquifer. To get an indication of the potential for compaction would require a geotechnical engineer to take undisturbed samples of some of the finer materials from a borehole in order to assess compressibility under different pressures in a laboratory test.

LEAKY ARTESIAN BORES

Many of the drains within the Awanui area are thought to intercept old artesian bores that have corroded and become leaky. In 2007 NRC commissioned a study to determine the impact that these bores have on the Aupouri Aquifer (SKM, 2007).

The Awanui study consisted of a detailed Modflow model at a 100 to 200m grid resolution. Leaky bores were simulated in the model by placing drain cells in the shellbed layer at locations where leaky bores were thought to occur. Leakage would then occur at these model cells when water levels rose above ground level. The model predicted that, on average, 4,865 m^3/d would be discharged through these leaky bores, which is about 6% of the recharge over the model domain. Variability of groundwater levels throughout the year is quite low, so discharge through the leaky bores would only fluctuate by 30% of the average value.

One of the main limitations of the study was an understanding of the number and locations of leaky artesian bores in the area. The results of the study were reported to be indicative only until further data on bore locations become available.

Leaky bores have not been included in this report because of the uncertainty in their location and total discharge volume. Also, this study differs from the Awanui model in that it is of a regional nature in both its scale and resolution. However leaky bores could be included within the current model if there was more certainty about their number and location.

CLIMATE CHANGE PREDICTIONS

Predictions of climate change at a national and regional level have been carried out by NIWA (Mullan *et al*. 2005, MFE, 2008). Climate projections for New Zealand were derived by the statistical downscaling of a number of global climate models, and these were downscaled further to generate predictions at a regional level. The results of this downscaling indicate that Northland’s annual temperature is expected to increase 0.9°C by 2040, and 2.1°C by 2090 (MFE, 2008).

RAINFALL PREDICTIONS

Figure 17 shows the predicted future variability in annual rainfall across New Zealand. These predictions are based on downscaled precipitation changes for the twelve best global climate models, re-scaled to match the IPCC global warming range for six indicative emission scenarios (MFE, 2008). It can be seen that Northland is expected to behave similarly to much of the east coast of New Zealand, and will become drier as the global temperature rises, particularly the far north.

Table 9 shows the expected future change in rainfall at Kaitaia with the lower and upper limits of the predictions shown in brackets (MFE, 2008). Annual rainfall is expected to decrease by approximately 3% by 2040 and 6% by 2090 with most of this reduction occurring in the winter and spring. Summer rainfall may increase slightly, however a previous, more detailed report does predict an increase in future drought risk for Northland (Mullan *et al.* 2005).

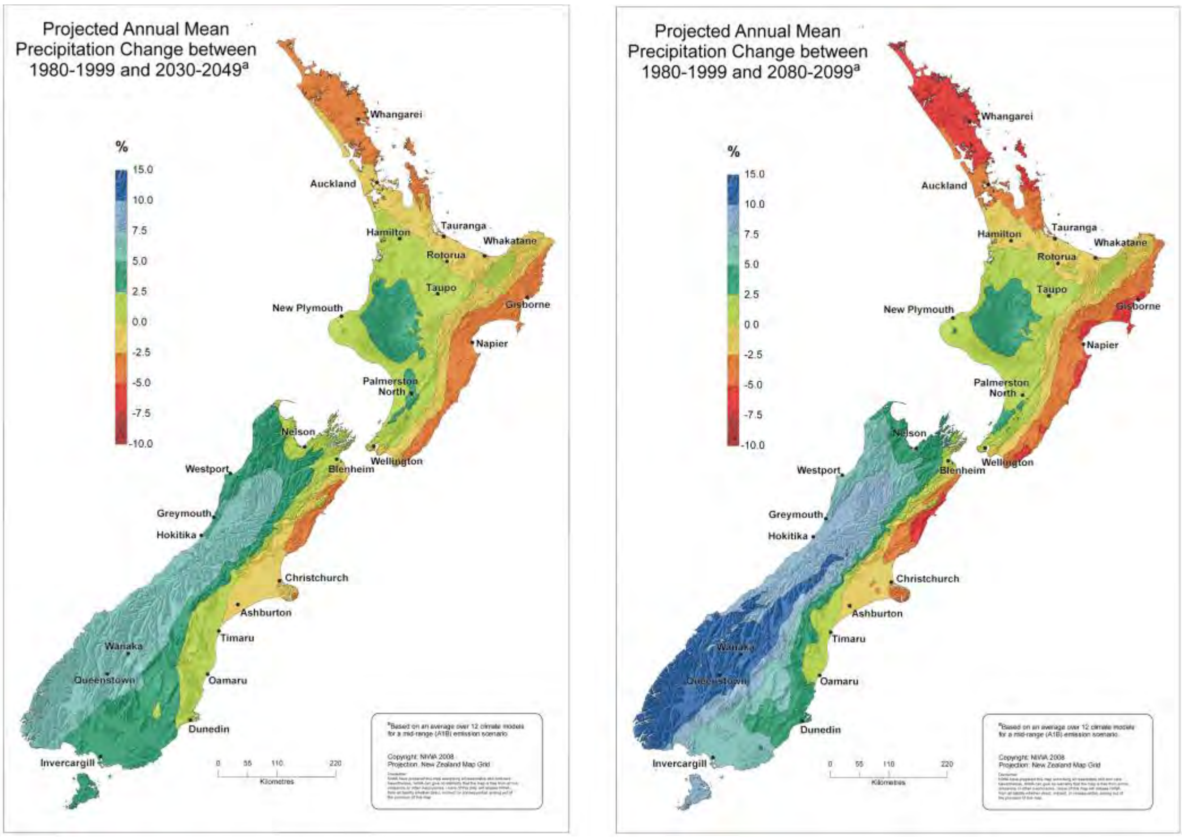


Figure 17 Predicted future change in precipitation for New Zealand[2]

While the climate models predict a drier future climate for Northland in the future, we can also expect more extreme events. For every degree of warming, the atmosphere can hold 8% more moisture. Rainfall is expected to become considerably more variable, with individual events becoming less frequent but more intense, particularly those associate with ex-tropical cyclones. Drought events are likely to become more common and more intense.

Table 9 Projected percentage change in seasonal and annual rainfall at Kaitaia (MFE, 2008)

Period	Summer	Autumn	Winter	Spring	Annual
1990-2040	1 (-15, 20)	0 (-14, 16)	-5 (-23, 1)	-6 (-18, 4)	-3 (-13, 5)
1990-2090	-1 (-26, 21)	-3 (-22, 11)	-8 (-32, 2)	-11 (-33, 8)	-6 (-22, 5)

The expected impact that the predicted climate changes will have on the Aupouri Aquifer is a slight increase in recharge during the winter and spring period because of the increase in rainfall intensity. However, the predicted increase in dry weather will mean that there is less recharge occurring during the spring and autumn. This will result in a net loss in aquifer recharge.

There will also be an increase in demand in the future because of higher temperatures and evapotranspiration rates, and less frequent rainfall events during summer and autumn. This increase applies to existing consent holders, but there is also likely to be additional water demand as landholders that don't currently irrigate apply for consents. A drying of the climate is also likely to increase the length of the irrigation season, and we can expect an increase in the length of the shoulder seasons, as well as the demand within those shoulder seasons.

In theory it is possible to make quantitative predictions about the influence that climate change will have on groundwater resources. To do this would require either the generation of generic synthetic rainfall and

[2] Source: NIWA: https://www.niwa.co.nz/our-science/climate/information-and-resources/clivar/scenarios

evapotranspiration records, or the application of corrections to historical datasets. These records could then be used as input datasets for our soil moisture balance model to estimate groundwater recharge and irrigation demand. However, guidance on generating region-specific records for predicting future rainfall intensity and frequency are not yet available for New Zealand let alone for specific regions. More generalised regional-scale predictions are currently the best information we have available, so any assessment of future climate impacts on groundwater resources can only be made at a qualitative level.

SEA LEVEL RISE

One factor that can be incorporated in our groundwater flow model in a quantitative manner is the impact of rising sea level. The Fifth IPCC Assessment Report estimates a global mean sea level rise of 0.60 (0.42 to 0.80) m by 2100 relative to 1986–2005, and 0.57 (0.40 to 0.76) m by 2090–2099 relative to 1990 (IPCC, 2013).

A change in sea level is expected to have two main impacts on the Aupouri Aquifer. Firstly, it will move the position of the saline interface further inland. The second impact that sea level rise will have is to raise the hydrological base level of the entire freshwater system by increasing water levels at the coastal discharge points. This has the effect of raising the water table, thereby increasing the extent of wetland areas and raising water levels in streams and drains. During wetter periods this has implications for flooding, and the discharge efficiency of existing watercourses and drainage networks. During drier periods, there will an increased risk of saline water encroaching further inland via the same water courses.

A third impact of sea level rise is for seawater or brackish estuarine water to extend further up the tidal range of rivers and estuaries. In some instances, the introduction of saline water has the effect of inducing the infiltration of salty water into fresh groundwater supplies. The study of this kind of impact requires detailed surveys of coastal estuary and stream bed levels, and is not feasible at the resolution of modelling carried out for this study.

A sea level rise scenario was tested in the numerical model by raising the constant head boundary to 0.57m. This rise was also added to the depth of the aquifer base for each of the coastal monitoring sites to adjust the Ghyben-Herzberg thresholds, although this makes very little difference to the threshold values. Additional demand was included by pumping the full allocation, and the irrigation season was extended from October to April to account for drier conditions.

The resulting groundwater levels for the sea level rise scenario are shown in Appendix 7. The results of the modelling predict that sea level rise will have no impact on the integrity of existing groundwater supplies. The model predictions show that raising the constant heads simply raises groundwater heads in the aquifer. There is no reversal of flow across the sea boundary, and groundwater levels are maintained above the coastal threshold levels (with the exception of the previously discussed Motutangi sub-region).

RECOMMENDATIONS

MANAGEMENT RECOMMENDATIONS

The aquifer is currently being used in a sustainable manner. The results of this study indicate that the aquifer is receiving recharge well in excess of its pumping demand. The aquifer is also fairly robust, as it has a large volume of storage to draw upon.

However, this does not mean that the aquifer is not vulnerable to being over-pumped. Because it has formed as a tombolo, the Aupouri Aquifer is long and narrow, and there is nowhere in the aquifer that is far from the coastline. This means that pumping impacts can affect the seawater interface at a local scale, which makes it a challenge to monitor and sustainably manage the aquifer.

Fortunately, the locations of domestic wells and existing consents are clustered into quite distinct areas. It is recommended that the aquifer zones and monitoring site thresholds that have been proposed in this report be adapted for monitoring and management purposes. In the short term, new coastal monitoring sites are recommended firstly at Paparore and Waihopo. A threshold and water level recorder should also be placed at Houhora.

Groundwater allocation management limits for each aquifer sub-region have also been proposed in Table 8 of this report, and it is recommended that these limits be adopted until better information becomes available within individual zones. In particular, it would be prudent to conduct more detailed zone-specific future resources investigations followed by more detailed modelling in the areas of highest demand, such as Houhora and Sweetwater.

The numerical model shows that low-lying parts of the aquifer have less potential to sustain higher allocation volumes since their hydraulic gradients are relatively flat, and less groundwater storage is held above sea level in these areas. The current allocation in these low-lying areas is currently quite small so there is no immediate cause for concern, although demand in the Awanui and Ahipara areas in particular should be closely monitored.

TECHNICAL RECOMENDATIONS

- Additional groundwater monitoring would be of great benefit for the purposes of constraining numerical modelling to refine allocation volumes. There is a shortage of data at Sweetwater, Ahipara, Waipapakauri Beach, Motutangi, Waiparera, and Waihopo.
- Fluxes in the groundwater model are largely dependent on land surface recharge calculations. There is currently no soil monitoring data available to verify the recharge results. Recharge estimates would benefit from the installation of lysimeters at locations representative of the main soil types. Recharge estimates can also be greatly improved if there is a better understanding of the effect that forest interception has on land surface recharge.
- New consents should carry out an aquifer test to improve knowledge of aquifer properties. These tests should be carried out with an observation piezometer to enable the assessment of vertical hydraulic conductivity and storage coefficient values.
- The groundwater quality monitoring programme could be optimised to focus more on land use impacts (samples from the unconfined rather than confined aquifer), and coastal impacts.
- Flows in surface water ways should be gauged or monitored to estimate aquifer discharge, particularly the Awanui River. Surface-groundwater exchanges should be characterised by conducting a series of concurrent flow gauging surveys on the main surface water bodies.
- The relationship between dune lakes and groundwater can be assessed by dipping neighbouring shallow wells and comparing them to lake levels on the DEM.
- Groundwater quality sites should be dipped for water level prior to sampling. This takes very little time to do in the field, and would make a great difference to the available data for numerical modelling.
- Bore 200210 (Houhora Waterfront) should be considered as a coastal monitoring site for detecting the onset of seawater intrusion. Water level and conductivity recorders are recommended for this site, and also for any future coastal monitoring bores.
- A new early warning coastal monitoring site is recommended at Paparore.
- Additional coastal monitoring sites are recommended at the locations specified for the Waihopo, Waiparera, Awanui, and Ahipara zones if the volume of allocated groundwater increases significantly in these areas.
- Consider bore development and maintenance regime particularly for the Burnage Road Bore

REFERENCES

Allen, R., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements, *Irrigation and Drainage Paper 56*. FAO, Rome, 300p.

Boulton, N.S., 1963. Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage. *Proceedings, Institute of Civil Engineering 26*, 469-482.

Callander, P. Lough, H., Steffens, C., 2011. Guidelines for the monitoring and management of sea water intrusion risks on groundwater. PDP Report C02085500, prepared for Envirolink Project 420-NRLC50, 104 p.

Cuthbert, M.O., 2010. An improved time series approach for estimating groundwater recharge from water level fluctuations. *Water Resources Research 46 (9)*.

Daughney, C.J., Raiber, M., Moreau-Fournier, M., Morgenstern, U., van der Raaij, R., 2012. Use of hierarchical cluster analysis to assess the representativeness of a baseline groundwater quality monitoring network: comparison of New Zealand's national and regional groundwater monitoring programs. *Hydrogeology Journal 20*, 185-200.

Daughney, C., Randall, M., 2009. National groundwater quality indicators update: state and trends 1995-2008. GNS Science Consultancy Report 2009/145, 54p.

de Silva, C.S.; and Rushton, K.R. 2007: Groundwater recharge estimation using improved soil moisture balance methodology for a tropical climate with distinct dry seasons. *Hydrological Sciences Journal 52:5*, 1051-1067.

Doherty, J.E., and Randall, R.J., 2010. Approaches to highly parameterised inversion: a guide to using PEST for groundwater-model calibration. US Geological Survey Investigations Report 2010-5169, 59p.

Domenico, P.A., and Schwartz, F.W., 1998. *Physical and Chemical Hydrogeology*. Wiley, New York, 506p.

Edbrooke, S.W., 1997. Assessment of lignite investigations at Sweetwater, Northland. GNS client report 51660A.10 prepared for Northpower Limited, 22p.

Freeze, R.A. and Cherry, J.A. 1979: *Groundwater*. Prentice Hall, Englewood Cliffs, NJ, 604p.

Green, S., 2010. The SPASMO-IR tool to determine reasonable water use for the Northland region. Plant & Food Research, Client Report prepared for Northland Regional Council, 32p.

Groundwater Consultants NZ, 1987a. Aupouri Peninsula Water Resources Assessment Investigation Drilling Programme. Report prepared for the Northland Catchment Commission and Regional Water Board.

Groundwater Consultants NZ, 1987b. Seismic Refraction Survey, Sweetwaters and Houhora. Report prepared for the Northland Catchment Commission and Regional Water Board.

Groundwater Consultants NZ, 1990. Geophysical Investigations Ahipara / Awanui / Karikari. Report prepared for Northland Regional Council.

Harbaugh, A., 2005. MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process. U. S. Geological Survey Techniques and Methods 6-A16, variously paginated.

HydroGeo Solutions, 2000. Aupouri Aquifer Sustainable Yield Groundwater Modelling Study. Report prepared for Northland Regional Council.

Intergovernmental Panel on Climate Change, 2013. *Climate Change 2013: The Physical Science Basis. Working Group Contribution I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (AR5). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 p.

Isaac, M.J., 1996. Geology of the Kaitaia Area. Institute of Geological & Nuclear Sciences 1:250 000 geological map 1, 1 sheet + 44p.

Johnson, A.I., 1967. *Specific yield: compilation of specific yields for various materials*. USGS Water Supply Paper 1662-D, Washington DC, 74p.

Langevin, C.D., Thorne, D.T., Dausman, A.M., Sukop, M.C., Guo, W., 2008. *SEAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport.* U. S. Geological Survey Techniques and Methods 6-A22, 39 p.

McLaren, R.G., and Cameron, K.C., 1996. *Soil Science* (2nd ed.). Oxford University Press, 304p.

Ministry for the Environment 2008. Climate Change Effects and Impacts Assessment: A Guidance Manual for local Government in New Zealand. 2nd Edition. Mullan B; Wratt D; Dean S; Hollis M; Allan S; Williams T, Kenny G and MfE. Ministry for the Environment, Wellington, 149 p.

Ministry for the Environment, 2008a. Coastal Hazards and Climate Change. A Guidance Manual for Local Government in New Zealand (2nd edition). Revised by Ramsay, D, and Bell, R. (NIWA). Prepared for Ministry for the Environment, 127 p.
Ministry of Health, 2008. Drinking-water Standards for New Zealand 2005 (Revised 2008). Wellington: Ministry of Health.

Ministry for the Environment, 2008b. Proposed National Environmental Standard on Ecological Flows and Water Levels: Discussion document.

Mullan, B., Porteous, A., Wratt, D., Hollis, M., 2005. Changes in drought risk with climate change. NIWA Client Report WLG2005-23 prepared for Ministry for the Environment and Ministry of Agriculture and Forestry, 58p.

Niswonger, R.G., Prudic, D.E., Regan, R.S., 2006. *Documentation of the Unsaturated-Zone Flow (UZF1) Package for modelling unsaturated flow between the land surface and the water table with MODFLOW-2005*. U. S. Geological Survey Techniques and Methods 6-A19, 62 p.

Petty, D.R., 1975. Geo-hydrological Investigation of Kaitaia Region. *New Zealand Geological Survey Report M46*, 37p.

Rawls, W.J., Ahuja, L.R., Brakensiek, D.L., Shirmohammadi, A., 1992. Infiltration and soil water movement. In: Maidment, D.R. (ed.), 1992. *Handbook of Hydrology*. McGraw-Hill, New York, 1424p.

Rowe, L., Jackson, R., Fahey, B., 2002. Land use and water resources: Hydrological effects of different vegetation covers. *SMF2167: Report No. 5*. Report prepared by Landcare Research for Ministry for the Environment.

Rushton, K.R.; Eilers, V.H.M.; Carter, R.C. 2006: Improved soil moisture balance methodology for recharge estimation. *Journal of Hydrology 318*, 379-399.

Scotter, D., Heng, L., 2003. Estimating reference crop evapotranspiration in New Zealand. *Journal of Hydrology (NZ) 42*, 1-10.

Sinclair Knight Merz, 2007. Awanui Artesian Aquifer Numerical Modelling. Report prepared for Northland Regional Council, 46p + Figures.

Sinclair Knight Merz, 2007a. King Avocado Orchard Drilling and Aquifer Testing. Report prepared for King Avocado Limited, 33p.

Soil Conservation Service, 1972. *National Engineering Handbook: Section 4, Hydrology*. SCS, US Department of Agriculture.

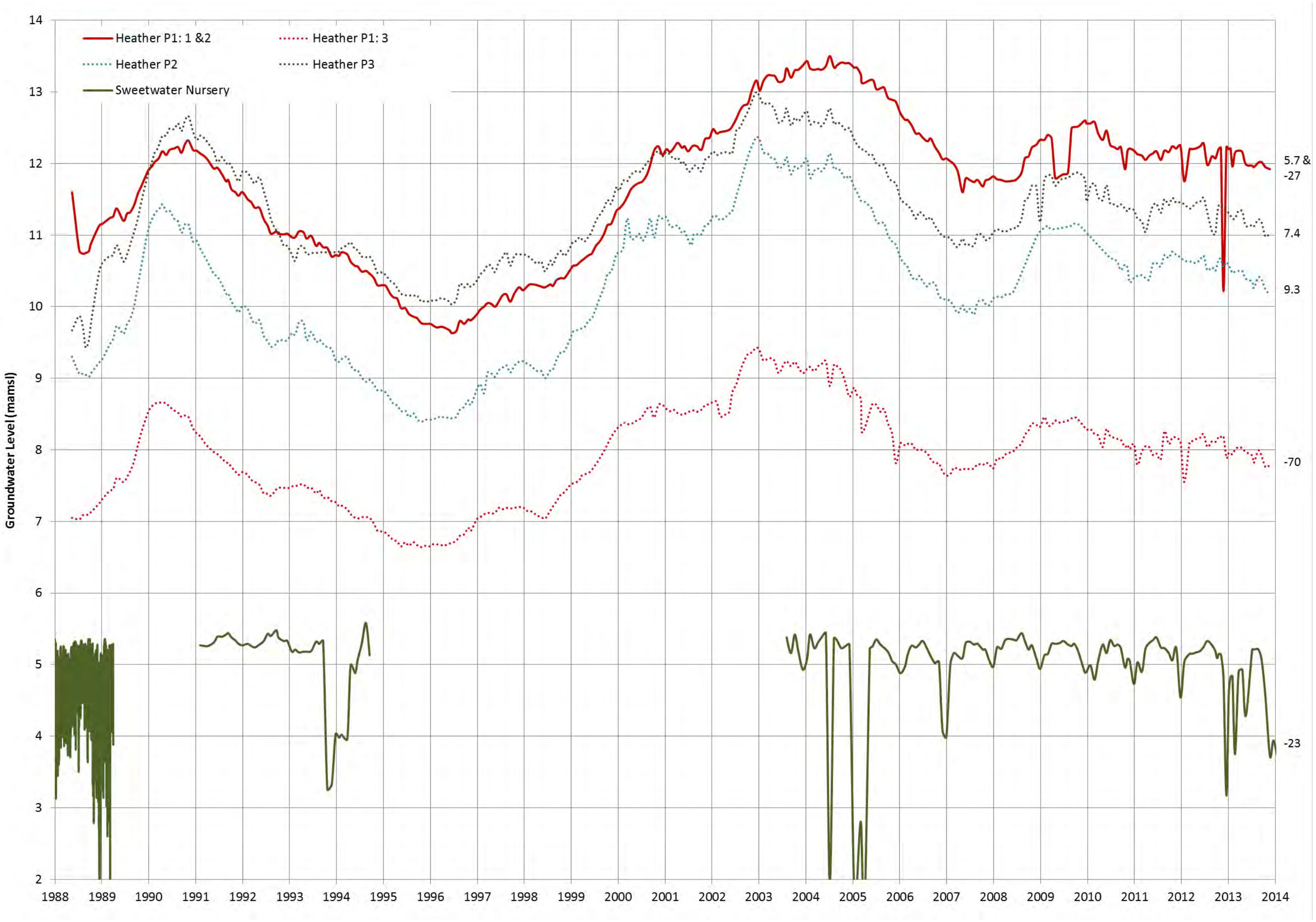
Stagpoole, V. M., Edbrooke, S. W., Christie, A. B., Davy, B. W., Caratori-Tontini, F., Soengkono, S., Cox, S. C., Isaac, M. J., 2012. Northland airborne magnetic and radiometric survey: a geological interpretation. GNS Science Report 2011/54: 113p, 1 disc.

Ward, A. D., Elliot, W. J., 1995. *Environmental Hydrology*. CRC/Lewis Publishers, Boca Raton, Florida, 462p.

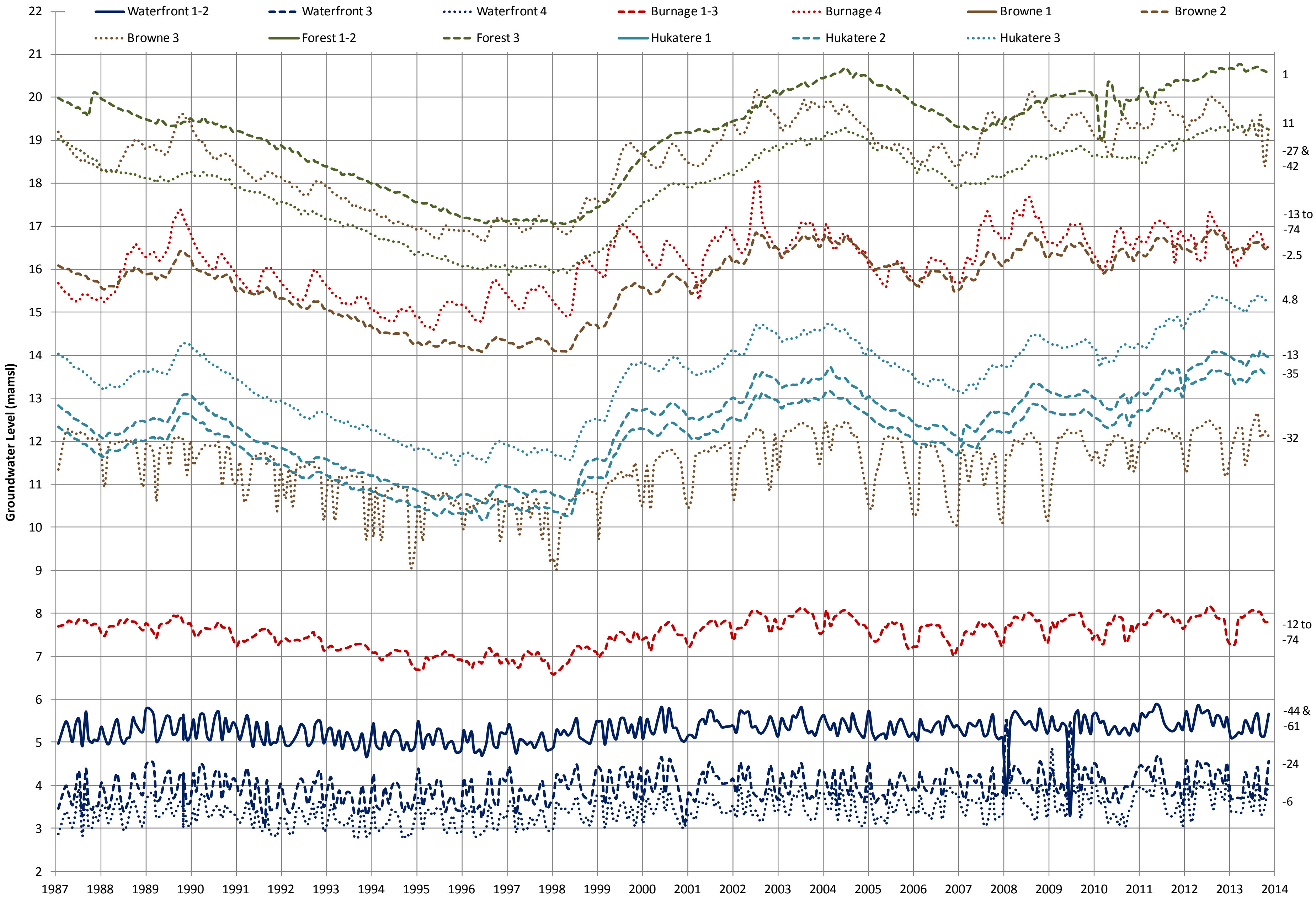
Wilson, S.R.; and Lu, X. 2011: Rainfall recharge assessment for Otago groundwater basins. Otago Regional Council technical report, 42p.

Appendix 1: Water level records (top of screen is annotated on right hand side of graph)

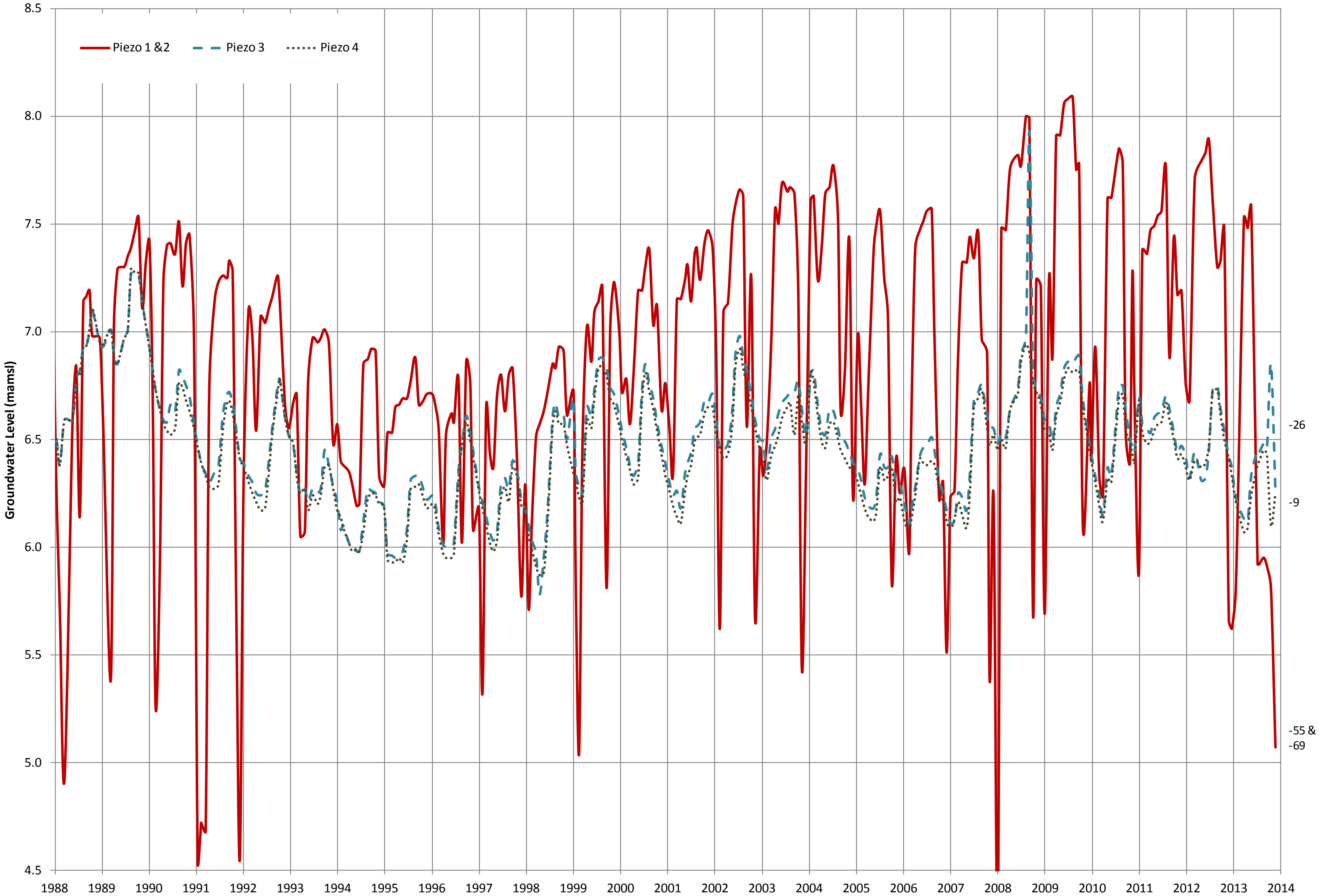
Lake Heather



Houhora to Hukatere



Paparore



Piezo 1 &2
Piezo 3
Piezo 4
Groundwater Level (mamsl)
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
-26
-9
-55 &
-69

Appendix 2: Summary of water quality monitoring data

Median values

Bore	Name	Screen elevation	Samples	Br	Ca	Cl	DRP	F	Fe	HCO_3	K	Mg	Mn	Na	NH_4	NO_3	Si	SO_4	E.Coli	Conductivity (mS/m)	pH	Redox status
200250	Fish Club, Houhora	-67.1	43	0.03	30.0	63	0.074	0.03	0.06	88	3.3	2.8	0.017	51	0.070	0.001	21	13.5	0	44	7.8	Ox?
200059	Colville, Houhora	-22.1	68	0.29	6.3	42		0.08	1.40	48	1.4	4.4	0.060	31	0.005	0.015	41	7.45	0	24	6.6	Ox?
200211	Fitzwater, Paparore	-63.8	70	0.17	34.0	52		0.07	0.06	145	2.7	5.7	0.110	42	0.060	0.015	41	8.55	0	41	7.8	Ox
209536	West Coast Rd, Waipapakauri	-55	8	0.04	9.0	33	0.035	0.04	0.01	30	0.8	1.5	0.008	29	0.003	0.001	16	3.10	0	27	8.4	Ox
201563	Vinac, Awanui	-27.9	44	0.01	11.0	68	0.001	0.01	0.22	55	2.5	2.7	0.019	63	0.001	0.001	15	0.03	0	48	7.7	Anox
209330	Waipapakauri	-43.7	18	0.06	7.0	35	0.060	0.01	0.001	26	0.7	1.6	0.0001	25	0.001	0.001	22	2.45	8	25	8.2	Ox
210449	Long Bore, Ahipara		59	0.07	4.3	32		0.02	1.50	34	1.7	3.5	0.040	25	0.090	0.290	36	6.60	0	19	6.3	Anox?

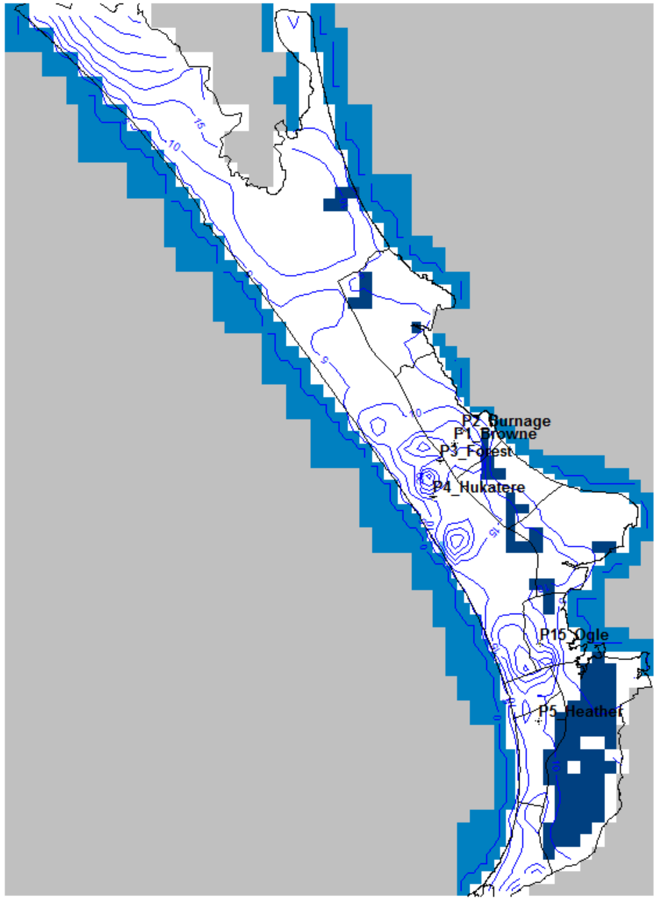
Maximum values

Bore	Name	As	B	Br	Ca	Cl	DRP	F	Fe	HCO_3	K	Mg	Mn	Na	NH_4	NO_3	Si	SO_4	E.Coli	Conductivity (mS/m)
200250	Fish Club, Houhora	0.001	0.04	0.36	35.0	90	0.11	0.24	0.11	110	3.9	3.4	0.021	56	0.24	0.50	47	16.5	14	47
200059	Colville, Houhora	0.001	0.00	0.44	9.1	58	0.08	0.14	6.90	65	2.4	6.9	0.090	37	0.13	0.48	50	9.95	0	28
200211	Fitzwater, Paparore	0.001	0.06	0.22	38.0	55	0.15	0.15	0.12	154	13.9	6.9	0.170	45	0.50	0.43	47	9.40	2419	46
209536	West Coast Rd, Waipapakauri	0.000	0.03	0.13	19.0	38	0.19	0.11	0.03	78	2.1	3.4	0.018	31	0.03	0.04	35	7.23	0	27
201563	Vinac, Awanui	0.001	0.07	0.39	27.2	92	0.36	0.27	0.60	141	6.6	6.4	0.120	72	0.60	0.03	65	24.1	1190	56
209330	Waipapakauri	0.004	0.02	0.26	17.2	39	0.15	0.07	0.03	64	1.9	3.8	0.007	29	0.06	0.02	46	7.10	326	44
210449	Long Bore, Ahipara	0.001	0.00	0.14	6.0	35	0.05	0.08	7.10	43	2.2	4.2	0.071	28	0.36	0.77	42	9.90	0	41

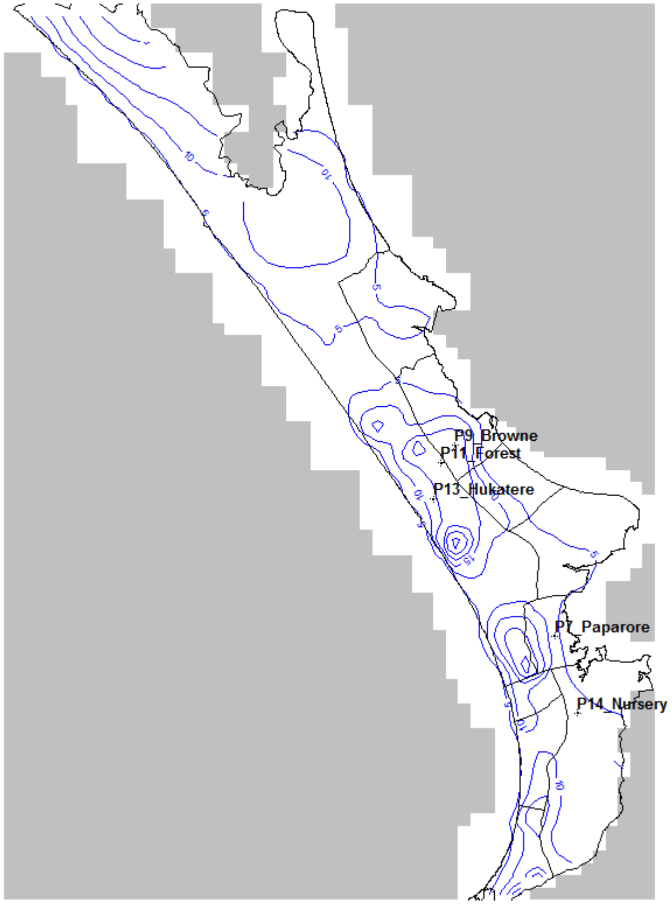
Values shown in red exceed guideline values in the NZ Drinking Water Standards (Ministry of Health, 2008)

Appendix 3: Numerical model structure

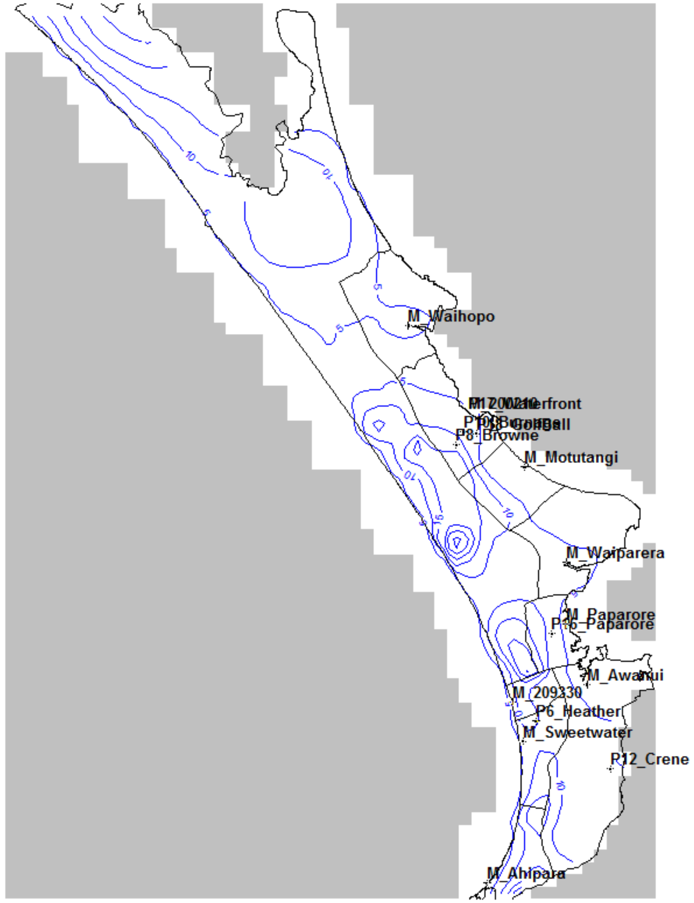
Layer 1



Layer 2

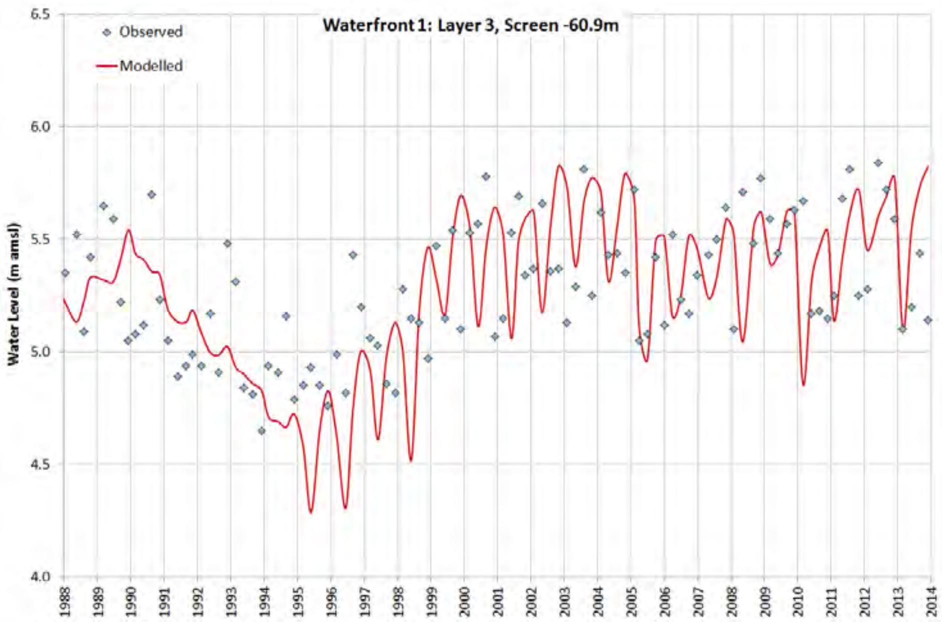


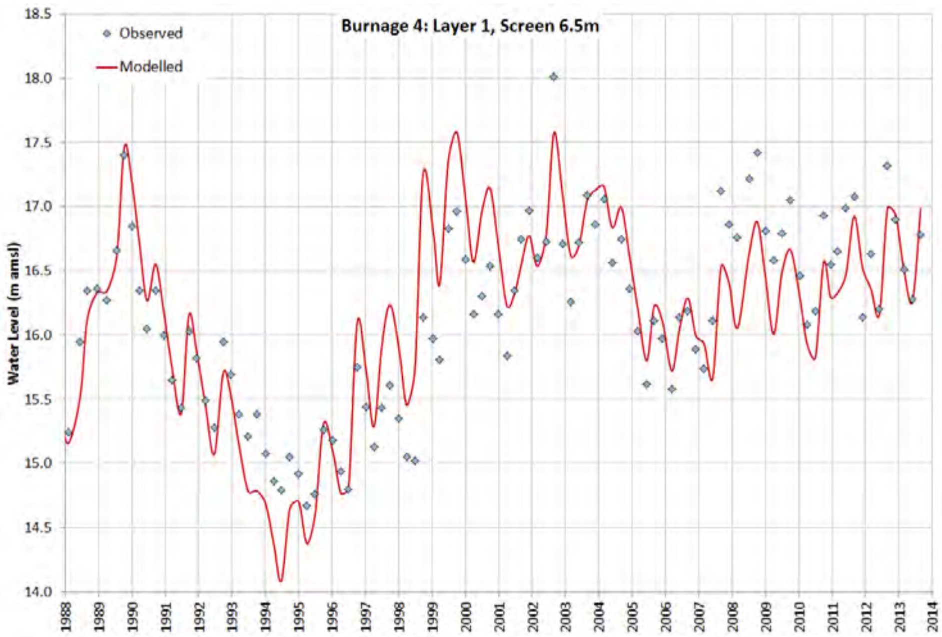
Layer 3

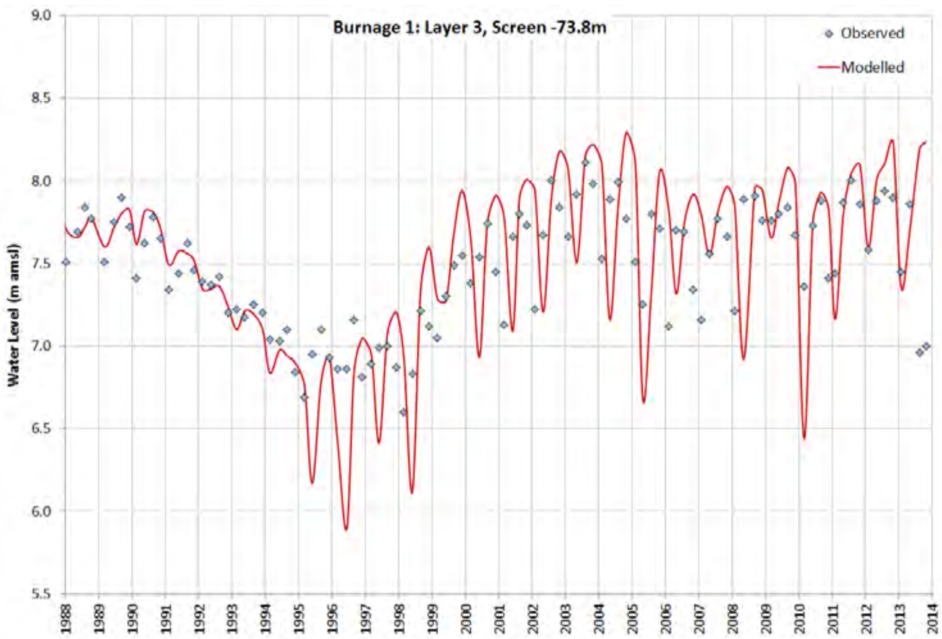


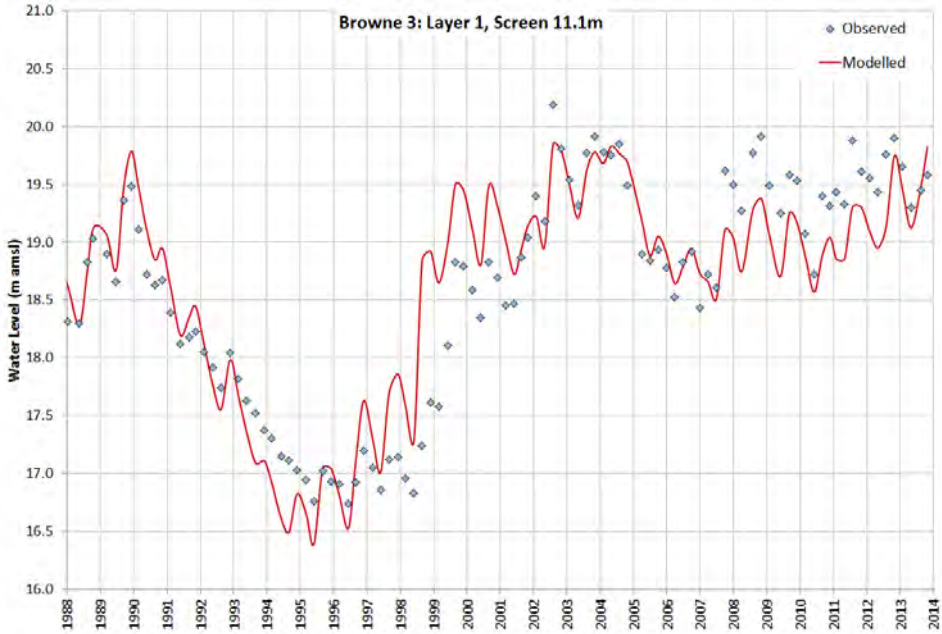
Water levels for each layer have been calculated for November 2003

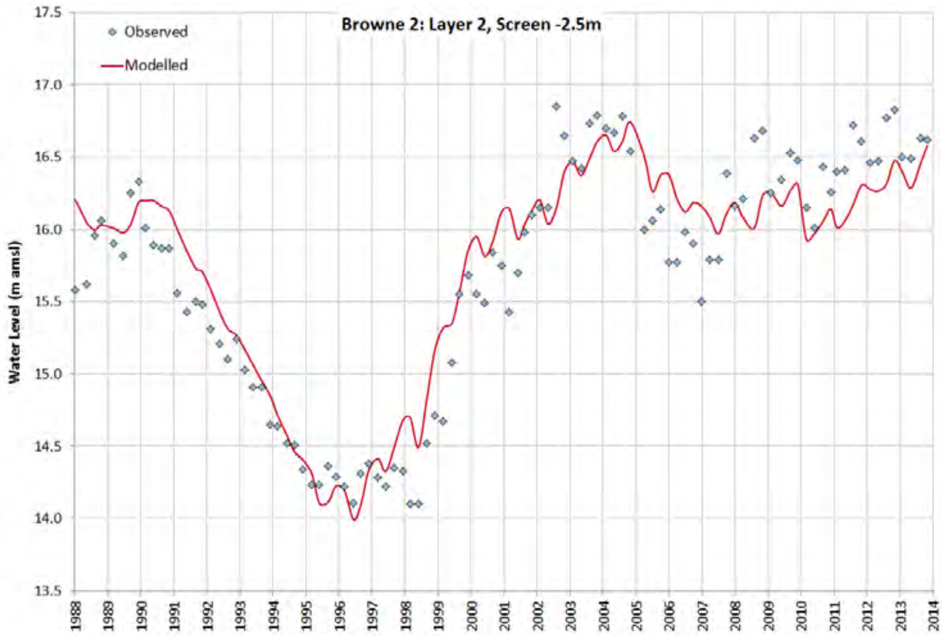
Appendix 4: Numerical model transient heads

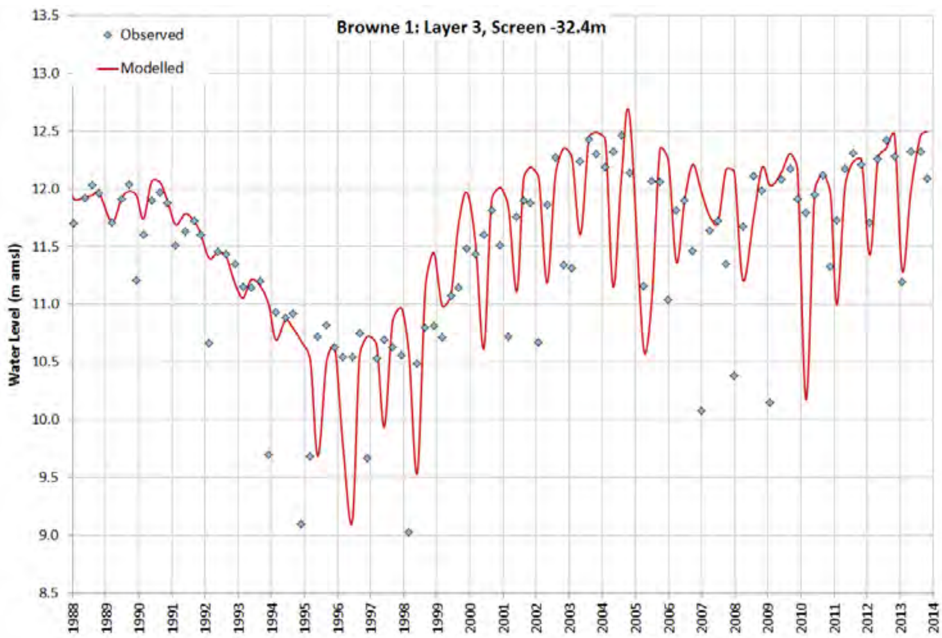


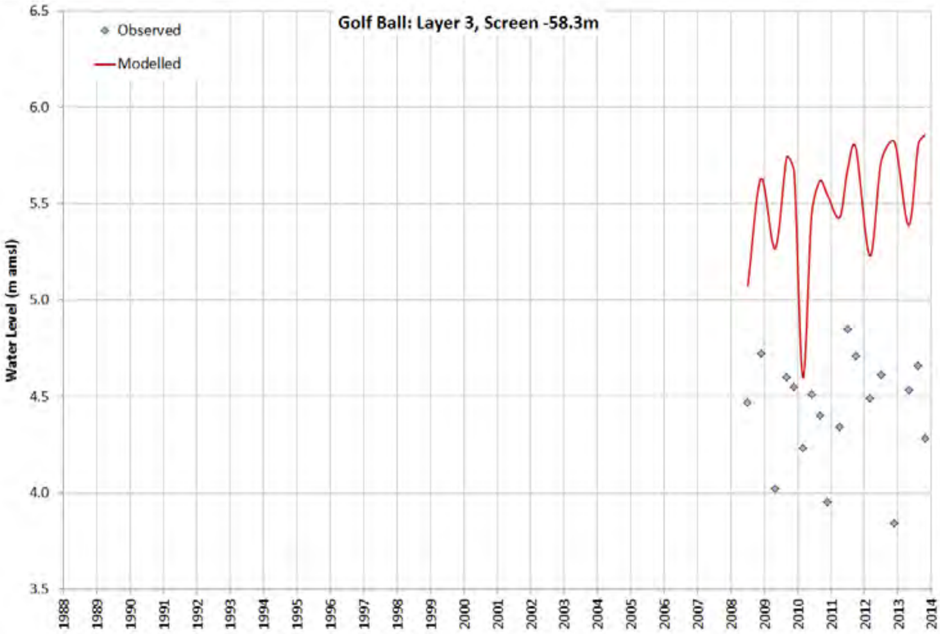


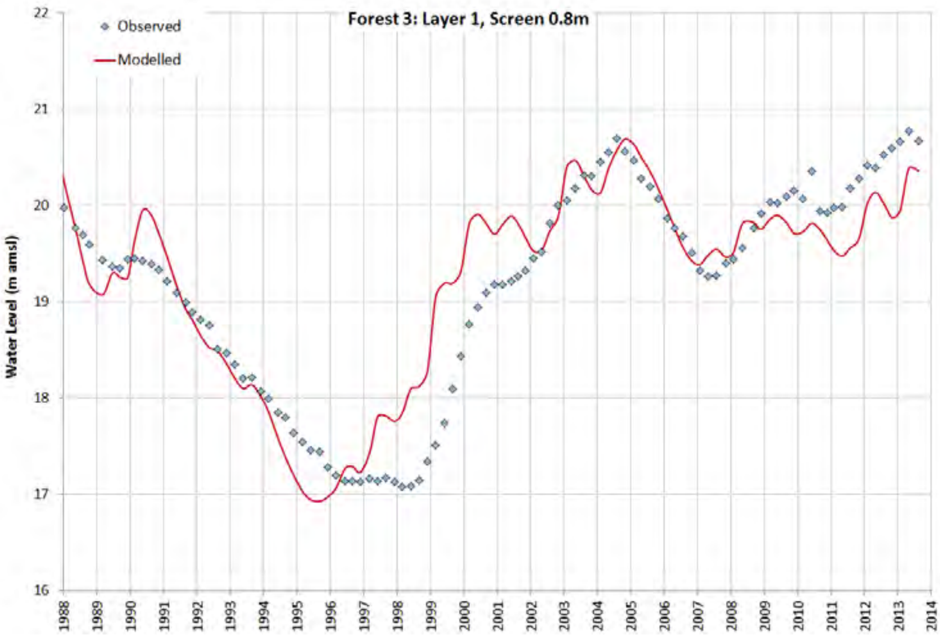



Browne 3: Layer 1, Screen 11.1m
Observed
Modelled
Water Level (m amsl)


Browne 2: Layer 2, Screen -2.5m
Observed
Modelled
Water Level (m amsl)


Browne 1: Layer 3, Screen -32.4m
Observed
Modelled
Water Level (m amsl)


Golf Ball: Layer 3, Screen -58.3m
Observed
Modelled
Water Level (m amsl)
6.5
6.0
5.5
5.0
4.5
4.0
3.5
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014


Forest 3: Layer 1, Screen 0.8m
Observed
Modelled
Water Level (m amsl)
22
21
20
19
18
17
16
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
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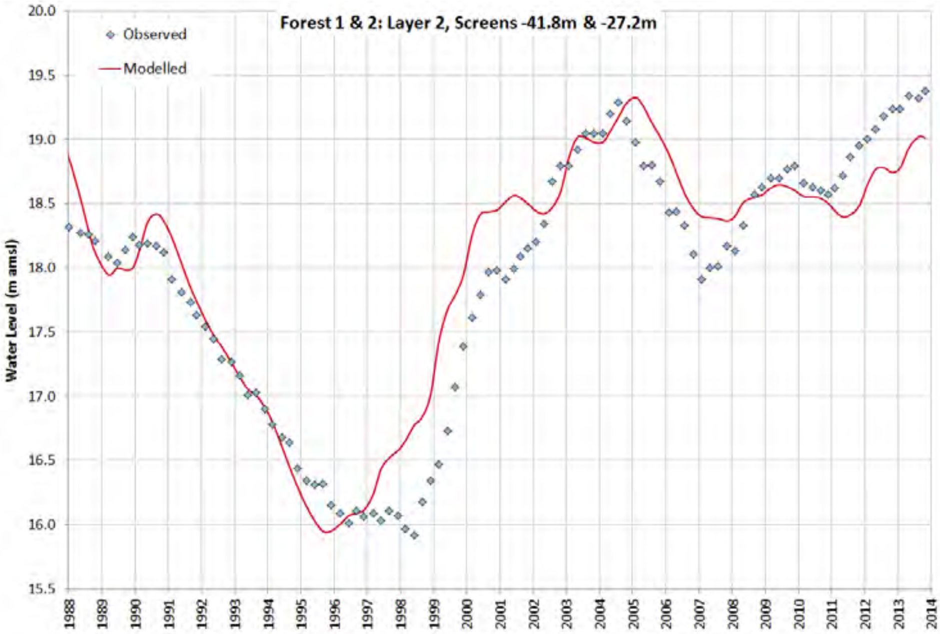
2007
2008
2009
2010
2011
2012
2013
2014


Forest 1 & 2: Layer 2, Screens -41.8m & -27.2m
Observed
Modelled
Water Level (m amsl)
20.0
19.5
19.0
18.5
18.0
17.5
17.0
16.5
16.0
15.5
1988
1989
1990
1991
1992
1993
1994
1995
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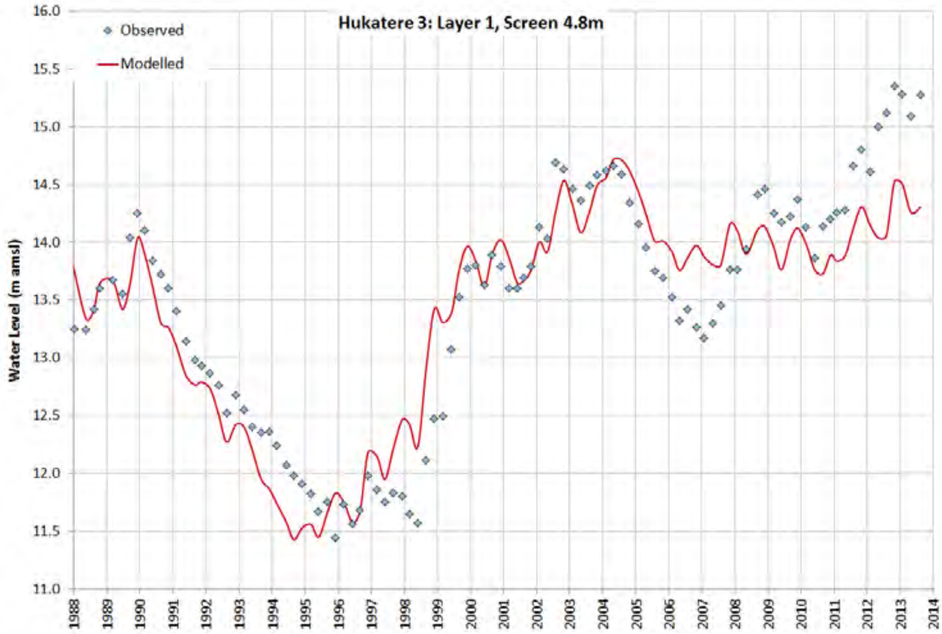
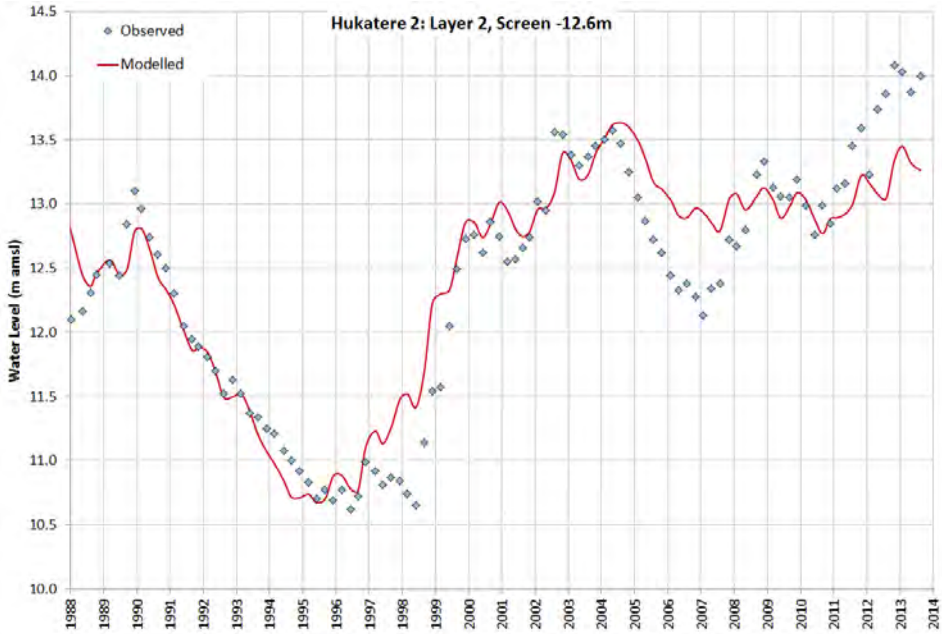
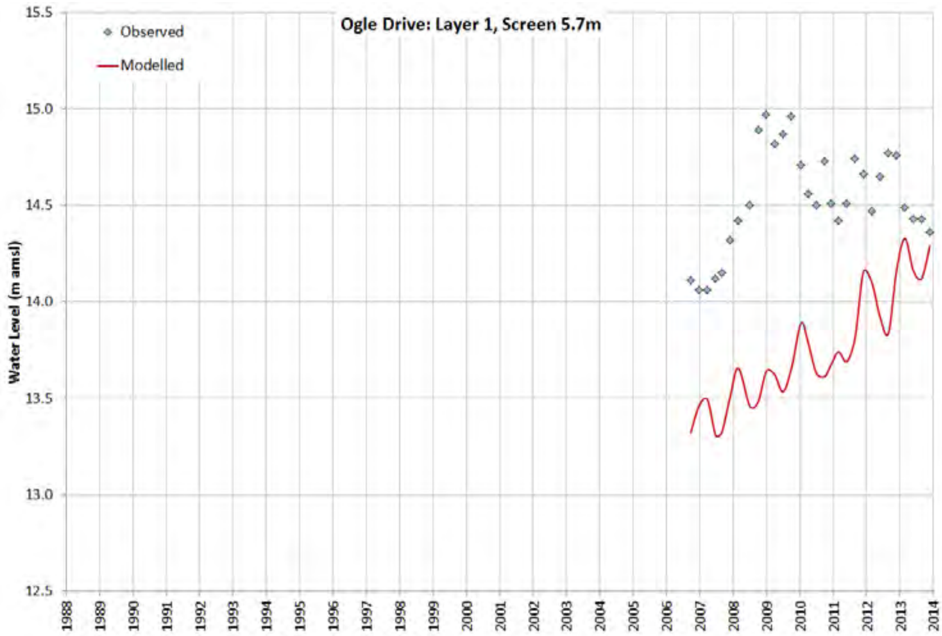
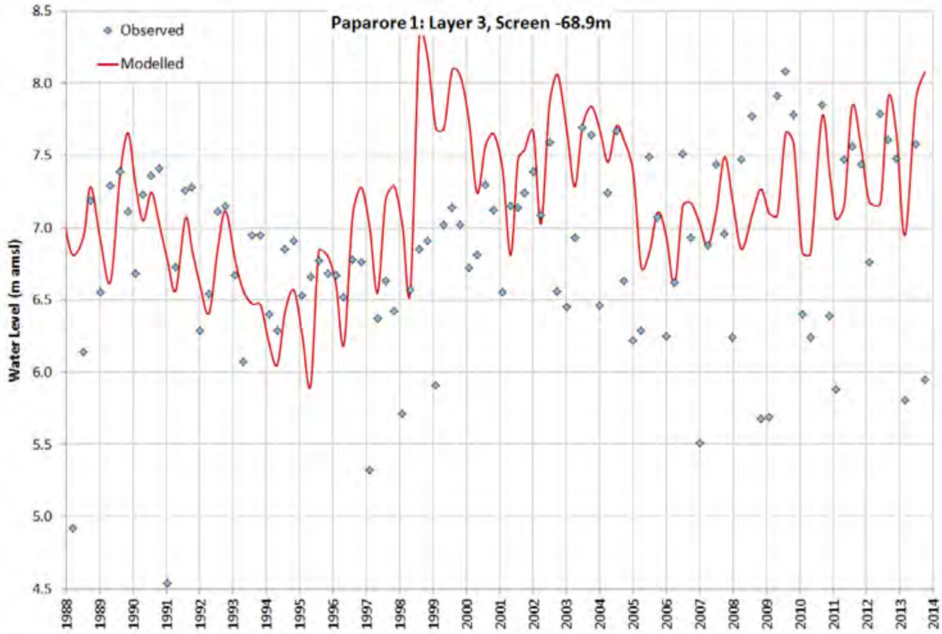
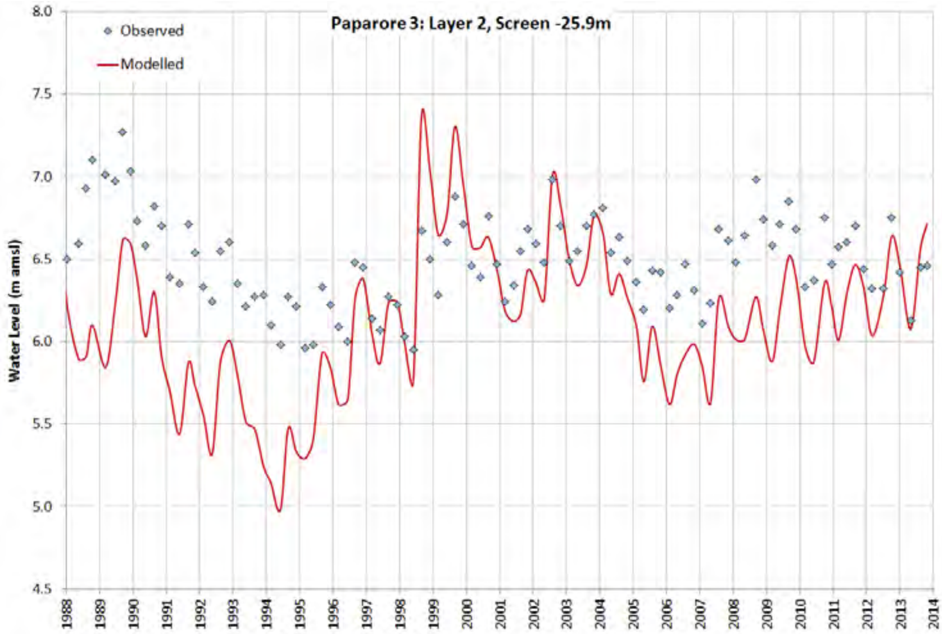
2010
2011
2012
2013
2014

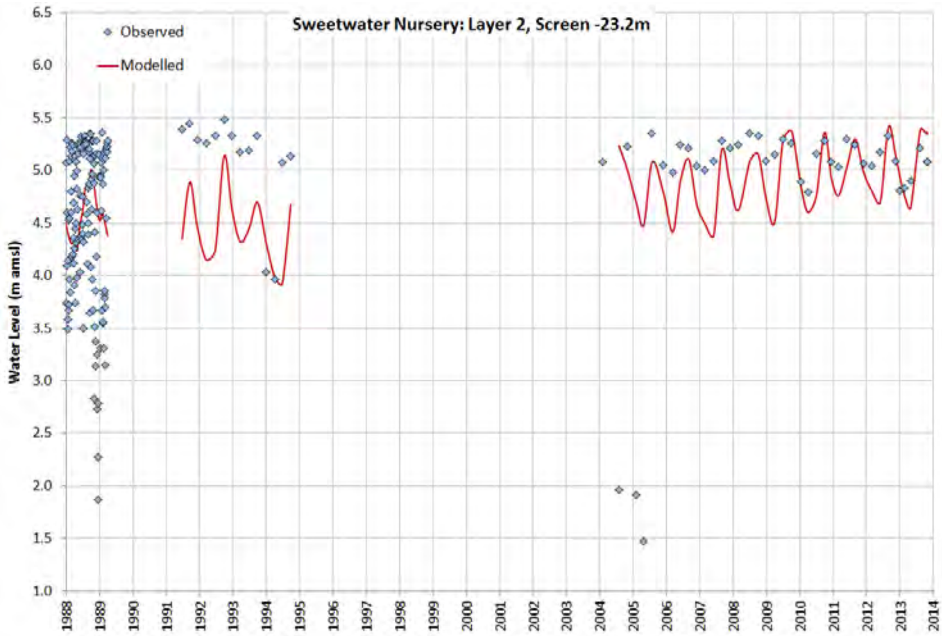

Hukatere 3: Layer 1, Screen 4.8m
Observed
Modelled
Water Level (m amsl)

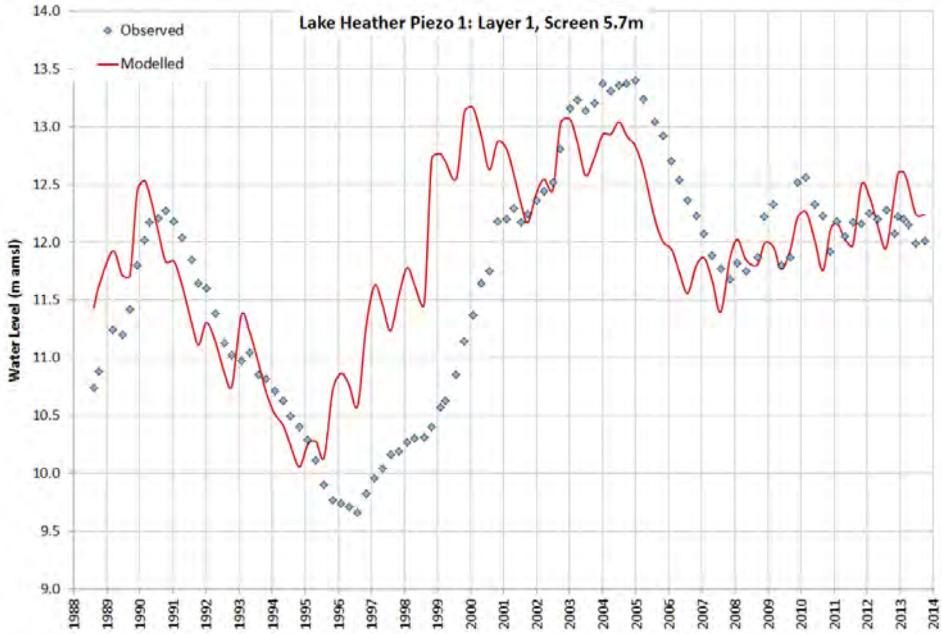

Hukatere 2: Layer 2, Screen -12.6m
Observed
Modelled
Water Level (m amsl)

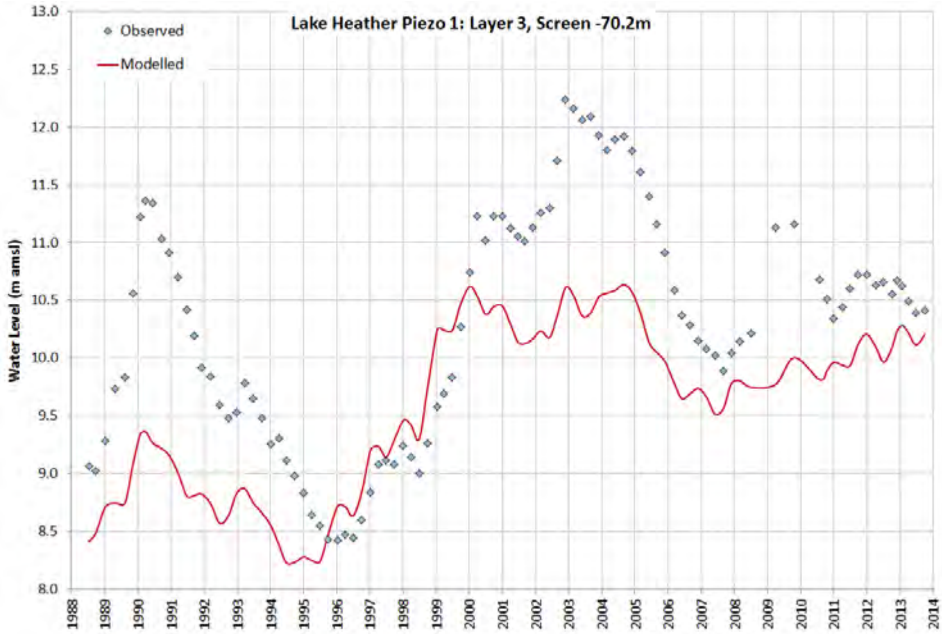

Ogle Drive: Layer 1, Screen 5.7m
Observed
Modelled
Water Level (m amsl)

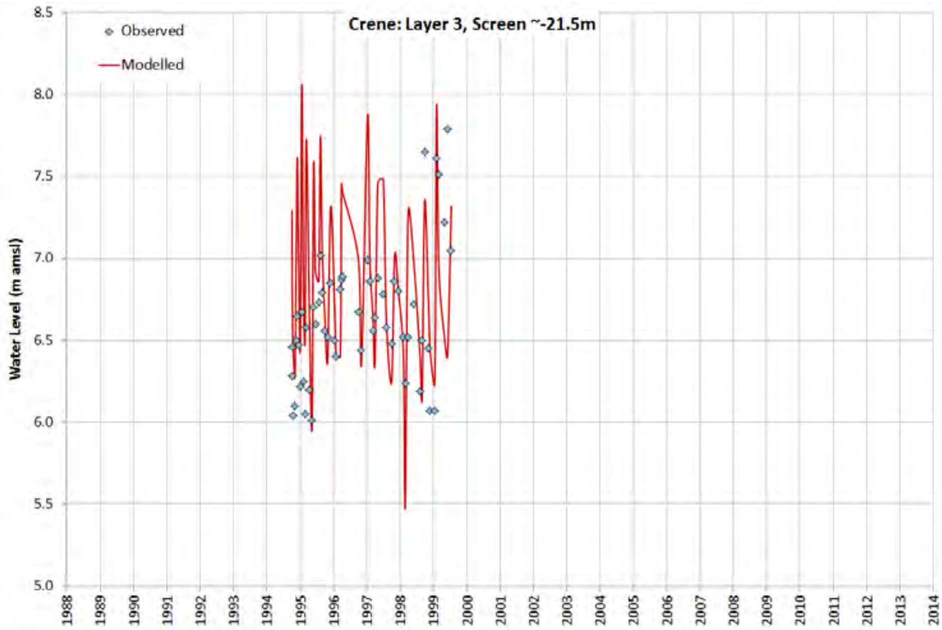

Paparore 1: Layer 3, Screen -68.9m
Observed
Modelled
Water Level (m amsl)


Paparore 3: Layer 2, Screen -25.9m
Observed
Modelled
Water Level (m amsl)


Sweetwater Nursery: Layer 2, Screen -23.2m
Observed
Modelled
Water Level (m amsl)

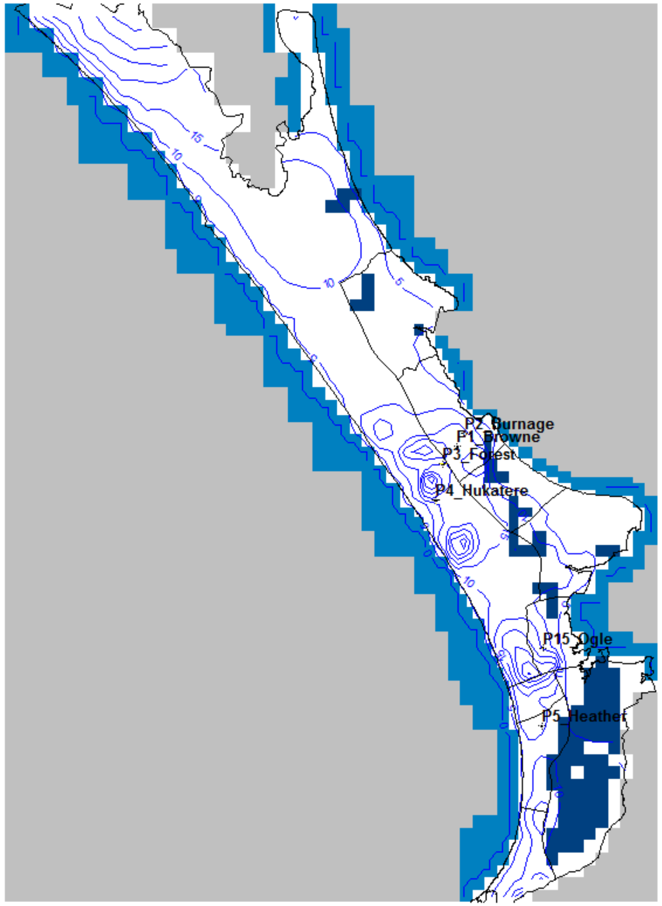

Lake Heather Piezo 1: Layer 1, Screen 5.7m
Observed
Modelled
Water Level (m amsl)


Lake Heather Piezo 1: Layer 3, Screen -70.2m
Observed
Modelled
Water Level (m amsl)

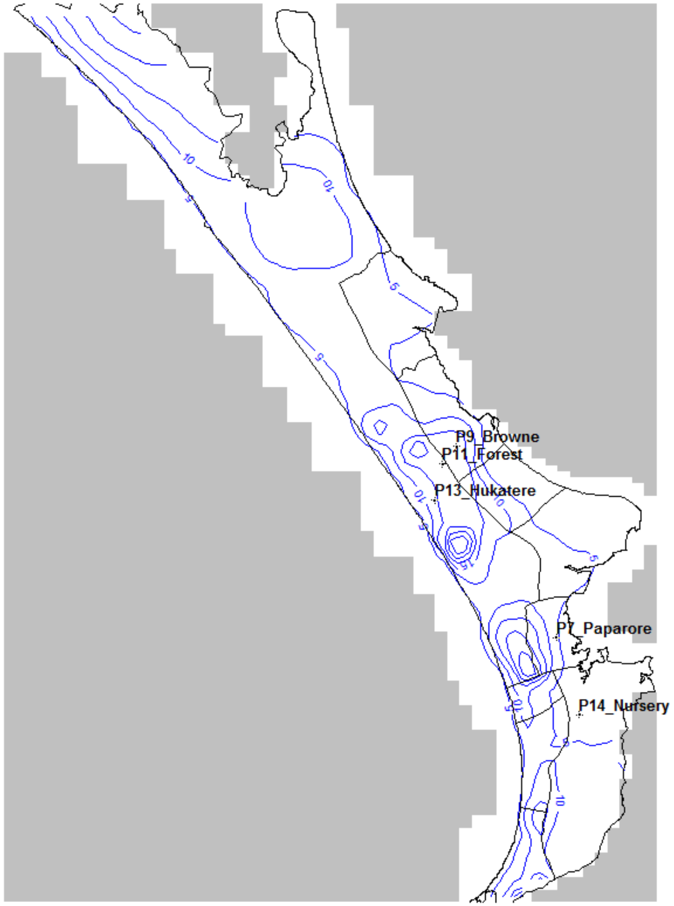

Crene: Layer 3, Screen ~-21.5m
Observed
Modelled
Water Level (m amsl)

Appendix 5: Groundwater levels for the current full allocation

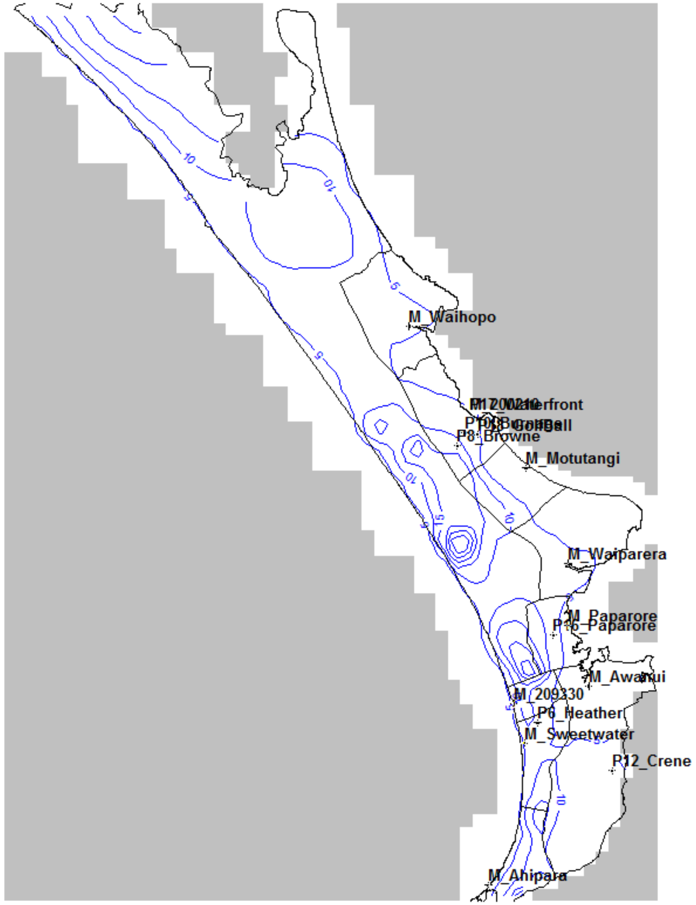
Layer 1



Layer 2



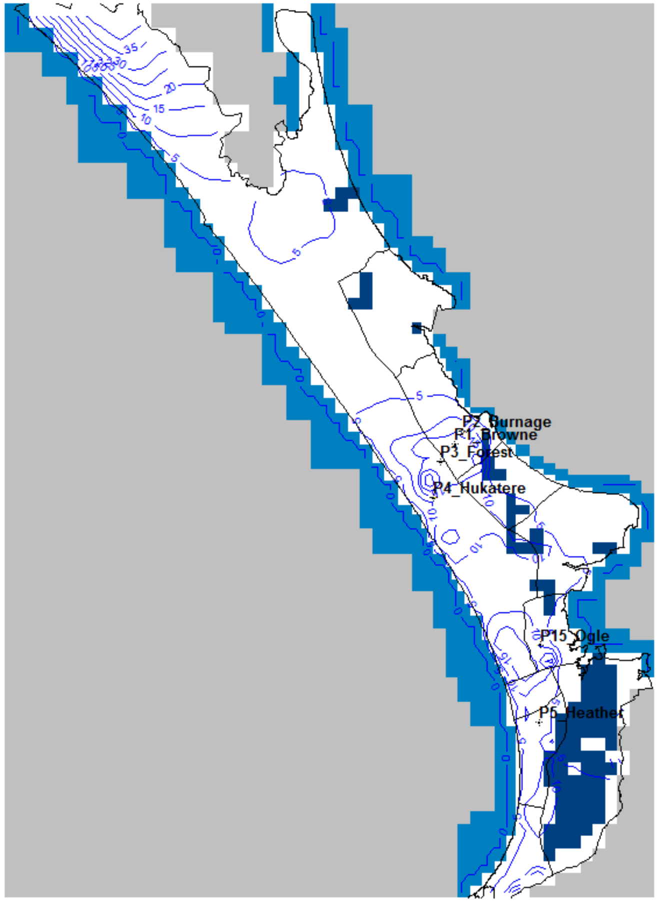
Layer 3



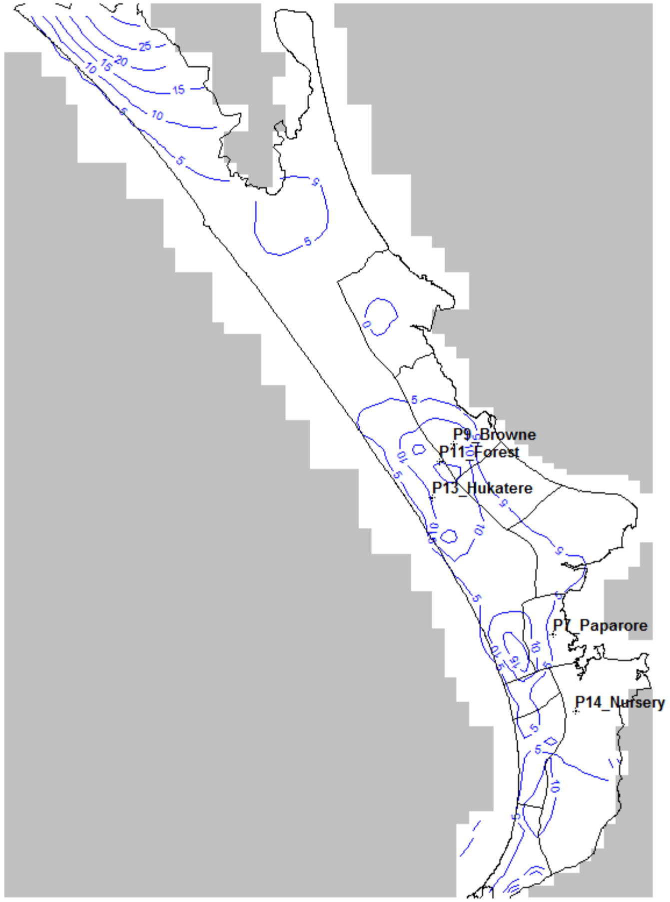
Water levels for each layer have been calculated for March 1995

Appendix 6: Groundwater levels for a maximum allocation scenario

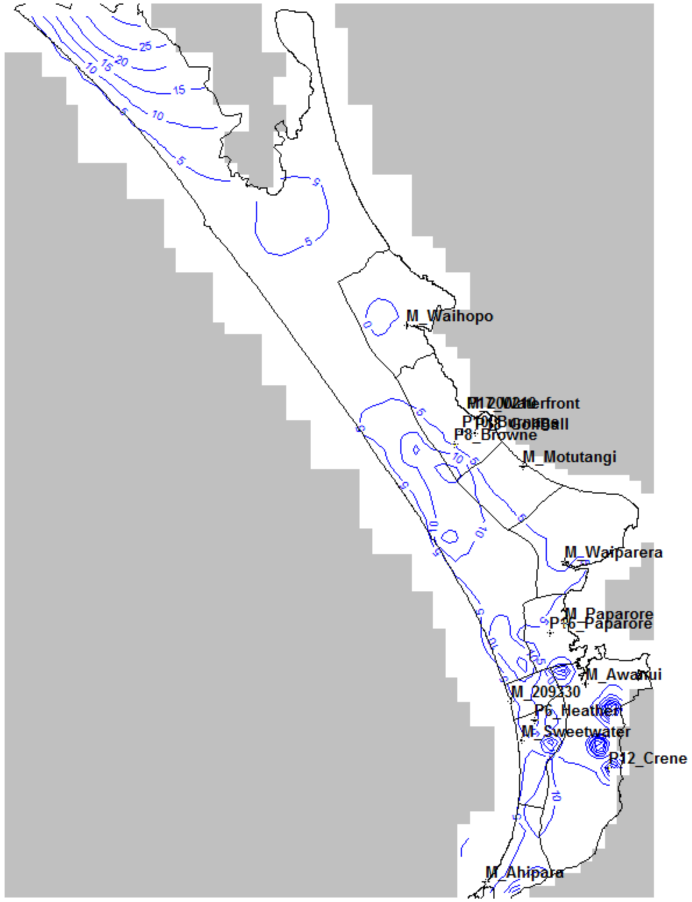
Layer 1



Layer 2



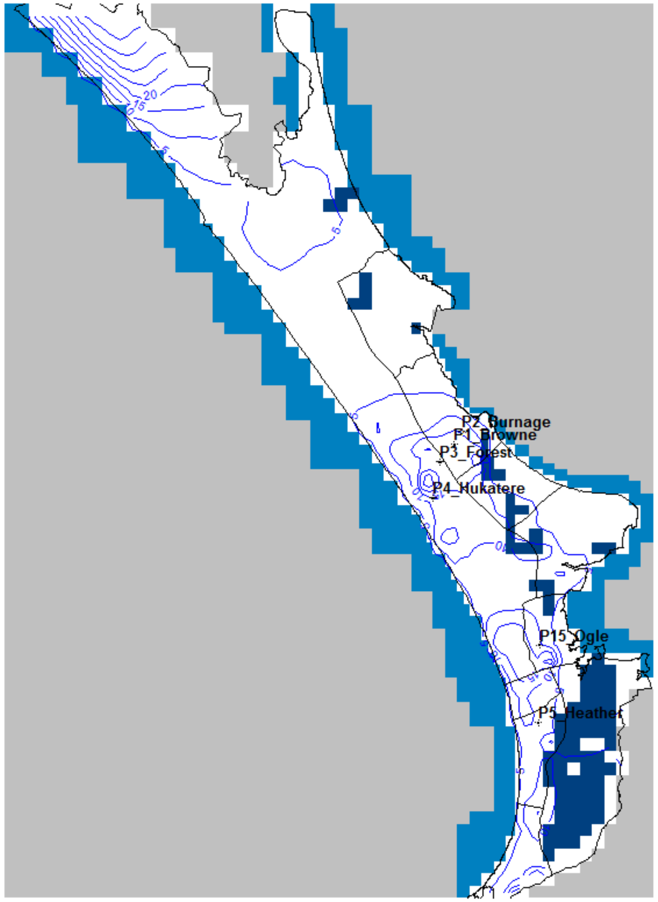
Layer 3



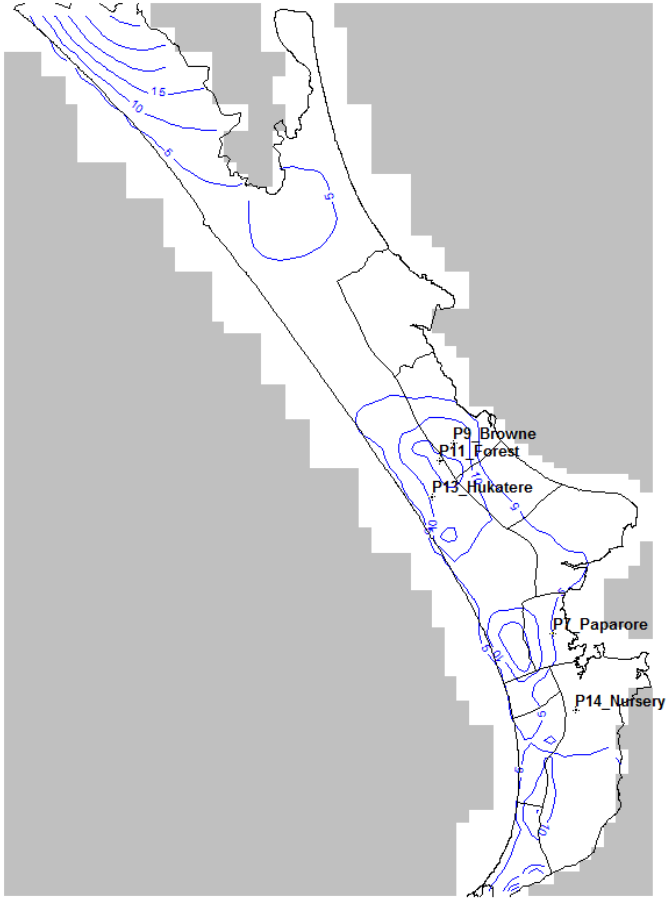
Water levels for each layer have been calculated for March 1995

Appendix 7: Groundwater levels for climate change scenario with 0.57m sea level rise and current full allocation

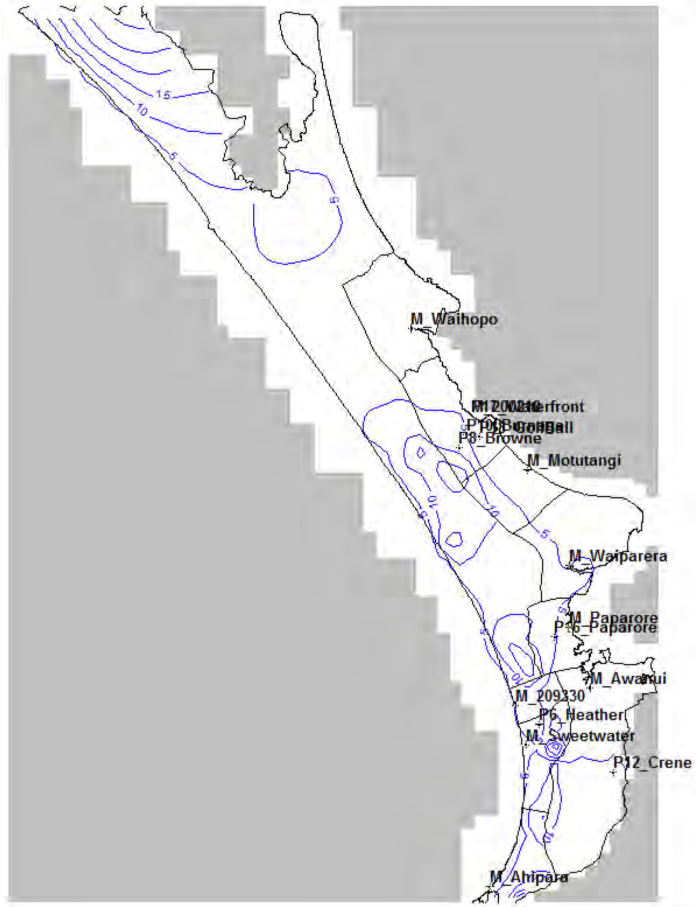
Layer 1



Layer 2



Layer 3



Water levels for each layer have been calculated for March 1995