Aupouri Aquifer Sustainable Yield
Groundwater Modelling Study
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For:
Northland Regional Council

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Contents

List of Tables

List of Figures

List of Appendices

Executive Summary

At the request of Northland Regional Council (NRC), HydroGeo Solutions was commissioned to undertake a numerical modelling assessment of the hydrogeological conditions and sustainable yield of the Aupouri aquifer. The study was initiated as a result of noticeable groundwater depressurisations in NRC monitoring bores over the last decade, and concerns raised regarding the long-term sustainability of current groundwater allocations. The principle focus of the study was on two areas of high intensity horticulture at Houhora and Paparore-Sweetwaters, which have a heavy demand on groundwater resources during the summer growing season of November to April.

The Aupouri aquifer system is located north of Kaitaia within the relatively narrow stretch of land known as the Aupouri Peninsula, between Awanui and Ngataki. The sedimentary sequence of the aquifer consists of predominately clean fine aeolian sands in the west of the peninsula overlying older more consolidated silty sands. In the east the older sands are exposed at the surface and the occurrence of iron pans, and lenses of silt, clay and peat are more common. Underlying the sands is a high permeability coarse-grained shellbed that overlays basement rocks. The shellbed is up to 20 m thick in places and provides the highest groundwater yields.

The United State Geological Survey's finite-difference groundwater model MODFLOW was requested for the study. A dual-layer regional model consisting of 7,192 active cells and encompassing an area of approximately 430 square kilometres was developed. Conceptualisation of the model involved collation and review of previous reports and data provided by NRC. Data inadequacies encountered in some areas were resolved by making estimations based on sound hydrogeological principles. This necessitated simplification of the model over the regional scale.

The aquifer geometry utilised in the model was generated from lithological information from 38 bores that penetrate the shellbed. Sparse bore information in some locations meant that a high degree of interpolation was required.

The hydraulic property distribution in the model consisted of four zones in the upper model layer representing the progradation from west to east of clean to more silty sands, and a continuous distribution in the bottom layer representing the shellbed. The five hydraulic property zones in the model are summarised as follows:

- ***Zone 1 Dune Area*** – western peninsular and beachfront, relatively clean sands.
- ***Zone 2 Dune Area*** – eastern areas, older sands with higher proportion of silts.
- ***Zone 3 Plain Area*** – low lying areas in east, high proportion of surficial silts, clays and peat.
- ***Zone 4 Lake Area*** – wetlands and numerous clay sills (lakebeds).

- ***Zone 5 Shell bed*** – highly permeable shell deposits.

Vertical anisotropy is introduced into the hydraulic zones in the upper layer to attenuate groundwater percolation rates or leakage between layers, as indicated by bore hydrographic responses. The degree of anisotropy is more significant in eastern areas where a higher proportion of silt and clay occurs.

Three distinct groundwater recharge zones were identified based on borehole hydrographic responses, vegetation cover type, surface geology and topographic data. The characteristics of each zone are summarised below:

- ***Dune Zone*** - Surrounds the forest zone on the western and eastern side. Typically displays an assortment of vegetation types consisting of pasture, bush and orchards of low to medium height and density (moderate interception losses), smaller active root zone than forest (moderate interception and evapotranspiration (ET)), and high infiltration capacity (low surface runoff). The long term average water balance as a proportion of rainfall is; recharge 18.1%, ET 81.7%, runoff 0.2%.

- ***Forested Dune Zone*** – Corresponds to the Aupouri Forest and is located adjacent to Ninety Mile Beach on the western side of the Peninsula. Typically displays a high density of tall vegetation cover (high interception losses), has high soil moisture storage and infiltration capacity (low surface runoff), and a deep active root zone (high ET). Recharge 10.4%, ET 89.5%, runoff 0.1%.

- ***Plains Zone*** - Represents the low lying areas to the east which typically display low density vegetation (mostly pasture), higher proportions of silt, clay and peat within the surficial sediments to depths of up to approximately 20 mBGL (significant surface runoff), and numerous drainage features (draining of soil moisture). Recharge 12.0%, ET 64.2%, runoff 23.8%.

The model was calibrated to transient conditions from January 1987 to September 1999. Monthly groundwater observations from nine NRC monitoring bores were used for head matching purposes during the calibration. Aupouri forest rainfall for the corresponding period was utilised by a soil moisture water balance model (SMWBM) to generate a preconditioned groundwater recharge history for the groundwater model. The SMWBM calculates soil moisture, groundwater percolation and other water balance components on a daily basis using daily rainfall and mean-monthly pan evaporation data. It provides a more sophisticated method of calculating groundwater recharge because it accounts for antecedent soils moisture conditions and variable soil evaporation rates that depend on soil moisture status and time of year.

The calibrated model provides an acceptable approximation to measured field conditions over the simulation period. A sensitivity analysis of the model calibration was conducted to quantify uncertainty caused by limitations in model parameters. Root mean square (RMS) error was calculated for each observation bore at approximately twelve-month intervals. The average RMS error range during the calibration simulation was from 0.3 to 1.0 m, which equates to an error of approximately 3% to 10% of the average difference in groundwater elevation across the aquifer. Analyses where model parameters were varied by plus and minus 30% reveal that the model is most sensitive to recharge and hydraulic conductivity and least sensitive to storage parameters.

Predictive simulations of the model were conducted to assess the performance of the aquifer under incrementally increasing groundwater abstraction rates in the two high abstraction areas, and hence the sustainable yields. Simulation involved 105 year runs utilising precondition groundwater recharge calculated from the longterm Kaitaia rainfall record from 1894 to 1967 and the Aupouri forest rainfall from 1967 to 1999. Five predictive model scenarios were simulated consisting of:

- Zero groundwater abstractions;
- 50% of currently allocated allowable abstraction;
- 100% of currently allocated allowable abstraction;
- 250% of currently allocated allowable abstraction; and
- 500% of currently allocated allowable abstraction.

Results from the predictive simulations indicate negligible difference in the response of the aquifer after 105 years between the zero abstraction and 100% abstraction scenarios. This would indicate that the aquifer is currently not over allocated. Results for the 500% abstraction scenario indicates localised depressurisation in the area of the pumping bores, but little difference elsewhere in the aquifer.

Groundwater throughflow rates were calculated by the model for each scenario along four kilometres of the west and east coasts, adjacent to the Hukatere-Houhora transect and the Paparore area, respectively. Throughflow rates at the Houhora transect vary during dry and wet periods from approximately 1,500 to 4,000 m^3/day/km on the west coast and between 1,000 to 3,000 m^3/day/km on the east coast, for the zero abstraction scenario. These rates were reduced with the 500% abstraction scenario by approximately 6–15% and 12–35% for the west and east coasts, respectively.

Throughflow rates for the Paparore area were estimated to vary from approximately 1,000 to 3,000 m^3/day/km at the west coast, compared with 300 to 700 m^3/day/km on the east coast. With the 500% abstraction scenario, these rates are reduced by approximately 7–20% and 21–50% for the west and east coasts, respectively.

This modelling study has provided council with a preliminary model that has increased the level of understanding of the aquifer flow system and will assist in formulation of future management policies and decision making. The model is limited in a number of areas as identified in the report, and will require refinement or redefinition when additional data becomes available if more detailed assessments are needed in the future.

1. Introduction

The Aupouri aquifer system is located north of Kaitaia within the relatively narrow stretch of land known as the Aupouri Peninsula, between Awanui and Ngataki (Figure 1). The aquifer coves an area of approximately 430 square kilometres and is bounded in the west by Ninety Mile Beach and in the east by Rangaunu Bay, and Rangaunu and Houhora Harbours.

Groundwater is the main source of horticultural irrigation and farm water on the Aupouri Peninsula. Since the 1980's development and landuse changes such as subdivision of farmland for orchards and market gardening, planting of exotic forest plantations and development of tourist resorts have resulted in increased demand on the groundwater resource.

Noticeable groundwater depressurisations in monitoring boreholes over the last decade along with concerns raised regarding the long-term sustainability of current groundwater allocations prompted Northland Regional Council (NRC) to seek tenders for a study to improve their understanding of the aquifer system. Two areas of high intensity horticulture at Houhora and Paparore-Sweetwaters, which have a heavy demand on groundwater during the summer growing season of November to April, were of particular concern.

In November 1999, HydroGeo Solutions was commissioned by NRC to conduct a study of the Aupouri aquifer. The objectives and broad methodology of the study were as follows:

- Review available hydrogeological and climate data.
- Conceptualise and develop a computer-based numerical groundwater flow model using the United States Geological Survey's MODFLOW code through the Visual MODFLOW interface.
- Provide an assessment of long-term average sustainable yields from the aquifer, and in particular from the two areas of intensive groundwater abstraction.

The developed model will provide a tool for increasing the level of understanding of the aquifer flow system, identify areas where additional data is required, allow preliminary assessments of the effects of increasing groundwater abstraction rates and aid in formulation of management policies and decision making. Future refinement of the model when additional data becomes available will enhance the accuracy of model predictions.

This report addresses the agreed scope of works, provides summary findings and identifies areas where additional research is required. The work has been undertaken in accordance with HydroGeo Solution's proposal dated 28th September 1999 and NRC's short form agreement for consultant engagement signed 9th November 1999.

This report has been prepared for the benefit of Northland Regional Council with respect to the particular brief given to HydroGeo Solutions and may not be relied upon in other contexts or for any other purposes without our prior review and approval.

2. Background Information

Baseline data for the study has been obtained from various sources. Where appropriate the data has been collated in digital form and installed in the appropriate spreadsheet or database. All relevant spatial data have been incorporated into the appropriate AutoCAD and SURFER grid files. Details of the available data are provided below.

Hydrogeology: NRC prepared a water resource assessment of the Aupouri Peninsula in 1991 (NRC, 1991). This report provides a comprehensive review of previous hydrogeological investigations and compiles all relevant supporting information available at the time of publication, including:

- Descriptions of the study area's physical features including topography, surface drainage, geology, soil types, vegetation, landuse and climate.
- Summaries of test pumping results and groundwater abstraction allocations.

The reader is referred to this report for a more detailed description of the study area.

In addition, NRC provided all relevant updated data from their respective databases including groundwater and lake monitoring data, drilled borehole and lithological log data, groundwater consent data, and test pump records.

Topographic & Regional Cadastral Data: The topography of the Aupouri Peninsula area has been mapped by the Department of Land and Survey and covers three NZMS 260 series 1:50,000 scale map sheets entitled Kaitaia O04, Ahipara N04 and Houhora N03. NRC supplied this data and additional cadastral information in digital format from their ArcView GIS database.

Rainfall and Pan Evaporation: Historical daily rainfall records of varying length have been supplied for four sites within the study area, which were subsequently processed and validated for completeness. A summary of this information is provided in Table 1.

Table 1. Summary of available daily rainfall records.

Station Name	Station ID	Approx. Easting	Approx. Northing	Start Date	End Date	Length (years)	Days Missing	Complete (%)
Kaitaia*	A53121	2534400	6676600	01/10/1893	30/09/1999	106	1595	95.88
Waiharara	A43921	2528700	6694800	01/06/1956	08/05/1994	37.9	244	98.24
Aupouri Forest*	NRC 530204	2528800	6687800	10/03/1967	31/08/1999	32.5	1020	91.40
Kaitaia – Weissing*	NRC 530205	2534500	6676500	02/12/1992	31/08/1990	6.9	1	99.96

* Still in operation.

Raised daily pan evaporation data has been obtained for the Kaitaia Observatory for the period 26 April 1985 to 28 October 1999.

All additional data inputs are referenced where appropriate.

2.1 Topography

The topography and drainage patterns of an area have a significant influence on the pressure distribution of the underlying groundwater regime. Groundwater pressures are normally highly correlative with topography, displaying greater pressures in areas of higher relief and lower pressures in low-lying areas.

Figure 2 shows the regional topography of the study area, interpolated with the minimum curvature geostatistical technique.

In the Aupouri aquifer the presence of elevated topography immediately adjacent to low lying areas with semi-confining lithologies at or near the surface results in artesian groundwater pressures, as occurs in some areas at Sweetwaters and Houhora.

The land is characterised as hummock and swale country and consists of various terraces, interdunal flats, lakes and swamps. Ground surface elevations across the centre of the study area rise gently from mean sea level at the coast, to around 80 to 100 metres above mean sea level (mAMSL) on the western low rolling dune system. The southern and eastern plains adjacent to Ahipara, Awanui and Waipapakauri have a mean ground elevation of around 5 to 10 mAMSL. The southern boundary of the study area is defined by a rapid change in ground elevation associated with the rugged hills to the south of Kaitaia that rise to in excess of 300 m.

2.2 Rainfall & Pan Evaporation

Any study involving assessments of the water balance of an area and the interaction between surface and groundwater processes generally requires a clear understanding of local rainfall and evaporation characteristics. Rainfall is the most significant factor governing the generation of surface runoff and groundwater recharge,[1] as it determines the physical limit to the amount of water available for these processes. Evaporation on the other hand works to reduce the amount of rainfall available, both directly and indirectly through the interaction with vegetation and soils.

Rainfall over time is highly variable in frequency, intensity, duration and spatial distribution, with the variability primarily a function of prevailing weather systems in the short-term and changing climatic patterns in the long-term. Rainfall variability is significant in determining the amount of excess rainfall available for surface runoff or groundwater recharge. For example, a rainfall pattern of frequent light showers would result in high interception and evaporative losses and thus limited surface runoff or groundwater recharge. Whereas frequent heavy rainfall may more readily overcome surface moisture deficits and result in a greater proportion of excess rainfall.

[1] Other factors include topography, vegetation cover, soil type, underlying lithology etc.

Land mass influences also play a significant part in the variability of rainfall. For example, leeward coastal environments such as Aupouri are susceptible to less stable weather patterns than land locked or orographically protected locales such as Hawkes Bay and Canterbury. Rainfall from westerly-quarter frontal systems during winter and tropical cyclones during summer are likely to be more frequent on the Aupouri Peninsula.

Summary statistics of mean monthly rainfall and pan evaporation for the various stations are given in Table 2 and illustrated in Figure 3. Appendix A provides a more detailed analysis of rainfall data for the various stations and includes data tables and histograms for each station.

Mean annual rainfall for the various stations in the study area increases to the south with a range of 1161 mm at Waiharara (A43921) to 1377 mm for Kaitaia (A53121). This is a reflection of the orographic influence of the hills to the south of Kaitaia. The average standard deviation in mean annual rainfall is 230 mm, indicating that the variation in annual rainfall as a proportion of mean annual rainfall is generally within 17% to 20%.

Table 2. Summary statistics of mean monthly and annual rainfall (mm) for various stations and Kaitaia pan evaporation (mm).

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
Aupouri Forest 530204	75	70	73	110	100	146	137	134	113	97	85	78	1213
Waiharara A43921	66	80	75	94	107	138	132	134	110	84	76	73	1161
Kaitaia Weissing 530205	74	68	70	123	107	172	171	124	148	120	67	93	1306
Kaitaia A53121	91	88	81	109	134	157	157	145	127	109	90	88	1377
Kaitaia pan evaporation	171	149	131	87	63	46	52	62	83	114	132	157	1246

Figure 3 indicates that the greatest rainfall occurs during the winter months of June, July and August. However, summer rainfalls are still significant, as the average seasonal variation in rainfall is less than 50%.

Pan evaporation is highly seasonal with maximum rates occurring in the summer months of December (157 mm) and January (171 mm), and the minimum rates occurring during the winter months of June (46 mm) and July (52 mm). During the winter months of April to September rainfall exceeds pan evaporation, indicating that in terms of the regional water balance, groundwater recharge is likely to be most significant during this time.

Correlative statistics were performed on the respective gauging stations to determine their applicability to the study area. Methodology and results of this analysis are summarised in Appendix A. In general, rainfall data from all four stations displays a high degree of correlation on a 30-day moving average basis. This indicates that it is appropriate to implement data from one station to replace missing data from another.

A long-term historical rainfall record that will be used for groundwater recharge analysis has been developed based on Kaitaia (A53121) data from January 1894 to February 1967 and Aupouri Forest data from March 1967 to September 1999. Missing days were replaced with data from the other stations where available and in the following order of preference; Aupouri Forest, Kaitaia (Weissing) and Waiharara. Where no corresponding data was available, data from the other stations exhibiting similar monthly southern oscillation indexes were implemented.

Inspection of plots of annual moving total in Figure A1 and rainfall residual mass in Figure A2 are useful for indicating periods of above average (positive values) and below average (negative values) rainfall, and identifying rainfall cyclicity.

From this data it appears that the frequency of dryer than normal periods is greater from about 1960 to the current time. In addition, the duration and magnitude of wetter than average periods is reduced. This may suggest a long-term climatic variation, but whether this fluctuation is normal is difficult to determine without significantly longer historical rainfall records.

The cyclically of drought and wetter than average periods have in the past been linked to various phenomenon such as the appearance of spots on the sun (sun spots), the build-up and ebbing of green house gas emissions, and volcanic ash in the Earth's atmosphere, to name but a few. Over recent times however, an increasing amount of interest has focussed on the "El Niño - Southern Oscillation[2]" (ENSO) phenomenon and the impact this has globally.

2.3 El Niño Southern Oscillation

The El Niño is a natural fluctuation of the Earth's global climate system, occurring with the periodic development of unusually warm waters along the tropical South American coast and extending out along the Equator to the dateline. El Niño events occur about 3 to 7 years apart, typically becoming established around April or May and persisting for about a year thereafter.

The main impacts of El Niño events arise from shifts in global rainfall zones resulting in droughts in some regions and floods in others. New Zealand does not lie in a high-impact ENSO region, but our climate is affected by changes in atmospheric circulation (winds). In New Zealand, the El Niño is typically associated with more southerly winds in winter, more southwesterly winds in spring and autumn, and more westerlies in summer. This results in cooler conditions nationally, and higher than average rainfall in western regions, while drought occurs in eastern regions and Northland.

[2] The Southern Oscillation refers to the seesaw of sea-surface atmospheric pressure changes that occur between the southeast Pacific Ocean and the Indonesian region. The Southern Oscillation Index is the main ENSO indicator and refers to an "index" number indicating the pressure difference between these two regions. Negative numbers indicate El Niño while positive numbers indicate La Niña conditions.

Large climatic variations also arise from other natural unexplained and random causes, which can swamp the "typical" pattern of El Niño influences. For example, the El Niño summer of 1997-1998 was atypically very warm (Basher, 1998).

Between El Niño events, there often occurs an approximately opposite extreme known as a La Niña event, where cooling of South American Equatorial waters occur. La Niña events have weaker impacts on the climate and New Zealand tends to experience an increase in northeasterly winds, which bring more moist rainy conditions to northeast parts of the North Island. The last La Niña event was over the summer of 1998-1999, when 1 in 100 year flooding occurred in parts of Northland and greater than three times normal monthly rainfall occurred at the Aupouri Forest during April.

There is a strong correlation between the ENSO phenomenon and the occurrence of below and above average rainfall periods in the Aupouri aquifer region. Figure 4a shows a plot of rainfall residual mass for Kaitaia versus monthly SOI for 1890 to 1999[3] and demonstrates that negative SOI generally coincide with lower than normal rainfall while positive SOI correlate with greater than normal rainfall. There are some obvious departures from this when the complete opposite to that expected has occurred, such as during 1898, 1924, 1950, and 1973 to 1975.

Figure 4b indicates the same information for 1980 to 1999 on an expanded timescale and shows a strong correlation. The highly publicised El Niño periods of 1982 to 1983, 1987, 1991 to 1994, and 1997 to 1998 (Basher, 1998; B. Met., 1999) resulted in lower than average rainfall, although it is interesting to note that the 1997 to 1998 event did not have as great an impact as the 1982 to 1983 event, even though their respective SOI are similar in magnitude. This implies effects of other climatic influences as previously discussed.

From the second quarter of 1998 to the current time (November 1999) the SOI index has been moderately to strongly positive and rainfall for Kaitaia has also been well above normal, especially during January, February and April of 1999.

The ENSO phenomenon has direct and important implications for groundwater recharge, and ultimately sustainability of an area's groundwater resources. The highest demand on groundwater in the Aupouri aquifer region will be experienced during El Niño conditions and during these times rainfall is less than normal, and as a consequence groundwater recharge is significantly reduced. This may result in a two-fold reduction in groundwater storage levels in comparison to average times.

There is a need for decision-makers and resource managers to apply climate information and predictions to improve resource sustainability and management of risk to the resource. Simulations of predictive models need to consider the variation in climate and for this reason the long term historical rainfall record will be used in this study for predictive purposes.

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[3] SOI data courtesy of the Bureau of Meteorology Australia (www.bom.gov.au/climate).

2.4 Geology and Aquifer Geometry

The geology of the Aupouri aquifer consists of Quaternary to Recent unconsolidated sedimentary materials deposited in beach and dune (abandoned shorelines and marine terraces), intertidal estuarine, lakebeds and swamp environments. The sediments typically comprise fine-grained sands interspersed with sporadic gravel, peat, lignite, silt, clay and shell beds. Cleaner aeolian sands of younger age overlay older more silty sands in the west, while in the east these older sands are exposed and display a greater proportion of silts, clays, peat and iron pans (McIntosh, 1988; NRC, 1991).

Underlying the Aupouri aquifer are basement rocks, which vary from Tertiary argillaceous limestones, sandstones, mudstones and conglomerates in the south of the study area, to Lower Cretaceous volcanic rocks of the Mt. Camel formation in the north.

Drilling data indicates that the sedimentary sequence of the Aupouri aquifer may be broadly categorised into two lithological units, as described below.

- A high permeability basal shellbed blankets the basement rocks and varies in thickness from only a few meters in areas of basement highs to a maximum thickness of around 20 m in basement depressions. The shellbed consists of various sized Gastropod and Bivalve shell fragments in a fine-grained sand matrix, together with lenses of gravel and lignite in some locations. In general, the shell bed increases in thickness towards the west. The shellbed is split at some locations as is shown for boreholes 200, 311, 318 and 1512.
- Overlaying the shellbed is a sequence of predominantly clean unconsolidated fine-grained sands, varying in thickness from east to west from approximately 40 m to greater than 100 m. The sand sequence is interspersed with lensoidal (discontinuous) layers of alternating silt, clay and peat in the upper portion of the sequence. The occurrence of these lower permeability materials increases towards the east, although delineation is difficult due to historically poor quality lithological borelogs, and the fact that differentiation is not as clear-cut as for the shellbeds.

Figure 5 shows the depth to base of the Aupouri aquifer (hardrock), and indicates that the depth to base and hence aquifer thickness generally increases from east to west.

The base of aquifer plot in Figure 5 was generated from lithological data for bores registered on NRC bore database. Only those bores that had penetrated to basement rocks (generally limestone or basalt) or were considered near base due to increasing presence of shell fragments were implemented in the interpolation. Interpolation of the base of aquifer contours utilised the Kriging geostatistical gridding method with a linear variogram function and grid spacing of 500×500 m[4].

[4] The base of aquifer interpolation is an estimate only. It is based on available bore data at the current time and as such may change significantly as more boreholes are drilled to the base and the spatial coverage of observations improves.

2.5 Aquifer Hydraulic Properties

Groundwater is found in both the upper and lower sedimentary sequences of the Aupouri aquifer, although these materials show variability in their capacity to store and transmit water. This is primarily due to changes in grain size, compaction, the proportion of clay colloids and the occurrence of spatially heterogeneous clay lenses.

The most significant volumes of groundwater are found in the coarse grained shellbed deposits, which typically display an order of magnitude higher hydraulic conductivity than the overlying sands. Within the sands, it is anticipated that the interstitial porosity and hydraulic conductivity decrease with depth due to the increased overburden pressures, thus displaying a degree of vertical anisotropy. This is evident in some of the multi-piezometer boreholes, which indicate differing hydraulic pressures at varying depths.

Only limited hydraulic property information is available for the Aupouri aquifer. Information up to 1991 has been compiled and documented in NRC (1991) report, while NRC holds results of additional tests since this time.

Hydraulic testing consisted of test pumping of boreholes for various duration and intensity. Results give an estimate of the overall *bulk* hydraulic conductivity and storage (where available) for the particular location. No discrete testing of individual units has been conducted, therefore interpretation of results requires appraisal of the lithological logs to determine the hydraulic weighting of the various units.

Table 3 provides a summary of test pumping data results provided by NRC. The range in hydraulic conductivity estimates vary from 1.25×10^{-5} to 5.1×10^{-4}, which coincides with lower end of the typical range of published values for clean sand (10^{-5} to 10^{-2}) and the higher end for silty sand (10^{-7} to 10^{-3}) (Freeze and Cherry, 1979; Anderson and Woessner, 1992).

Table 3. Summary of aquifer hydraulic test results.

NRC Bore ID	Depth (m)	Top of screen (mBGL)	Aquifer type	SWL (mBGL)	T (m^2/day)	K (calculated) (m/s)	S (-)
43	55	52	Fine sand	9.3	240 – 280	$6\times10^{-5} – 7.1\times10^{-5}$	–
48	67	19	Med sand	5.3	80 – 300	$6.1\times10^{-5} – 7.1\times10^{-5}$	0.01–0.001
59 (s)	6	–	Fine sand	2.8	140	5.1×10^{-4}	–
59 (d)	55	49	Fine sand	13.4	190	5.3×10^{-5}	–
60	60	–	Fine sand	14.9	220 – 850	$5.6\times10^{-6}–1.3\times10^{-4}$	–
81	32	31	Fine sand	20.9	12 – 28	$1.25\times10^{-5} – 2.9\times10^{-5}$	0.07–0.03
152	66	60	Fine sand	30.1	260	8.4×10^{-5}	–
184	110	101	Shelly sand	17.2	140 – 340	$1.7\times10^{-5} – 4.2\times10^{-5}$	–
229 (211)	79	70	Shelly sand	2.6	140	2.1×10^{-5}	$1.4\times10^{-4} – 1.8\times10^{-3}$
230	88	63	Shelly sand	4.8	240 – 310	$4.3\times10^{-5} – 3.3\times10^{-5}$	–
1007	50	45	Fine sand	33.7	275 – 305	$2.1\times10^{-4} – 1.9\times10^{-4}$	–
1025	30	27	Fine sand	+1.55	60 – 103	$2.2\times10^{-5} – 3.7\times10^{-5}$	$2.5\times10^{-4} – 5.0\times10^{-4}$
1374	32	26.6	Fine sand	0.8	48	1.8×10^{-5}	$1.0\times10^{-5} – 2.0\times10^{-5}$
1424*	82	70	–	–	260	–	–

Notes: SWL is the standing water level at start of pumping, T is the aquifer transmissivity, K is the aquifer hydraulic conductivity, S is the aquifer storage coefficient.

2.6 Aquifer Recharge

Groundwater recharge is a complex process, governed by numerous processes including the characteristics of rainfall (intensity, frequency and duration), antecedent soil moisture, surface and sub-surface geology, topography, and meteorological characteristics of a region, to name but a few. Collectively, these features determine the partitioning of rainfall into recharge and the various other components of an areas water balance, which include evaporative and interception losses, surface runoff, and percolation to groundwater.

Groundwater recharge occurs when soil water from the unsaturated zone (vadose zone) crosses the water table, and may occur as diffuse recharge (precipitation induced), localised recharge (ponding induced), or lateral underflow (Stephens, 1995). Aquifer water levels may not necessarily rise in response to recharge because aquifer discharge processes may be in equilibrium.

In humid climates, groundwater recharge can be 20 to 50% or more of annual rainfall, while in arid climates groundwater recharge is usually a very small component of the water balance.

In some locations, interception losses and plant transpiration through root uptake may account for almost all of the infiltrated rainfall, depending on the state of vegetative development, type of vegetation (i.e., root structure, water requirements etc.) and season.

Groundwater recharge generally represents only a very small proportion of annual rainfall in hardrock terrains. However, unconsolidated unconfined aquifers generally have more significant groundwater recharge.

In moist climates such as Northland, groundwater recharge to sand aquifers as a proportion of annual rainfall is relatively large (5 to 50% or greater) in comparison to hardrock terrains (0 to 10%). This is primarily due to the influence of the readily drainable lithological materials at the surface that serve to infiltrate or take-up a greater proportion of rainfall. As a result, surface runoff and open water evaporative losses from sand aquifers are less significant than terrains with lower permeability materials at the surface.

The highly oscillatory nature of groundwater hydrographs for bores in sand aquifers provides further evidence of the rapid response to rainfall, although the response may be attenuated somewhat by depth to the groundwater table and surface factors as discussed above.

2.6.1 Estimating Groundwater Recharge

The accurate assessment of groundwater recharge requires long-term monitoring of groundwater levels and soil moisture through the lithological profiles above the water table. In reality, this is rarely achieved and estimates are usually made based on empirical analyses, or water balance models that solve recharge as the unknown variable.

Historically, the standard method for assigning rainfall recharge to groundwater models in coastal sand aquifers has been to appoint a constant recharge coefficient. The recharge coefficient is usually generated through an empirical analysis of groundwater recovery versus the responsible rainfall event or period (e.g., a wet month), given approximate aquifer storage properties. When this procedure is followed on a number of events over a long enough period to display a full climatic cycle (usually 20 years), ballpark estimates of the range in recharge coefficients can be calculated[5].

For sand aquifers in temperate climates the long-term average recharge coefficient is generally between 10% and 30% of rainfall. For discrete events the range may be from as little as 0% to greater than 50%, depending on the governing factors as discussed previously.

[5] It should be noted that this method is biased towards higher recharge coefficients, as analysis is usually only performed on groundwater recovery data. Recharge may still be occurring during aquifer depressurisation, but as the aquifer discharge processes exceed recharge and it is more difficult to analyse.

In order to provide a first approximation of groundwater recharge for the Aupouri aquifer, a one-dimensional empirical analysis was conducted for the bores monitored by NRC following the methodology outlined above. More detailed methodology and data results for this analysis are provided in Appendix B, while summary results are given below.

Comparison of groundwater hydrograph amplitude and waveforms for the various monitoring bores reveals high variability in groundwater responses between locations (Appendix B). This is a function of numerous features such as the proportion of silt and clay within the surficial sands, proximity to the Aupouri Forest, proximity to the perched dune lakes, depth to water table, and proximity to the drainage system on the plains.

Table 4 summarises the resulting range in recharge coefficients estimated for various rainfall events form 1988 to 1999 (see Appendix B for graphical summary). Results indicate variable recharge depending on bore location ranging from around 6% for areas with surface impedance (i.e., clay, silt and/or peat), high interception or evapotranspiration (ET) demand (i.e., forest), to around 23% for sand deposits, which consist of less dense vegetation cover.

Comparison of the Hukatere Road transect bores 206 to 209 west of Houhora indicates a clear pattern of increasing groundwater recharge with distance either side of the forest. Recharge coefficients range from 6.3% in the middle of the forest to 22.9% with greatest distance from the forest.

Bores 81 and 211, which are located on the eastern margin of the dunes and on the plains at Paparore respectively, show similar recharge coefficients averaging 9%, although bore 211 is slightly greater due to the shallow nature of the water table and greater distance from the forest. Both locations have a high incidence of swamps in the surrounding areas.

The Lake Heather bores all show a similar response with groundwater recharge averaging about 7%. Considering that the surrounding area is sand dunes, it would suggest that the value is conservatively low. The influence of the lakes is not known, but it is thought that the attenuated and delayed recharge that is occurring is derived from slow-release leakage from the lakes and the presence of significant peat deposits would attenuate recharge.

Table 4. Summary results of preliminary groundwater recharge analyses.

Bore	No. Obs.	Median	Min.	Max.	Comments
081	6	7.0%	1.3%	18.2%	Located on eastern edge of forest, therefore high ET impact from trees. Attenuated responses to rainfall consistent with lower permeability lithologies (iron pans and clay) and large unsaturated zone (approx. 22 m).
206	4	14.7%	5.1%	34.6%	Delayed response to rainfall of approx. 4 months. Borelog indicates very fine sand from surface to about 16 mBGL, then 3 m of clay (which is probably only localised). Unsaturated zone of 12 m. Piezometer below clay layer.
207	2	7.8%	3.7%	13.3%	Located in the middle of the forest. Shows highly attenuated recharge due to trees and large vadose zone (approx. 20 m).
208	7	19.5%	7.9%	42.6%	Located on the eastern edge of forest. Less impact from trees. Borelog indicates peat, but no silt or clay layers. Unsaturated zone of approx. 9 m.
209	12	25.2%	6.2%	44.5%	Located approximately 1800 m east of the forest edge. Higher proportion of peat and silts in lithological log than more western piezometers in forest transect. Rapid response to rainfall, therefore high permeability (silt lenses probably only localised). Also, only approx. 8 m unsaturated zone.
211	12	11.4%	4.6%	19.2%	Located on eastern plains. Oscillatory response due to small unsaturated zone of only 2.7 m., but only low magnitude to oscillations - indicative of lower specific yield. Borelog indicates 4 m of peaty silt at surface, however only slight delay suggests well coupled to surface.
226	3	7.1%	1.8%	15.0%	Located near Lake Heather. Delayed and attenuated response to rainfall. Borelog indicates presence of major peat band 7 m thick from 12 mBGL. Unsaturated zone of approximately 21 m.
227	3	10.3%	5.2%	22.3%	Similar lithological characteristics to 226, but slightly more responsive.

2.7 Bore Hydrographs & Water Table Geometry

The water table geometry established within a region results from the interaction of numerous complex processes, including aquifer recharge, aquifer discharge (seepage in low-lying or coastal areas), the aquifer transmission potential and groundwater abstraction.

Analysis of both discrete bore hydrographs and groundwater piezometric surface plots provide essential information describing the flow regime of an area, the potential presence of zones with differing hydraulic and recharge properties, discontinuities in lithological structure and the response to differing climatic phases.

NRC has conducted groundwater monitoring on a monthly basis at eleven borehole sites since 1987. Prior to this very little groundwater information was available except for two NRC monitoring bores where three years of daily data was recorded from October 1975. In addition, occasional one-off observations made by drilling contractors are available.

2.7.1 Hydrographic Trends

Bore hydrographs for NRC monitoring bores along with a discussion of the respective features for each hydrograph are provided in Appendix C.

Comparison of groundwater hydrograph amplitude and waveforms for the various monitoring bores reveals high variability in groundwater responses between locations (Appendix C). This is a function of numerous features such as the proportion of silt and clay within the surficial sands, proximity to the Aupouri Forest, depth to water table, and proximity to perched dune lakes and drainage system on the plains.

Overall, the bore hydrographs indicate a general decline in groundwater levels since 1975, although annual rainfall (while varying from year to year), is only slightly below average for the period overall.

The reduction in groundwater pressures is most pronounced along the Hukatere to Houhora transect. For example, groundwater levels at bore 48 have dropped from approximately 18 mAMSL in 1975 to 12 mAMSL in 1998, an overall decline of 6 m. In comparison, groundwater levels at bore 81 at Ogle Drive have dropped approximately 1.25 m over the same period, from 14.5 mAMSL to 13.25 mAMSL. This may be partly explained by the timing of forest planting, which occurred prior to 1970 at the Ogle Drive site, and occurred to the south of Hukatere Road in 1973 and north of Hukatere Road in 1978. Therefore, the impact on the Ogle Drive bore is likely to have been well advanced by the time monitoring commenced in 1975 (NRC, 1991). In addition, the proximity of the Ogle Drive bore to the lakes, which may provide leakage to the underlying sand aquifer thus maintaining recharge, explains the lower magnitude of groundwater depressurisation.

2.7.2 Regional Piezometric Surface

Mapping of the regional water table (upper aquifer) has been established through groundwater measurements at the eleven NRC monitoring bores, extrapolation of driller's water level observations for 43 bores, and assignment of mean sea levels along the coast. Groundwater levels used in the interpolation consisted of January 1987 for NRC bores and various times of bore completion for the remaining bores.

In most cases the driller's data is the only groundwater elevation data available or collated for the bores, and is highly variable due to the differing reporting times. In addition, no survey information is available for the boreholes, so the groundwater observations were reduced to mAMSL by interpolation to topography, which in itself is highly inaccurate being generated from 1:50,000 map series.

The resulting interpolated regional piezometric surface and flow directions are shown in Figure 6. Because of the varying recording times of groundwater measurement, the piezometric surface provides an indicative approximation only.

Figure 6 indicates that groundwater pressures rise gently from the coast to between 15 and 20 mAMSL in the middle of the peninsula. Flow directions radiate east and westward to either coast from the central high or groundwater divide. In the south of the study area flow occurs in a northerly direction, driven by the higher heads in the hills to the south of Kaitaia.

2.8 Groundwater Abstraction

Groundwater from the Aupouri aquifer is abstracted for various requirements, which in order of significance consist of; horticulture, irrigation, farm water supplies, domestic water supplies, commercial and industrial uses.

Irrigation usage is by the far the largest consumer of groundwater even though the irrigation season is generally only four to five months in duration, from November to March. The frequency of irrigation demand is variable, depending on prevailing weather conditions, crop type, area and age.

Information provided by NRC indicates that there are currently 46 bores with registered groundwater allocations in the Aupouri aquifer region, as shown in Figure 7. Figure 7 indicates that the groundwater users are primarily concentrated in two areas, at Houhora and Paparore-Sweetwaters.

Allocations for individual consent holders range from 1 to 800 m^3/day with an average of 197 m^3/day, and a total allocation for the aquifer area of 9050 m^3/day.

2.9 Soils and Vegetation

The study area can be broadly divided into two main groups of soils:

1. flood plains adjacent to Awanui and Kaitaia, which have soils derived from marine muds and alluvial material, and
2. the Aupouri Peninsula to just south of Te Paki Stream, which is comprised of aeolian sands of varying ages.

The peninsula can be subdivided into two distinct areas. The western margin comprises young sand dune complexes overlying older dunes, and to the east occurs older more fertile sand/peat complexes with frequent iron pans located within the surficial sediments to meters below the surface. The presence of significant iron pans tends to restrict soil drainage and plant growth (NRC, 1991).

Land cover in the region is grouped into the following five broad categories; pasture (37%), scrub (23%), exotic forest (25%), lakes and wetlands (7%) and unconsolidated bare dune sand (7%) (NRC, 1991).

2.10 Landuse and Effects of Change on Hydrology

Landuse on the eastern side of the peninsula consists of dairying, sheep and beef farming, and horticulture. The estuarine flats are generally Kaitaia clay loam and are used primarily for dairying and cropping, with small areas in horticulture (NRC, 1991).

Over the past thirty years landuse has changed dramatically on the western edge of the Aupouri aquifer. In the 1970's planting of predominately *Pinus radiata* occurred over approximately 30,000 hectares to both stabilise the scrub covered wind blown sand dunes and serve as exotic plantation forest for lumber production. The forest occurs along the West Coast between Waipapakauri in the south and Te Paki in the north and has an average width of four kilometres (NRC, 1991).

Changes in vegetation cover alter the interception, ET, rooting depth and soil evaporation regimes of the affected area and thus have the potential to alter the amount of water available for surface runoff and groundwater recharge.

Interception is the component of rainfall that falls onto a vegetative surface and is subsequently lost by evaporation. In general, interception is greater for dense canopies than it is for sparse canopies. For mature closed-canopy pines it has been estimated at between 18% and 49% of annual rainfall (Duncan, 1997), with the variability mainly due to the characteristics of local rainfall. The difference in interception among vegetation covers is generally accepted as the main mechanism responsible for variation in catchment discharge following landuse change.

Tall vegetation, as a function of their height, mass and water demands require a deeper rooting system than short vegetation. They are able to abstract water for transpiration from greater soil volumes and depths than shorter vegetation, and because of this may continue transpiring while shorter vegetation cease due to the high surficial soil moisture deficits.

Transpiration is the metabolic process in plants where groundwater is drawn up through their root system and transpired through bark and leaves. The process is extremely complex because of the numerous rate-controlling variables, such as physical environmental features (i.e., solar radiation, relative humidity, air temperature and wind speed) and plant physiological features (i.e., stomata and hydraulic capacity of xylem). ET is the combination of plant transpiration and understorey evaporation.

Numerous paired catchment experiments throughout the world have shown that establishment of forest cover on sparsely vegetated land increases interception and ET and hence decreases catchment discharge, whereas a reduction in forest cover has the opposite effect (Bosch and Hewlett, 1982; Fahey and Rowe, 1992; Fahey, 1994; and Stednick, 1996).

Results of New Zealand paired catchment experiments where pines replaced pasture and tussock indicate that on average, catchment discharges have been reduced by an average of 57% (Duncan, 1997). Other New Zealand studies by Duncan (1995), Fahey and Watson (1991) and Smith (1987) show that replacing pasture and tussock with pines significantly reduces low flows. As low flows are predominately fed by groundwater, this implies a reduction in groundwater recharge and consequently groundwater pressures (the driving force of groundwater flow).

On the western margin of Aupouri Peninsula, streams are rare due to the high infiltration capacity of the sands. This indicates that surplus rainfall is predominately directed to groundwater recharge rather than surface runoff, and thus groundwater throughflow to the coast is the main mechanism of catchment discharge. The conversion of the dunes to forest vegetation cover on the peninsula would have the effect of reducing groundwater recharge, groundwater levels and ultimately throughflow rates. The impact of this not only effects groundwater users, but also the maintenance of ecosystems dependent on groundwater leakage or flushing. For example, groundwater fed wetlands and possibly shellfish beds on the coast.