Executive Summary

This study was commissioned by Northland Regional Council to provide an assessment of the Russell groundwater resource and was formulated to assist the Council in effectively managing the groundwater resource. The study coincides with a number of impending groundwater abstraction resource consent renewals. The study follows on from previous investigations conducted by the Northland Catchment Commission in 1987 and Sinclair Knight Merz in 2001, which assessed the current state of the aquifer and sustainable yield using analytical methods.

In this study a numerical groundwater flow model (MODFLOW) was developed to enable dynamic sustainable yield and the effects of wastewater reticulation to be assessed. Reticulation of the sewage system for Russell township began in 1998 with completion expected by 2006. The specific objectives of the study included:

- Assessment of the effects of reduced recharge due to wastewater reticulation;
- Refinement of the sustainable aquifer yield specified in SKM (2001) and assessment of future sustainable yield based on proposed wastewater infrastructure development; and
- Development of appropriate aquifer management procedures.

The groundwater model is comprised of three layers to represent the gravel and greywacke aquifers and covers an area of approximately 159 ha. The model is specifically discretised into even granularity with 25 m cell widths. Boundary conditions include general heads to represent the coastline, pumping from consented bores and no-flow cells along the catchment divide. Rainfall recharge in the groundwater model was handled by implementing results from a soil moisture water balance model and wastewater recharge was applied as a separate coverage.

The model was calibrated to groundwater level observations from six bores over a 17-year period (1985 to 2002). The model replicates observed heads closely in most locations, with changes in groundwater mass replicated well. Hydraulic properties in the calibrated model were within the range of measured and literature values, with hydraulic conductivity for the gravel of 20 m/day and 0.4 m/day for the greywacke. The gravel aquifer was specified a specific yield of 0.3 and specific yield/specific storage for the unconfined/semi-confined greywacke aquifer was 0.02 and 0.0001, respectively.

Predictive simulations utilised the calibrated model set-up and historical climatic conditions for the 56-year period from 1946 to 2002. The simulations conducted assessed the effect of wastewater reticulation on groundwater recharge and the sustainable yield of the aquifer during the driest period on record (9 May 1950). Sustainable yield at Russell is defined by the position of the saltwater interface and existing production bore depths. The position of the salt water interface and was determined using the Ghyben-Herzberg equation with groundwater levels simulated in the model.

The results showed that under natural conditions (no pumping) the saltwater interface intersects the base of deep bores located near the coast during dry conditions. With groundwater abstraction and wastewater reticulation the position of the interface is higher. Bores located greater than 350 m from the coast are unaffected by the

saltwater interface and could be used as an alternative water supply source during dry periods. These results indicate that climate rather than groundwater abstraction is the main influence on sustainable yield at Russell.

The sustainable yield of the Russell groundwater resource was estimated at 255 m^3/day, based on community supply bores positioned greater than 350 m from the coast to depths of 74 m. This depth is considered the requirement to achieve practical bore yields given the aquifer hydraulic capability. Sustainable yield may be greater with different supply bore configurations than that modelled in this study (i.e., shallower, larger diameter bores).

Three groundwater management options were identified in this study including:

- Maintain the status quo in terms of abstraction quantities and provide information to the community that indicates there is no guarantee that saline water will not occur in their bore during dry periods. Secondly provide an alert service notifying the community when a potential saltwater intrusion event is about to occur based on groundwater levels in a sentinel monitoring bore.
- Limit the depth of bores along the foreshore to a predetermined level that is above the position of the saltwater interface during dry times for current aquifer abstraction rates; and
- Provide a community water supply scheme based on a purpose built borefield further inland.

Contents

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1. Introduction

Sinclair Knight Merz Ltd was commissioned by Northland Regional Council (NRC) to provide an assessment of sustainable yield for the Russell groundwater resource. NRC requires this information in order to make informed aquifer management decisions, particularly as a number of groundwater abstraction consents in Russell are due for renewal in 2002.

Sustainable yield for the Russell aquifers was initially assessed by the Northland Catchment Commission in 1987 and reviewed in 2001 by Sinclair Knight Merz. Both investigations used analytical methods to determine sustainable yield. In this study a numerical groundwater flow model (MODFLOW) was developed to simulate groundwater pressures and flow rates in a transient (time-varying) manner. This enables sustainable yield to be determined dynamically, which more accurately reflects actual environmental occurrences.

The specific objectives of the study included:

- Assessment of groundwater recharge and discharge dynamics;
- Assessment of the effects of reduced recharge due to wastewater reticulation;
- Refinement of the sustainable aquifer yield specified in SKM (2001) and assessment of future sustainable yield based on proposed wastewater infrastructure development; and
- Development of appropriate aquifer management procedures.

The report contained herein provides a description of the MODFLOW model and details the modelling methodologies and study results.

2. Aquifer Simulation Model

The application of computer based numerical modelling to problem solving in groundwater engineering, provides a powerful tool for the rationalisation of spatially and temporally varying field conditions. The groundwater modelling process is a technique for simulating aquifer flow using a system of mathematical equations based on Darcy's law for water flow through porous media. This is achieved through discretisation of the area of interest into a number of blocks or cells, which are independently solved for head using conditions in neighbouring cells.

Groundwater modelling overcomes many of the difficulties and restrictions inherent with analytical methods of groundwater analysis, which assume regular aquifer geometry, homogeneity, uniform recharge and other simplified conditions.

The modelling process requires conceptualisation of the aquifer system in respect of the following:

- aquifer geometry including lateral and depth extent;
- aquifer hydraulic property distributions (e.g., for an unconfined aquifer - hydraulic conductivity and specific yield);
- regional groundwater pressure distributions (e.g., groundwater mass, flow directions and boundary fluxes); and
- groundwater recharge processes.

2.1 Modelling Objectives

The objectives of the groundwater-modelling component of this study were as follows:

- To develop a model that accurately simulates groundwater pressures and flow.
- To determine the effect of reduced recharge as a result of wastewater reticulation.
- To refine current estimates of sustainable yield and determine future yield based on proposed wastewater infrastructure development.
- To determine appropriate aquifer management options.

2.2 Sustainable Yield

The sustainable yield of an aquifer is the volume of groundwater that can be abstracted annually without causing any deleterious effects. A deleterious effect is difficult to define as it varies depending on the area and aquifer concerned, and requires consideration of environmental, social and economic factors.

Criteria that require consideration when assessing sustainable yield for the Russell aquifers include:

- **Saltwater intrusion** – the Russell aquifers are susceptible to saltwater intrusion due to piezometric heads that are close to mean sea level, pumping-induced water levels that decline below mean sea level, and high permeability aquifers.

- **Groundwater quality** – reduction of groundwater pressures and a consequent increase in the position of the saltwater interface will reduce dilution factors, resulting in deterioration of groundwater quality.
- **Efficient use of the groundwater resource** – due to the ability of the Russell aquifers to rapidly recover during wet periods, the volume available for abstraction will vary depending on the conditions prevailing (i.e. during wet periods when groundwater levels are higher the sustainable yield will be greater).

2.3 Model Description

Several numerical modelling strategies are available for groundwater flow modelling. In this study the modular finite difference groundwater flow model – MODFLOW - developed by the United States Geological Survey was selected.

MODFLOW simulates three-dimensional flow of constant density groundwater through porous earth materials using the finite difference method. The finite difference method provides an approximate solution to the partial-differential equation describing the three-dimensional flow of groundwater[1].

This modelling method requires the modelled area to be divided into a grid of rectangular cells defined by numbered columns and rows. The number of cells within the model is determined by the spatial variations occurring in aquifer properties and the anticipated hydraulic gradients developed by imposed stresses (e.g., groundwater infiltration or pumping). A compromise between accuracy and computing efficiency results in different sized cells. Small cells are used in areas where steep gradients or complex flow patterns are expected, while larger cells are employed in areas where shallow gradients occur or localities distant from the main areas of interest.

A local model was developed using the aquifer geometry and hydraulic properties reported in SKM (2001) and NCC (1987) and as determined from test pumping of the Russell Top 10 Holiday Park production bore.

2.4 MODFLOW Configuration

2.4.1 Model Domain

The model developed consists of three layers comprising 344 active cells in Layer 1 and 2,547 and 2,504 active cells in Layers 2 and 3, respectively. The model represents an area of approximately 159 hectares. The model is specifically discretised into evenly spaced cells of 25 m width (see Figure 2-1), with the model granularity appropriate for the level of detail required for this study.

[1] For a full description of the MODFLOW code refer to McDonald, M. G. and A. W. Harbaugh (1988). A modular three-dimensional finite-difference ground water flow model, United States Geological Survey.

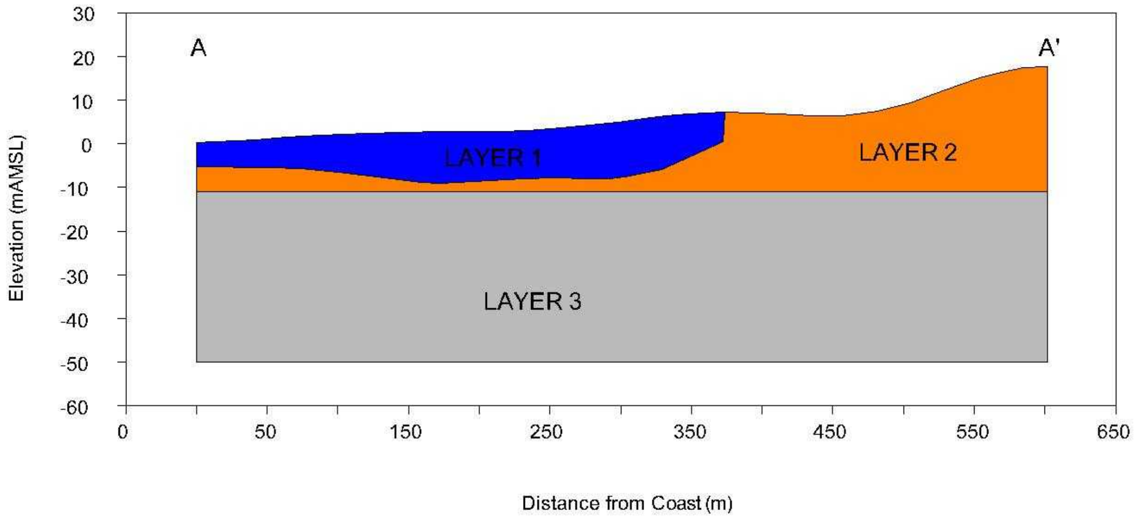
2.4.2 Layer Geometry

Model discretisation in the vertical direction is handled by specifying a number of layers. The model equations are based on the assumption that hydraulic properties within individual cells are uniform, which is more likely to occur when model layers conform to hydrogeologic units. In practice, a compromise is usually made between the number of layers and the accuracy and computational time of the model, as each additional layer adds proportionately to the simulation time.

The model constructed consists of three unconfined layers, representative of the gravel (Layer 1) and greywacke aquifer (Layers 2 and 3), as shown in Figure 2-2. The base of the gravel aquifer was determined from borelogs, as shown in Figure 2-3. The base of the greywacke aquifer was set at a nominal depth of 50 mBMSL (see Figure 2-2), because this depth is assumed great enough to have negligible influence on the hydrodynamics of the shallower points of interest in the aquifer.

It is common for lithological units to exhibit spatially heterogeneous (variable) hydraulic properties. This is particularly true for the gravel aquifer of Russell, which is typically interbedded with lower permeability sand, silt and clay. Groundwater flow is likely to be impeded in places where silt and clay occur and preferential flow paths will prevail where the gravels are predominant.

Aquifer test results from discrete locations serve as an indication of the aquifer hydraulic characteristics within the model. Bulk aquifer properties are assigned to the model, which averages the permeability distribution over the areal scale of the model. For this reason, point scale responses that are influenced by preferential flow paths may be difficult to replicate without greater data coverage or density.



■ **Figure 2-2. Cross-Section Showing Layer Geometry.**

2.4.3 Boundary Conditions

Boundary and initial conditions are those features applied to a numerical model that provide control on the solution process and determine the way in which the model domain communicates with outside areas. Boundaries of a model include such features as defined pressure head, specified flux or recharge. These features and the model hydraulic properties act to govern or constrain groundwater pressure responses within the model.

The boundary conditions of the model, as shown in Figure 2-1, were chosen to coincide with known or assumed natural boundaries such as the coast and catchment divides.

Key boundary features of the Russell model include:

- ***Coast* -** simulated using general heads along the western and southern boundary of the model. In reality, head elevations will vary in time depending on tide, and wind and wave set-ups. A head of 0 mAMSL and a conductance of 1 m/day were assigned to the gravel aquifer and a head of 0 mAMSL and a conductance of 0.1 m/day was assigned to the greywacke aquifer.

- ***No-Flow Cells* -** located along the catchment divides on the northern and eastern boundary of the model. Flow is only permitted along (not in or out) of the model at these boundaries.

- ***Pumping Wells*** – prior to April 2002 there were ten resource consents for groundwater abstraction located within the modelled area. The majority of these consents expired in April 2002. The maximum permitted takes were applied to the pumping bores in the model where appropriate (i.e. transient simulations) as detailed in Table 2-1.

- **Table 2-1. Resource Consents to Take Groundwater.**

WellArc No.	Application No.	Client Name	Easting	Northing	Expiry Date	Abstraction Volume (m^3/day)
-	909	A Skinner	2613130	6659176	April 2002	6
1244	930	H David	2613400	6659000	April 2006	4
1224	1687	Motel Russell	2613200	6658700	April 2002	6
-	1694	HR Morton & HA Montgomery	2612700	6659100	December 2049	1
-	1695	Far North District Council	2613000	6659500	April 2002	150
1227	2547	D Gifford	2612970	6659300	April 2002	30
1217	3024	Russell Bowling Club (Inc)	2613010	6659370	April 2002	10
-	3146	W Young	2613100	6659500	April 2002	6
-	3536	Far North District Council	2613000	6659300	April 2002	50
-	4200	Eastern Services Ltd	2612900	6659050	April 2007	5

2.4.4 Aquifer Recharge

Groundwater recharge is a complex and variable process governed by numerous features including:

- rainfall characteristics (intensity, frequency and duration);
- evaporation rates;
- antecedent soil moisture conditions; and
- surface and sub-surface geology and hydraulic characteristics.

Collectively, these features determine the partitioning of rainfall into recharge, surface runoff, soil moisture storage and the various catchment evaporative losses.

Groundwater recharge at Russell occurs by direct infiltration of rainfall at differing rates within the gravel and greywacke areas, infiltration within the gravels of surface runoff from the surrounding hardrock hillslopes, and wastewater leakage from septic tanks. The complexity of the combined catchment recharge processes makes assignment of recharge to the groundwater model a challenging task requiring matching of field responses to climatic conditions. The rainfall recharge and surface runoff recharge components were handled by implementing results from a soil moisture water balance model (SMWBM).

The SMWBM utilises daily rainfall data and mean-monthly evaporation totals to calculate soil moisture conditions, percolation to the groundwater table, surface runoff and interception storage. A detailed description of the model and parameter values utilised is given in Appendix A.

Daily rainfall from the Russell station (A54211) for the period 1 January 1985 to 31 May 2002 was used in the SMWBM. Missing data was patched for modelling purposes with mean daily values for the particular month. Evaporation in the model comprised average monthly pan evaporation for Kerikeri (A53191).

Total surface runoff determined by the SMWBM was calculated for the greywacke hillslope catchment areas. A proportion of the surface runoff total from the hill slopes that drain towards the gravel aquifer was assumed to recharge the gravel aquifer. This proportion was estimated at 0.1545 through an iterative calibration process.

The recharge component derived from wastewater systems was applied to the model by proportioning the total wastewater loads for the town across property boundaries. Groundwater recharge is further discussed in Section 3.2.2.2.

3. Model Calibration

The calibration of a numerical model is an iterative trial and error process that requires adjustment of model variables to achieve an equivalent model response to the measured field conditions. During calibration, the conceptual model is further refined with model parameters adjusted accordingly as model responses are observed.

The input of high quality data and correct judgement in respect of spatial and temporal discretisation should normally result in a model of high accuracy and relatively straightforward calibration. Poor quality data, unrealistic model parameter values and coarse discretisation can lead to calibration difficulties and an unrepresentative model. In addition, complex aquifer geometry often lead to calibration difficulties due to the dry cell phenomenon (i.e., model cells switching from saturated to dry conditions) and the consequent change in flow conditions that result in the problem areas.

The calibration process of the MODFLOW model utilised in this study comprised two stages:

- Preliminary Steady State Calibration; and
- Transient (Time-Varying) Calibration.

3.1 Steady State Calibration

Steady state simulations consist of a set of stresses that are held constant for the duration of the simulation (i.e., recharge, throughflow, pumping etc.). The model simulates to quasi-infinite time, stopping when a stable solution is achieved, which occurs when the water table and flow responses are in equilibrium with the stresses imposed on the model (i.e., model outputs equal model inputs).

In general, the process involves generation of a groundwater table and flow regime as a function of average input conditions. The process simply attempts to verify the conceptual model by indicating that the hydraulic conditions and model parameters are representative of field conditions.

In this study, the steady state calibration simulations provided improvements to the preliminary conceptual model and data in the following areas:

- The hydraulic property distribution and recharge magnitude;
- The water table geometry that could be adapted as the initial condition for subsequent transient simulations.

The model was further refined during the transient calibration process.

3.2 Transient Calibration

In contrast to steady state simulations, transient simulations involve stresses imposed on the aquifer that are time dependent such as recharge and pumping. As such, transient simulations can be used to analyse problems or predict outcomes that are time dependent. In order for a model to be employed accurately for predictive purposes in a transient sense, it must first be calibrated to historical conditions.

Transient simulations are inherently more complicated than steady state simulations for the following reasons:

- the storage characteristics of the aquifer must be specified;
- initial conditions giving the head distribution in the aquifer must be given for the particular starting time;
- imposed stresses for each stress period must be calculated and imported into the model; and
- time discretisation (i.e., stress period length and computation of time stepping – see Section 3.2.1) must be appropriate for the objectives of the model.

Groundwater level observations for the following bores between 1985 and 2002 were implemented for history matching purposes:

- Hananui bore – WellARC No. 1317;
- Hananui piezometer – WellARC No. 1318;
- Ambulance 1 – WellARC No. 1346;
- Ambulance 2 – WellARC No. 1347;
- Ambulance 3 – WellARC No. 1348; and
- Russell Bowling Club – WellARC No. 1217.

The model simulation length utilised in the transient calibration corresponded to the calibration data available.

3.2.1 Stress Periods and Time Steps

A transient simulation is divided into a set of discrete stress periods, with each period further divided into time steps. Sink/source boundaries and recharge conditions, while constant for the duration of each stress period, vary between periods to represent changes that occur in the natural environment.

Stress period lengths vary depending on the time scale of the physical processes acting on the groundwater system and on the numerical accuracy of the model solution required. In contrast to surface water systems, groundwater systems generally respond slowly to changes in imposed stresses. As a result it is reasonable to use averaged surface processes to drive the model. However, inappropriately large stress periods can result in loss of definition in the model response with short-time scale events not observed.

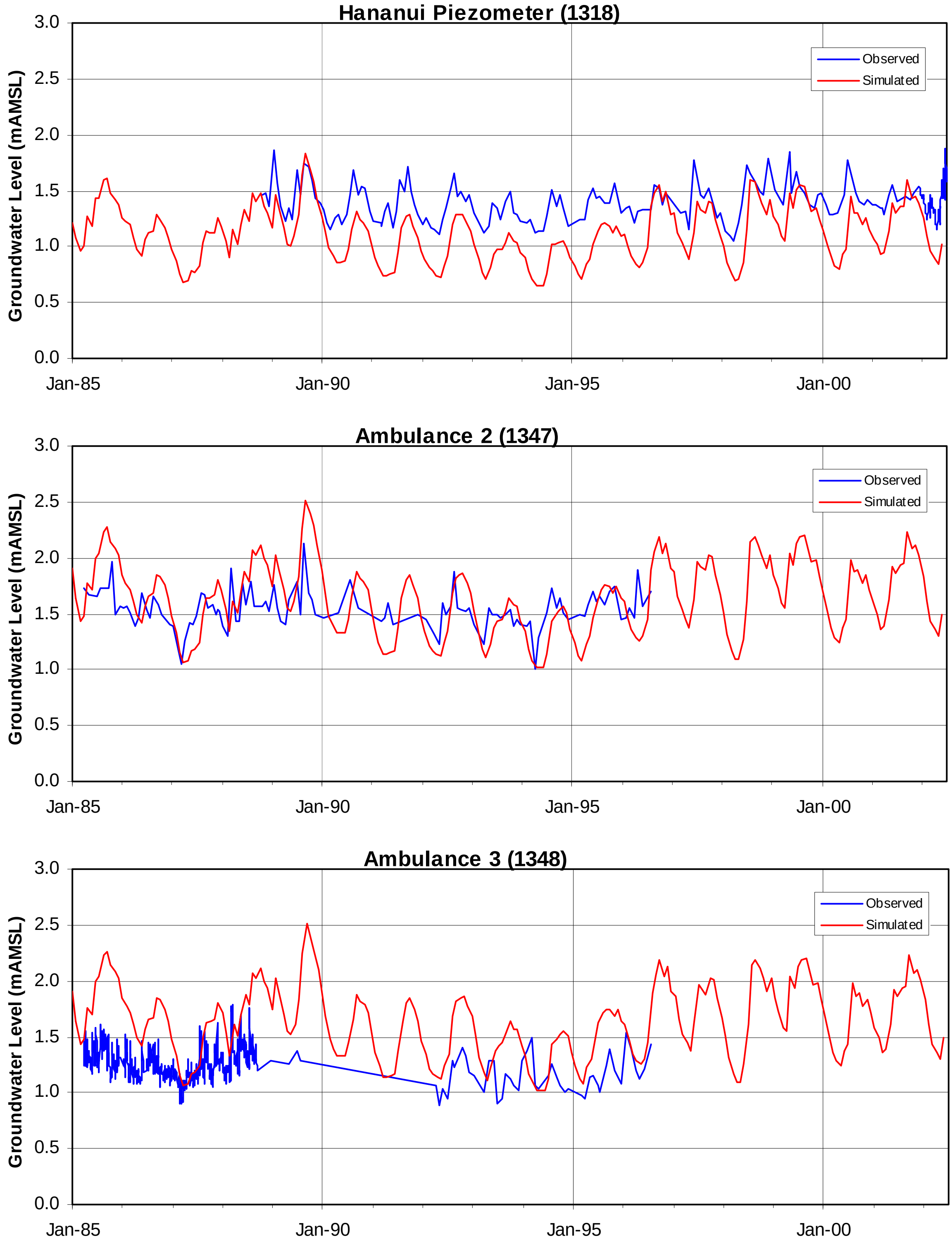
28-day stress period lengths were implemented in this model, with a total number of stress periods comprising 227 equating to a simulation time of 6,356 days. Each stress period was further divided into ten uniform time steps. Model output was saved to computer disk at the end of each stress period.

3.2.2 Transient Calibration Results

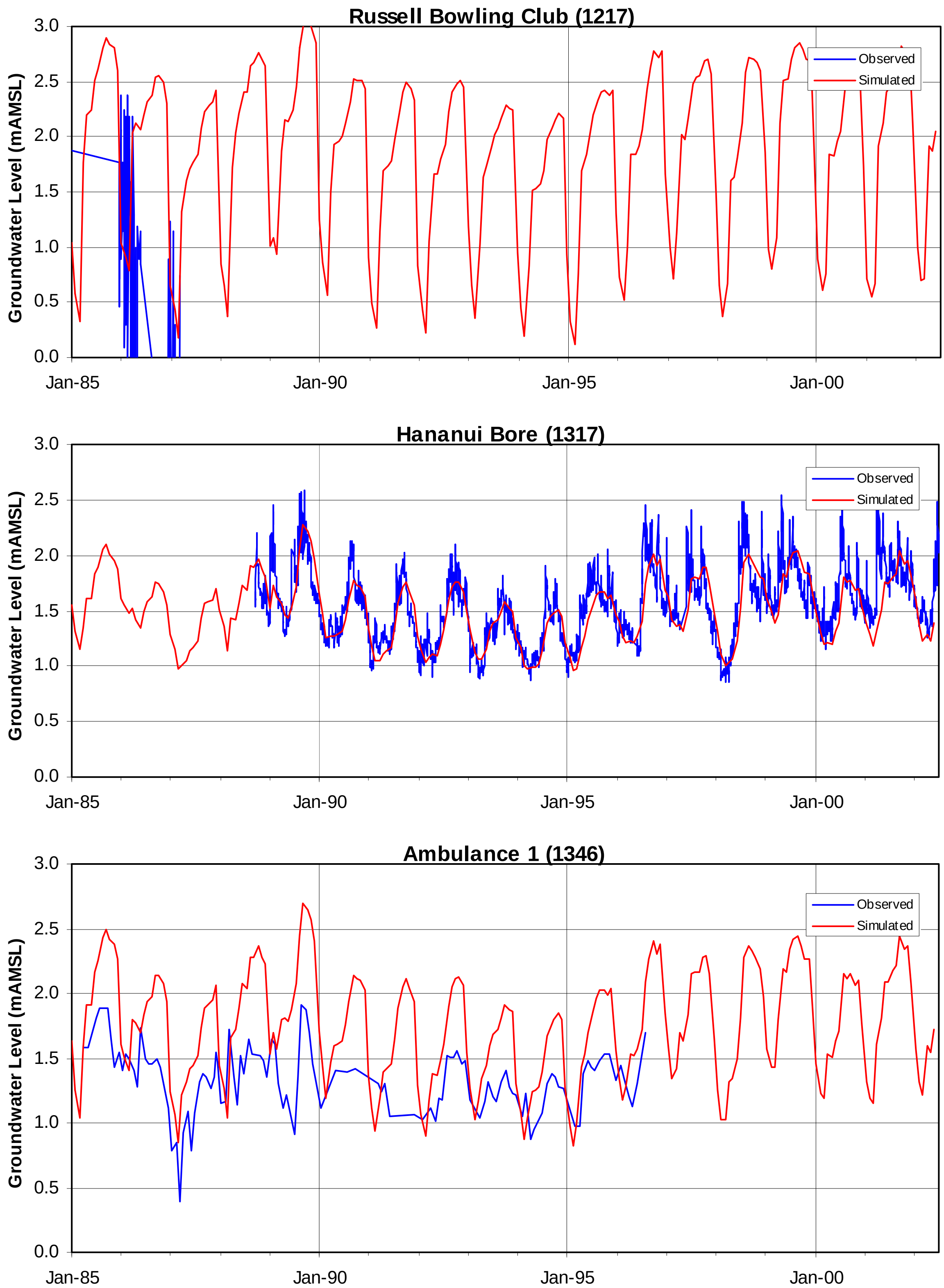
During the calibration procedure recharge, hydraulic conductivity and specific yield properties of the model were adjusted within sensible ranges for the respective layers until an appropriate match was achieved.

Figures 3-1 and 3-2 show plots of modelled versus measured heads for the calibrated model. In general, the match is reasonable, as increases in groundwater mass are replicated well by the model. The match between modelled and measured heads for the Hananui Bore (Layer 3), which has the highest frequency monitoring data, is excellent. Uncertainty associated with top of casing (TOC) elevations and low frequency of monitoring for the Ambulance and Russell Bowling Club bores makes it difficult to obtain as good a match for these bores as for the Hananui Bore.

The large amplitude of the modelled response for the Russell Bowling Club bore is due to pumping of the Bowling Club bore and surrounding bores. Ambulance 2 and 3 bores, which are both screened in the gravel aquifer and located in close proximity to each other, have different observed water levels. This reflects the spatial variability of aquifer properties. The model, which has uniform hydraulic properties, shows a similar response in modelled water levels.



■ **Figure 3-1. Gravel Aquifer Calibration Bore Hydrographs.**



- **Figure 3-2. Greywacke Aquifer Calibration Bore Hydrographs.**

Table 3-1 provides a summary of the volumetric flow budget for the transient calibration for a dry period (20/4/1987) and wet period (5/9/1989) respectively.

■ **Table 3-1. Volumetric Flow Budget (m^3/day) for Transient Model Simulations for Dry and Wet Periods.**

Fluxes into respective layer	**Dry – 20/4/1987 (m^3/day)**		**Wet – 5/9/1989 (m^3/day)**	
	Gravel	**Greywacke**	**Gravel**	**Greywacke**
Recharge	325	352	1,836	642
Accessions from Storage	0	25	0	0
Seepage from Ocean	0	0	0	0
Throughflow (from Gravel or Greywacke Aquifer)	244	0	232	6
Total In:	569	377	2,068	648
Fluxes out of respective layer				
Accessions to Storage	53	38	486	240
Seepage to Ocean	516	95	1,576	176
Throughflow (to Gravel or Greywacke Aquifer)	0	244	6	232
Total Out:	569	377	2,068	648
In-Out Discrepancy	**0**	**0**	**0**	**0**
% Discrepancy	**0**	**0**	**0**	**0**

3.2.2.1 Hydraulic Properties

The calibrated model consists of hydraulic conductivity for the gravel aquifer of 20 m/day and a specific yield of 0.3. The hydraulic conductivity and specific storativity for the greywacke aquifer is 0.4 m/day and 0.02, respectively.

The calibrated model parameters are within the range of typical published values for sands and gravels as demonstrated in Table 3-2.

Aquifer test pumping was conducted at the Russell Top 10 Holiday Park during September 2002 to provide additional supporting information on aquifer properties for use in this study. Analysis of the pumping data indicated average hydraulic conductivity and storativity values of 1.1 m/day and 0.022, respectively (Sinclair Knight Merz, 2002). The hydraulic conductivity is at the lower end of previously reported values for the greywacke aquifer, and storativity is higher. The high storativity value obtained from the aquifer test pumping indicates that the greywacke aquifer behaves like an unconfined or semi-confined aquifer (i.e. specific yield). Further details on the test pumping are contained in Appendix B.

■ **Table 3-2. Calibrated Hydraulic Properties Compared to Typical Published Values.**

Lithology/Location	**K (m/day)**	**Sy (-)**	**Reference**
Gravel aquifer (calibrated model)	20	0.3	This study
Greywacke aquifer (calibrated model)	0.4	0.02	This study
Gravel aquifer	27 – 32[1]	-	NCC (1987)
Greywacke aquifer	0.045 - 22	0.0003 – 0.022[2]	NCC (1987), test pumping[3]
Fine sand to coarse gravel	2.5 to 150		Todd (1980)
Clean sand to gravel	0.08 to 86,400		Freeze & Cherry (1979)
Sandstone	9×10^{-6} to 0.09		Freeze & Cherry (1979)
Unconfined aquifers		0.01 to 0.30	Freeze & Cherry (1979)
Confined aquifers		0.005 to 0.00005[4]	Freeze & Cherry (1979)

Note: K is hydraulic conductivity; Sy is specific yield. [1]Data from one bore only – Ambulance 2; [2]Data from two bores. [3]Test pumping conducted at the Russell Top 10 Holiday Park in September 2002. [4]Storativity.

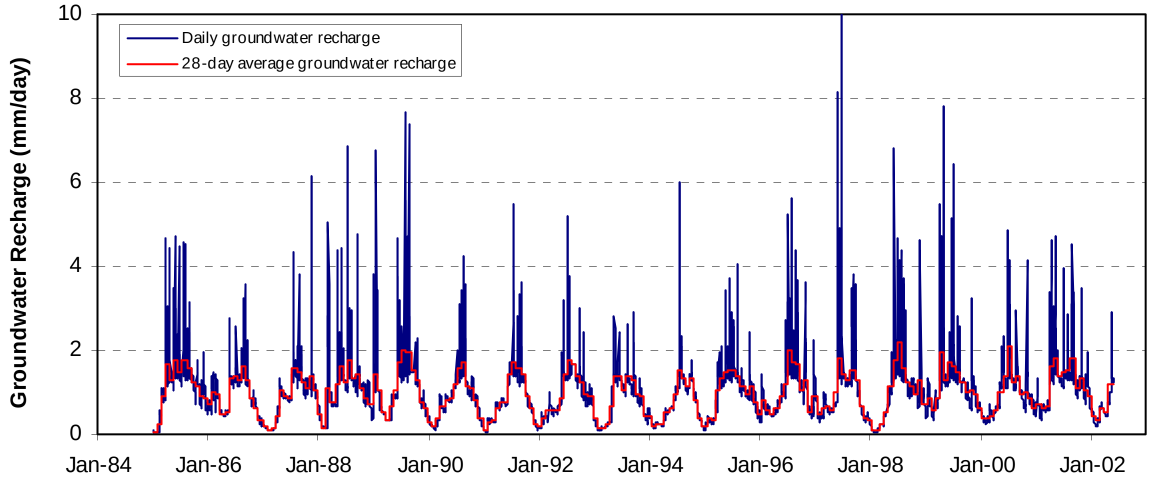
3.2.2.2 Groundwater Recharge

As indicated in Section 2.4.4, groundwater recharge to the groundwater model is from three sources:

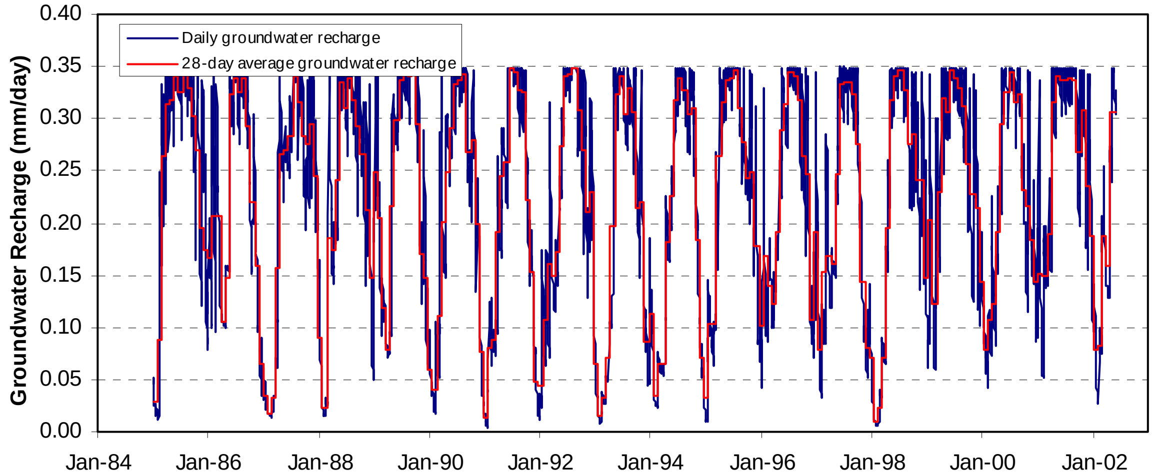
- Direct infiltration from rainfall;
- A proportion of the surface runoff from surrounding greywacke hillslopes (gravel aquifer recharge only); and
- Wastewater leakage.

Groundwater recharge from the first two sources was estimated on a daily basis using the SMWBM for the calibration period January 1985 to May 2001. The daily data was then averaged over a 28-day period to replicate the number of stress periods in the model. Figures 3-3 and 3-4 are plots of the daily groundwater recharge history and block average trace for the gravel and greywacke aquifers. Figure 3-3 for the gravel aquifer does not incorporate the surface water runoff component from the surrounding greywacke hillslopes.

Groundwater recharge in the gravel aquifer is approximately three times higher than groundwater recharge in the greywacke aquifer due to the lower greywacke permeability. Groundwater recharge is approximately 1.5 mm/day and 0.27 mm/day higher during the winter months for the gravel and greywacke aquifers, respectively.



- **Figure 3-3. Groundwater recharge history for the gravel aquifer.**



■ **Figure 3-4. Groundwater recharge history for the greywacke aquifer.**

Recharge derived from wastewater infiltration from septic tanks was applied to the model as an additional areal recharge coverage. The volume of wastewater that results in groundwater recharge was estimated from:

- estimates of average wastewater generation per household (ARC, 1994) based on population statistics;
- wastewater reticulation data for recent times, which effectively reduces groundwater recharge derived from wastewater; and
- estimates of the wastewater losses or removal from the aquifer system during infiltration in the unsaturated zone.

Water losses in the unsaturated zone are assumed to be 5% and 30% within the gravel and greywacke aquifers, respectively. The losses are greater in the greywacke aquifer due to the lower permeability and greater depth to the water table on average.

Table 3-3 summarises the groundwater recharge volumes derived from wastewater implemented in the model and also gives the total wastewater volume for the various periods. Table 3-4, 3–5 and 3–6 summarise the methods utilised to get this data. Figure 3-5 shows the property distribution that recharge derived from wastewater was applied to.

■ Table 3-3. Calibrated Hydraulic Properties Compared to Typical Published Values.

Period	Recharge from Wastewater	Wastewater Volumes	Comments
Prior to December 1998	435 m^3/day during peak periods and 147 m^3/day for average periods	572 m^3/day during peak periods and 193 m^3/day for average periods	This is based on per capita wastewater design flow estimates and population estimates for Russell (prior to reticulation) as given in Table 3-4. Recharge applied to model is calculated in Table 3-6.
December 1998 to January 2001	419 m^3/day during peak periods and 108 m^3/day for average periods	522 m^3/day during peak periods and 173 m^3/day during average periods	Reduced recharge due to reticulation developments. These volumes were determined by subtracting reticulated wastewater (see Table 3-5) from the total wastewater volume mentioned above. See Table 3-6 for model recharge calculations.
January 2001 to May 2002	324 m^3/day during peak periods and 98 m^3/day for average periods	428 m^3/day during peak periods and 129 m^3/day during average periods	See Table 3-5 for total wastewater volumes and Table 3-6 for model recharge volumes.

■ Table 3-4. Wastewater Design Allowances and Population Estimates.

Period	Population	Wastewater design allowance (m^3/pp/day)	Maximum wastewater volume generated per day (m^3/day)
Average period:			
Households & Accommodation	1,052	0.18	189
Commercial properties	175	0.0225	4
Total			**193**
Peak period:			
Households & Accommodation	2,982	0.18	537
Commercial properties	1,560	0.0225	35
Total			**572**

Notes: Households and accommodation typically generate 180 L per person per day. Commercial properties typically generate 22.5 L per person per day (ARC, 1994).

■ Table 3-5. Average Reticulated Wastewater Volumes and Wastewater Recharge Estimates.

Period	Typical dry weather flow[1] (m^3/day)	Wastewater recharge volume with reticulation[2] (m^3/day)
December 1998 to January 2001:		
Peak period	50	572 – 50 = 522
Rest of year	20	193 – 20 = 173
January 2001 to June 2002:		
Peak period	144	572 – 144 = 428
Rest of year	64	193 – 64 = 129

Notes: [1]Typical dry weather flows (i.e wastewater flows during periods of no stormwater infiltration) received at the Russell Wastewater Treatment Plant from Russell township since reticulation began in December 1998; [2]Maximum wastewater volumes for peak and average periods are 572 m^3/day and 193 m^3/day, respectively (see Table 3-4).

■ Table 3-6. Wastewater Recharge Coverage Calculations.

Period	Property boundary area (m^2)	Proportion of total property area	Recharge coefficient	Total wastewater volume generated (peak/average) (m^3/day)	Wastewater recharge (peak / average) (m^3/day)
December 1998 to January 2001:					
Greywacke properties	657,161	0.76	0.7	572 / 193	305 / 103
Kororareka Bay gravel properties	132,864	0.15	0.95	572 / 193	84 / 28
Matauwhi Bay gravel properties	72,969	0.08	0.95	572 / 193	46 / 16
Total					**435 / 147**
December 1998 to January 2001:					
Greywacke properties	657,161	0.76	0.7	522 / 173	294 / 76
Kororareka Bay gravel properties	132,864	0.15	0.95	522 / 173	81 / 21
Matauwhi Bay gravel properties	72,969	0.08	0.95	522 / 173	44 / 11
Total					**419 / 108**
January 2001 to May 2002:					
Greywacke properties	657,161	0.76	0.7	428 / 129	228 / 69
Kororareka Bay gravel properties	132,864	0.15	0.95	428 / 129	63 / 19
Matauwhi Bay gravel properties	72,969	0.08	0.95	428 / 129	33 / 10
Total					**324 / 98**

Notes: Wastewater recharge applied to model = area proportion x recharge coefficient x wastewater volume.

4. Limitations of Model

Consideration of model limitations is required if the model is to be implemented for predictive purposes. This ensures that the weighting given to model results is appropriate for the objectives of the study.

The main limitations of the groundwater flow model developed for this site are:

- The assumption of homogenous and isotropic aquifer conditions which in practice are unlikely to occur. This means that localised responses, for example the aquifer response to pockets of higher permeability, may not be well represented. However, the model will give a good indication of the average or bulk aquifer response.

- Model predictions are limited by the unknown top of casing (TOC) elevations for the Ambulance and Russell Bowling Club bores. In some cases the model would appear to over or under predict groundwater levels, so calibration is subjective at these locations.

- The assumption that the consented bores are pumping at their maximum allocation from December to March, which is unlikely to be the actual volume pumped from these bores. Groundwater abstraction from non-consented bores has also not been accounted for.

- The proportion of recharge to the gravel aquifer that arises from surface runoff from the surrounding greywacke hillslopes or from leaky wastewater systems has been estimated.

Overall, while the model predictions are considered to be reliable in terms of average conditions and relative responses, short-term variations and variations between different locations within the gravel and greywacke aquifers are predicted with less certainty. Given that the model is to be utilised to assess sustainable yield and the critical time for this is at the end of prolonged dry periods, these limitations are not restrictive in terms of the models application for the specific objectives of this study.

5. Predictive Simulations

Predictive simulations of the groundwater flow model were implemented to assess:

- the loss of groundwater recharge due to wastewater reticulation;
- the sustainable yield of the aquifers during extended dry periods accounting for proposed wastewater infrastructure; and
- groundwater management options.

The predictive simulations of the model utilised the calibrated model set-up and consisted of simulations with 726 stress periods each of 28-day duration using historical climatic conditions from 1946 to 2002.

5.1 Reduced Recharge

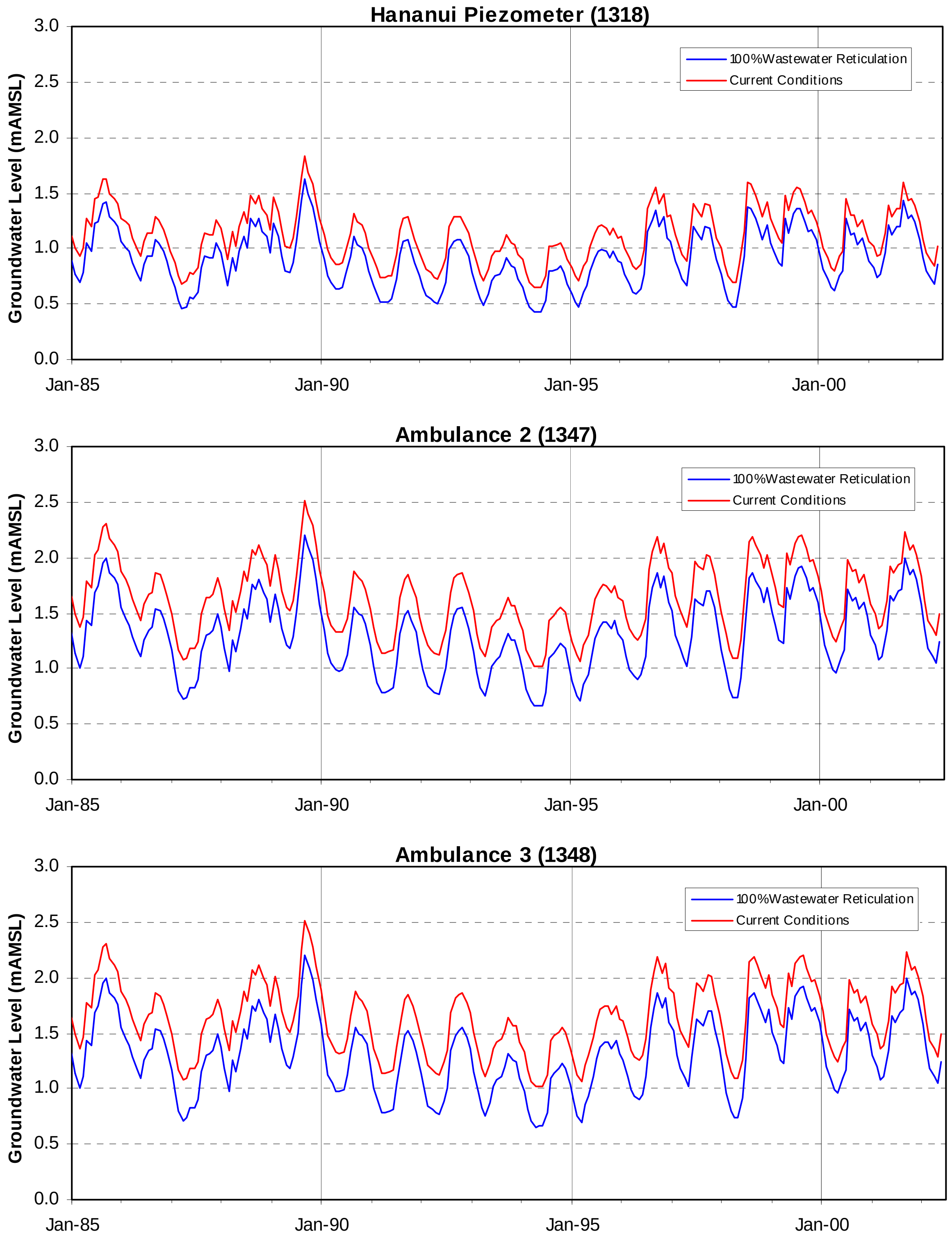
This analysis assessed the effects of reduced groundwater recharge on groundwater pressures due to future wastewater reticulation. To accomplish this the wastewater recharge component from the calibrated model was removed.

Results for the simulation are provided in Figures 5-1 and 5-2, which show the groundwater levels for the monitoring bores in the gravel and greywacke aquifer, respectively. In addition, Table 5-1 summarises the recharge budget for the driest and wettest times with the 56-year record, respectively. Simulation results indicate that:

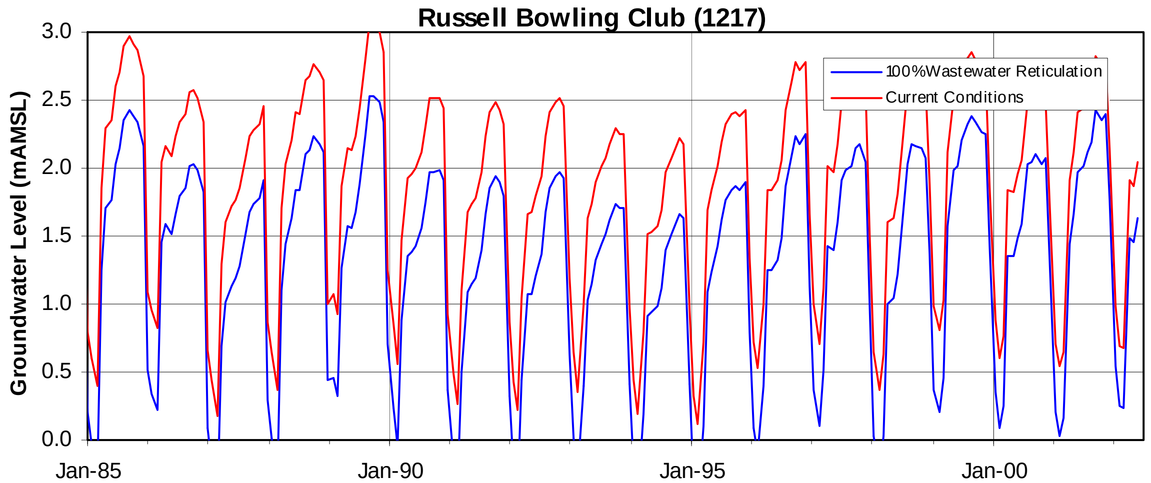
- During the driest period on record (9 May 1950) wastewater reticulation reduced recharge inputs by approximately 11% in the gravel aquifer and 30% in the greywacke aquifer;
- During the wettest period on record (21 August 1956) wastewater reticulation reduced recharge inputs by approximately 2% in the gravel aquifer and 19% in the greywacke aquifer;
- Groundwater levels have reduced by approximately 0.3 and 0.25 m in the gravel aquifer for a dry and wet period, respectively; and
- Groundwater levels have reduced by approximately 0.45 and 0.35 m in the greywacke aquifer for a dry and wet period, respectively.

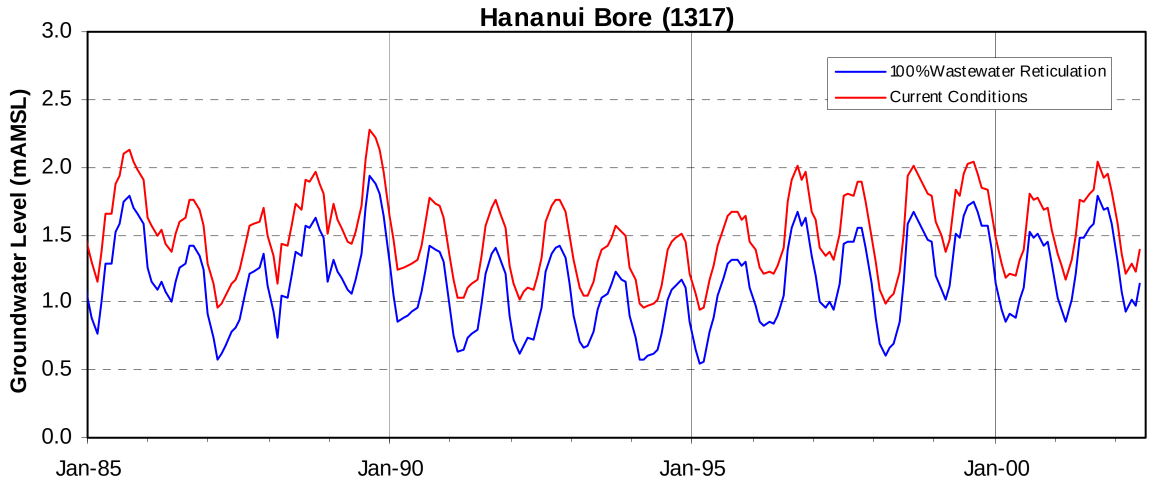
■ Table 5-1. Comparison of Groundwater Recharge for Dry Period (9 May 1950) and Wet Period (21 August 1956).

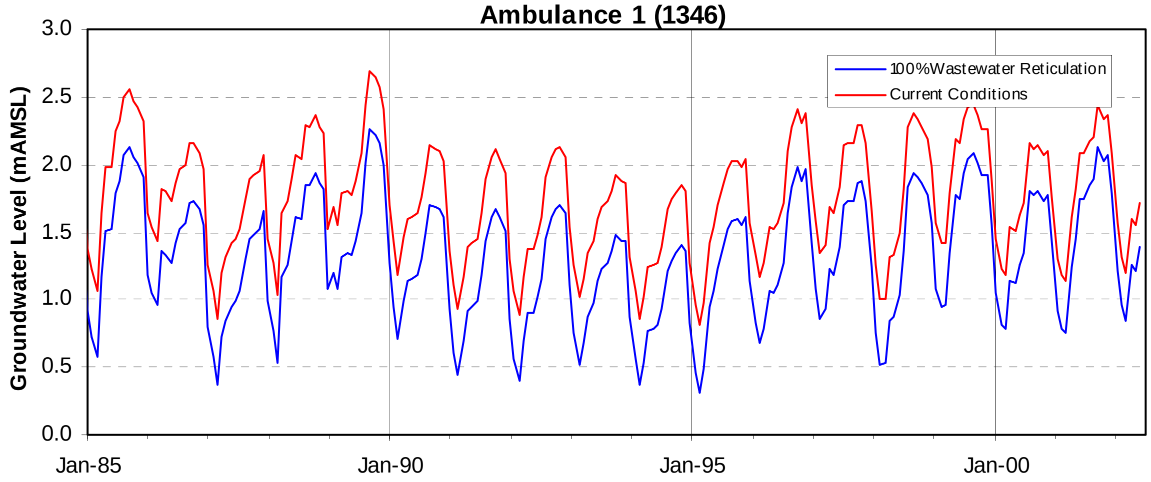
Simulation	Dry – 9/5/1950 (m^3/day)		Wet – 21/8/1956 (m^3/day)	
	Gravel	Greywacke	Gravel	Greywacke
Current Conditions	338.5	412.3	1971.4	652.4
100% Wastewater Reticulation	300.0	287.2	1932.9	527.4
Recharge Reduction	11%	30%	2%	19%



■ **Figure 5-1. Gravel Groundwater Levels: 100% Wastewater Reticulation.**







■ **Figure 5-2. Greywacke Groundwater Levels: 100% Wastewater Reticulation.**

5.2 Position of Saltwater Interface

This section assesses current and future dynamic sustainable yield as influenced by proposed wastewater reticulation. The modelling scenarios conducted included:

- **Scenario 1:** Simulations to determine the depth to the saltwater interface under existing conditions using the Ghyben-Herzberg equation. The depth to the saltwater interface was checked against anecdotal information of the occurrence of saltwater in various bores in the town.
- **Scenario 2:** Simulations to determine the depth to the saltwater interface under natural conditions, i.e no groundwater pumping.
- **Scenario 3:** Simulations to determine the depth to the saltwater interface with 100% wastewater reticulation and existing abstraction rates.
- **Scenario 4:** Simulations to determine the effect of different abstraction rates on the depth to the saltwater interface.

For each scenario the depth to the saltwater interface was determined along a transect passing through the deepest part of the gravel aquifer from the coast (see Figure 3-5 for the location of Transect A-A'). The existing pumping regime is detailed in Table 2-1.

The Ghyben-Herzberg equation is an analytical approach to estimating the position of the saltwater interface. It is the most commonly used one-dimensional analytical equation for approximating the depth to the saltwater interface and is expressed as:

$$z = 40h_f$$

Where h_f is the groundwater pressure above sea level, as determined from the model simulation.

The Ghyben-Herzberg equation assumes hydrostatic conditions in a homogenous, unconfined coastal aquifer. The equation gives a good approximation of the depth to the interface where groundwater flow is nearly horizontal (i.e away from the coastline) but tends to underestimate the depth to the interface near the coast where vertical flow is more pronounced. The Ghyben-Herzberg equation has been used in the following predictive simulations to provide a conservative estimate of the depth to the saltwater interface. This assumption has been checked against Glover's Method and was deemed to be valid.

5.2.1 For Current Conditions

Figure 5-3 shows the position of the saltwater interface along Transect A-A' assessed using the Ghyben-Herzberg equation for dry (20/4/1987) and wet (4/9/1989) periods with the 56-year record.

During the dry period the saltwater interface is approximately 23 m below ground level at the coast. The interface is above the base of a number of bores, as shown on Figure 5-3, including the Commodore Lodge bore and Russell Bowling Club production bore. This confirms the presence of the saltwater wedge during dry periods, as discussed in the following paragraphs.

The Russell Water Resources Report stated that saltwater intrusion was evident in Bore 27 during the sampling period of September 1984 to February 1987, located approximately 35 m from the beach to a depth of 31 m (NCC, 1987). In comparison, the Hananui Bore (27.1 m depth) did not show saltwater intrusion, even after a 19-hour pump test was conducted and drawdown of 5.5 m was recorded. Both bores are shown in Figure 5-3. The position of the saltwater interface is estimated at above the base of the bore for Bore 27 and below the base for the Hananui Bore, which matches the results from the Russell Water Resources Report.

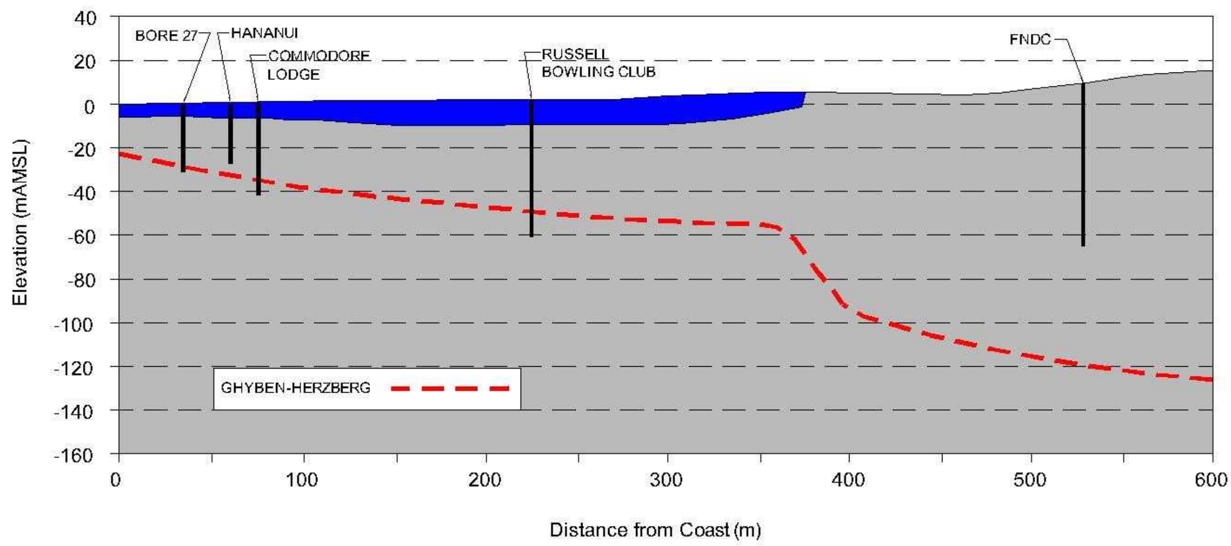
The Russell Bowling Club production bore, also shown on Figure 5-3 as intersecting the saltwater interface, was drilled to a depth of 58 mBMSL in 1996. Water quality data is only available for May 2001 when the climatic conditions were wetter than recorded in 1987 and did not indicate the presence of saltwater. There are no bores in close proximity to the Russell Bowling Club production bore that are deeper and have water quality information.

Electrical conductivity has been recorded continuously in the Hananui Piezometer since December 2001 (see Figure 5-4). The electrical conductivity ranges between 35 and 57 mS/m, which does not indicate saltwater intrusion[2] in the gravel aquifer during the period of monitoring. Rainfall over this period was slightly below average.

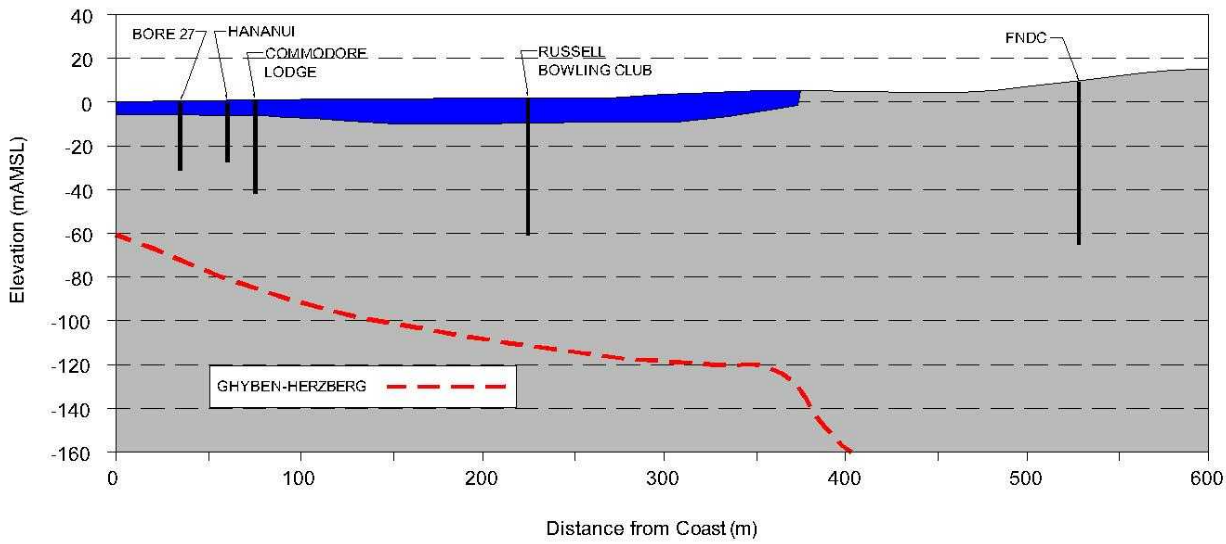
The depth to the saltwater interface during the wettest period is approximately 40 m lower than during the driest period. This suggests that the existing abstraction rates are sustainable during wet periods.

[2] Electrical conductivity of saltwater is typically 5,300 mS/m, which indicates that saltwater intrusion assuming 75% dilution would be from 1,325 mS/m.

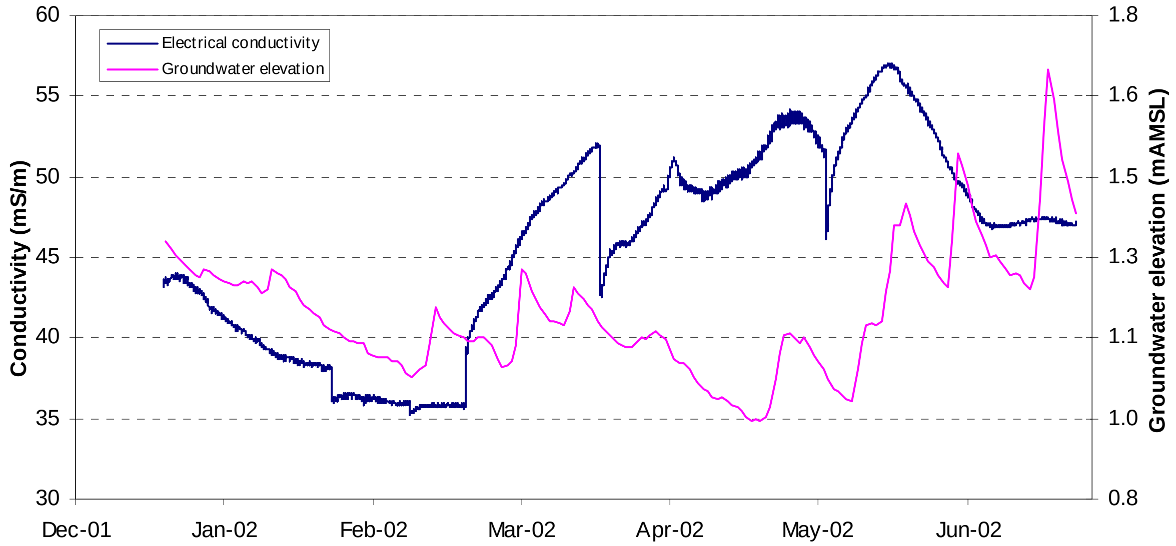
Dry Period (20 April 1987)



Wet Period (4 September 1989)



■ **Figure 5-3. Cross-Section Showing the Position of the Saltwater Interface for a Dry and Wet Period.**

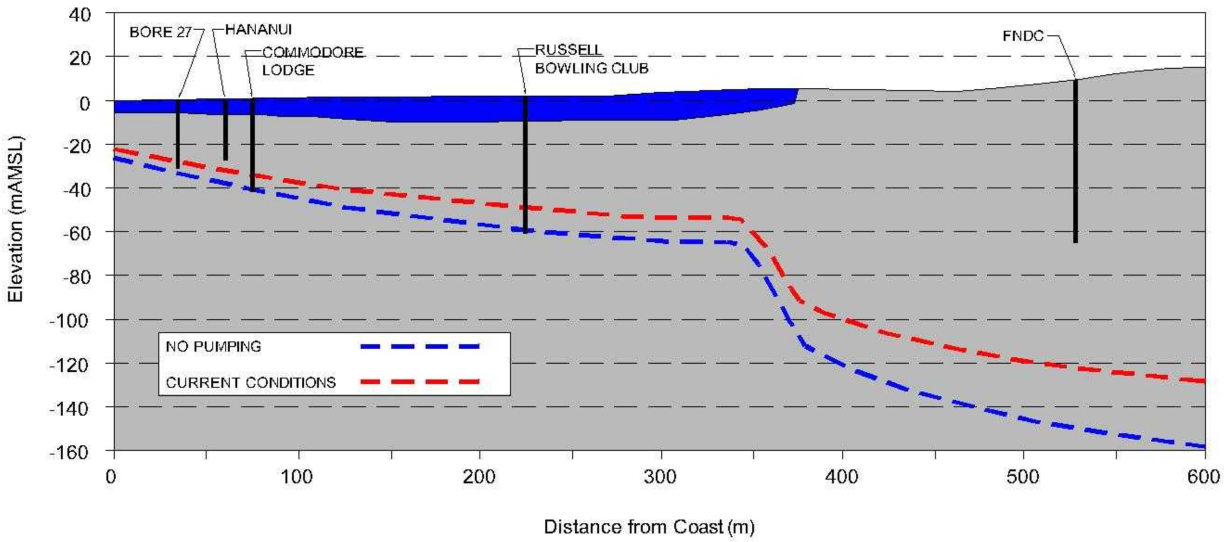


■ **Figure 5-4. Electrical conductivity at the Hananui Piezometer.**

5.2.2 For Natural Conditions

This simulation assessed the position of the saltwater interface under natural conditions, i.e. with no groundwater abstraction. The Ghyben-Herzberg equation was used to estimate the depth to the interface under the driest period on record (9/5/1950).

Figure 5-5 shows the position of the saltwater interface under natural conditions compared to current conditions with groundwater abstraction. Under natural conditions the position of the saltwater interface during dry periods is still close to or intersects the base of a number of coastal bores.

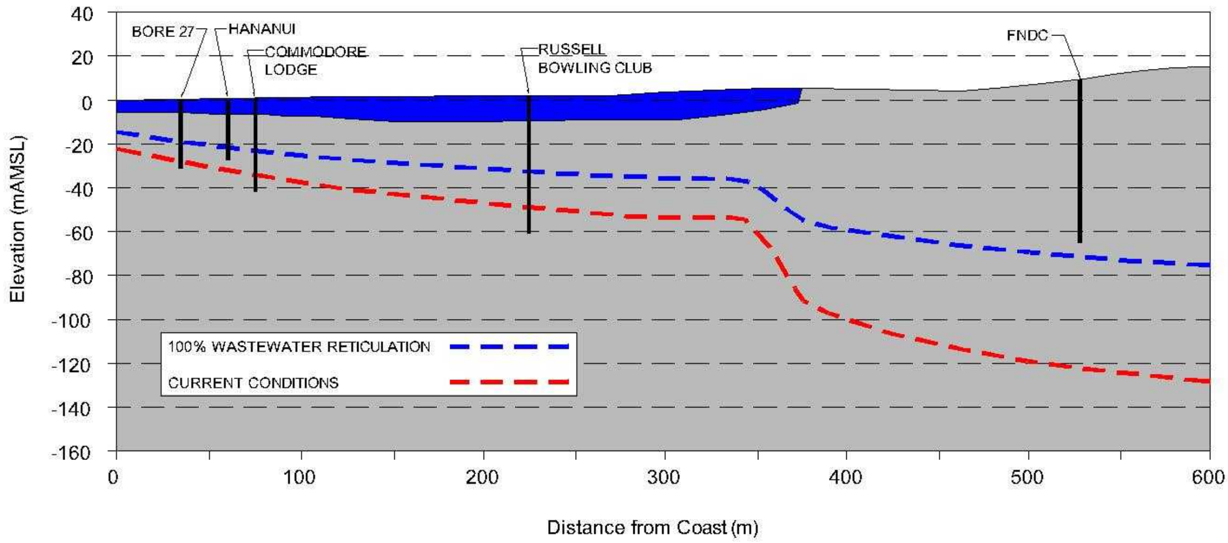


■ **Figure 5-5. Cross-Section Showing the Position of the Saltwater Interface with No Groundwater Abstraction.**

5.2.3 With Proposed Wastewater Infrastructure

This section assesses the impact of proposed wastewater reticulation on the saltwater interface due to reduced groundwater recharge. The simulation was conducted with 100% wastewater reticulation and existing consented abstraction rates.

Figure 5-6 compares the depth to the saltwater interface with 100% wastewater reticulation to current conditions. The position of the saltwater interface rises by approximately 7 m near the coast due to the reduction in groundwater recharge associated with wastewater reticulation. The saltwater interface still reaches the base of a number of deep bores, as shown on Figure 5-6. The Far North District Council community supply bore located approximately 530 m from the coast is not affected by the saltwater interface.



■ **Figure 5-6. Cross-Section Showing the Position of the Saltwater Interface with 100% Wastewater Reticulation.**

5.2.4 Implications of Predictive Simulations

The predictive simulations above indicate that the saltwater interface is likely to be present in all deep bores located near the coast during dry conditions. Abstracting groundwater from these bores during dry periods may not be sustainable.

The Far North District Council community supply bore, located approximately 530 m from the coast did not intercept the saltwater interface during the simulated dry period. This bore or bores located further from the coast could be used as an alternative water supply during dry periods.

The effect of the saltwater interface on bore water quality is dependent on the degree of saltwater mixing and dilution. Groundwater consumption from the bore may continue if the saltwater concentration is low. The degree of saltwater dilution that occurs due to freshwater mixing depends upon a number of factors including:

- The saturated thickness of the bore and the ratio of freshwater and saltwater within the water column.
- The location of high permeability zones along the screened column. For example, if the bore is abstracting most of its water from a fracture zone located above the saltwater interface then the presence of the interface within the bore at depth may not have a bearing on water quality.
- The location of the pump within the bore. If the pump is located within the freshwater zone then the freshwater will be abstracted preferentially as the saltwater is denser and resides near the base of the bore.
- The mixing efficiency of the bore - either from pumping or naturally occurring.

The position of the saltwater interface and mixing efficiency will be different for each bore at Russell due to the variable aquifer properties, bore construction and pump set-up details. Where one bore may be utilisable, another may not. This suggests that it will be difficult to apply sustainable yield criteria on an individual bore basis.

5.3 Assessment of Management Options

The above assessments have shown that under natural conditions the position of the saltwater interface intersects most of the bores drilled within 350 m of the coastline during dry times. Given this finding aquifer management options for the township are limited to quantifying the sustainable yield for inland areas only (i.e. greater than 350 m from the coast) and alerting bore owners of the likelihood of deteriorating water quality during dry periods.

The three management options include:

- **Option 1 – Alert trigger levels during high-risk periods:** This option involves the setting of groundwater pressure trigger levels to forewarn NRC and bore owners that the saltwater interface is nearing the base of bores and groundwater quality may decline. The groundwater pressure trigger levels are further discussed in Section 5.3.1.
- **Option 2 - Limiting the depth of bores along the foreshore:** Backfilling existing coastal bores to depths that do not intercept the saltwater interface may ensure that abstracted groundwater is not adversely affected by saltwater. As a result, the water supply for consent holders may need to be supplemented due to a lowering of the hydraulic capacity of the shallower bores (i.e reduced bore yields). The recommended depth of bores has been assessed in Section 5.3.2.
- **Option 3 – Community water supply:** The Far North District Council community supply bore or new supply bores drilled further away from the coast could be used as alternative water sources for those coastal bores affected by the saltwater interface. The sustainable yield for the community supply bores using this option has been assessed in Section 5.3.3.

5.3.1 Groundwater Pressure Alert Trigger Levels

Under this management option consent holders may continue to abstract groundwater at their consented allocation, but should be aware that groundwater quality may be adversely affected should the saltwater interface rise above the base of the bore. Excessive saltwater will make the groundwater unsuitable for drinking and intolerable to plants, and may cause corrosion to pipes and fixtures. The NRC and consent holders can be forewarned of declining water quality through the setting of a groundwater pressure trigger level.

The groundwater pressure trigger level was assessed using the Ghyben-Herzberg equation with reference to bore drilled depths. Results of this analysis indicate that when the position of the saltwater interface is at 40 mBMSL or deeper (i.e groundwater pressure is at a minimum of 1 mAMSL) all bores are above this level.

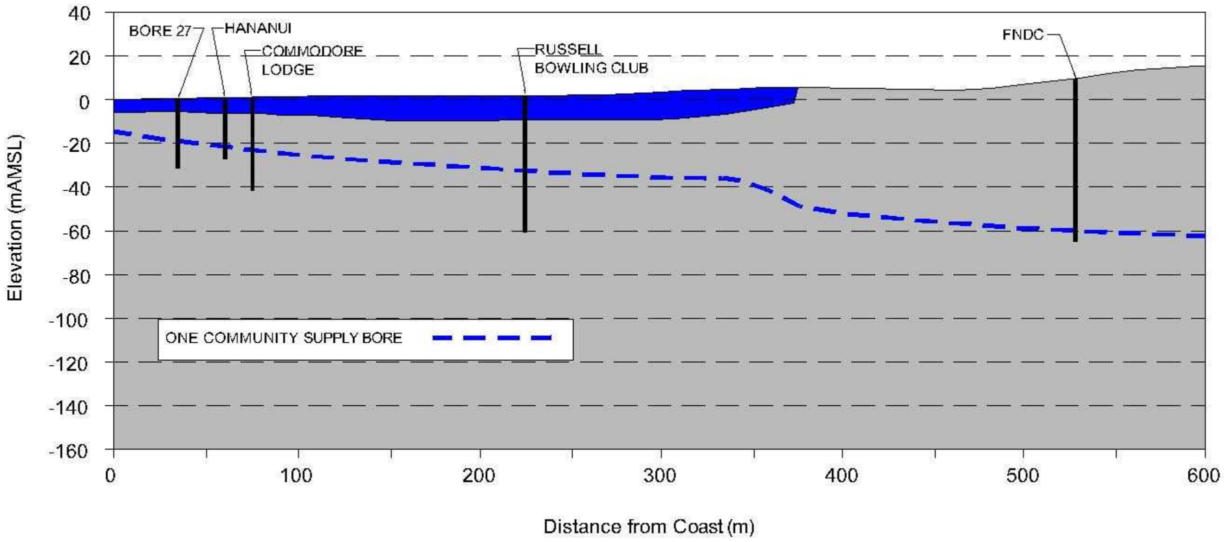
Groundwater pressures at the NRC Hananui monitoring bore have been recorded at or below 1 mAMSL for every summer between 1991 and 1995, as shown on Figure 3-2, and with wastewater reticulation these levels are expected to drop by an average of 0.45 m. The groundwater quality will be adversely affected by the saltwater interface until groundwater pressures sufficiently increase again during wet periods.

5.3.2 Limiting Depth of Coastal Bores

This option assessed the potential depth of bores located near the coast in order to avoid pumping saline water during dry periods when the position of the saltwater interface is high. Under this management option coastal bores may require a supplementary water supply during dry periods, as the volume of fresh groundwater that can be abstracted from shallow bores may be limited due to the reduced hydraulic capacity (i.e. it is likely that the current drilled depths are required to achieve the desired water yields).

A simulation was conducted with 100% wastewater reticulation and abstraction of the total existing consented allocation from the Far North District Council community supply bore only.

Figure 5-7 shows the position of the saltwater interface during a dry period with abstraction of 268 m^3/day from the Far North District Council bore. The position of the saltwater interface is located 20 mBMSL approximately 50 m from the coast and 35 mBMSL approximately 300 m from the coast (see Table 5-2). It is recommended that if this management option were to be followed bores near the coast should not be drilled greater than these depths.



■ **Figure 5-7. Cross-Section Showing the Position of the Saltwater Interface for a Dry Period with Abstraction from the Community Supply Bore Only and 100% Wastewater Reticulation.**

Table 5-2. Position of the Saltwater Interface with Abstraction from Community Supply Bore Only.

Distance from coast (m)	Maximum bore depth (mBMSL)
0	15
50	20
100	25
150	29
200	31
250	33
300	35

5.3.3 Community Water Supply

This analysis assessed the sustainable yield of the Russell groundwater resource using the driest period on record (9 May 1950) as an indicator of the worst case scenario. The criterion for determining sustainable yield is based on the volume of groundwater that can be abstracted from the aquifer under the existing bore configuration. Simulations were conducted with 100% reticulation and no pumping in all bores except for the Far North District Council community supply bore and two additional supply bores spaced greater than 100 m apart and located approximately 550 m from the coast. Details for the additional bores are given in Table 5-3. Abstraction rates from the bores were adjusted until the saltwater interface reached the base of the Far North District Council bore.

The saltwater interface reached the base of the Far North District Council bore when a total of 255 m^3/day was abstracted from the three supply bores. This value represents the lower limit of sustainable yield of the Russell groundwater resource with the current bore configurations described in Table 5-3.

The sustainable yield of the groundwater resource is influenced by climatic conditions and the supply bore configuration. Under wet conditions the sustainable yield of the aquifer is greater due to the higher hydraulic heads and consequent deeper position of the saltwater interface. The sustainable yield may also be higher if the supply bore configuration was different. For example, if the supply bores were at shallower depths and of similar hydraulic capacity than simulated above, the saltwater interface has to rise higher until the base of the bores are met. This is dependent on field conditions encountered during drilling and can not be assessed here.

Sustainable yield reported in SKM (2001) and NCC (1987) as determined by analytical methods was 184 m^3/day and 143 m^3/day, respectively. The dynamic sustainable yield of 255 m^3/day determined in this study is greater than previously reported, although below the current existing consented allocation of 268 m^3/day.

The assessment of sustainable yield using the Ghyben-Herzberg equation results in a conservative estimate of the position of the saltwater interface. Due to the assumptions inherent in the model (homogenous aquifer properties) and the Ghyben-Herzberg equation, the saltwater interface may not reside at exactly the level predicted.

■ Table 5-3. Details of Community Supply Bores.

Bore	Easting	Northing	Depth of bore (m)	Approximate distance from coast (m)	Abstraction rate (m^3/day)
Far North District Council	2613000	6659500	74	530	85
Supply Bore 2	2613420	6659470	74	660	85
Supply Bore 3	2613470	6659220	74	500	85
Sustainable Yield					**255**

6. Summary & Recommendations

This study was commissioned to investigate the current state of the Russell groundwater resource and assess dynamic sustainable yield. In addition the study objectives included assessment of:

- The effects of wastewater reticulation on groundwater recharge.
- Assessment of future sustainable yield based on proposed wastewater reticulation developments.
- Recommendations for groundwater management options.

To achieve the objectives of the study a groundwater flow model (MODFLOW) was developed. The model was calibrated over the period 1985 to 2002, which corresponded to the period of available groundwater monitoring data. Simulations of the model were conducted over the period 1946 to 2002 to assess aquifer sustainable yield and the effects of wastewater reticulation. Analysis of results from the period corresponding to the calibration simulations was used to verify the model calibration.

The main findings from this study include the following:

- Under current conditions the saltwater interface is likely to be present in all deep (>40 m) coastal bores (<350 m from the coast) during dry periods. Abstracting groundwater from these bores during dry periods will not be sustainable based on potable water quality criteria.
- The Far North District Council community supply bore does not intercept the saltwater interface during dry periods. This bore or bores located further from the coast could be used as an alternative water supply source during dry periods.
- The position of the saltwater interface is dependent mainly on groundwater recharge characteristics. Abstraction from the aquifer at current rates has negligible impact on the position of the saltwater interface compared to the influence of reduced rainfall recharge during prolonged dry times.
- Wastewater reticulation reduces groundwater recharge by 0.4 m on average across the aquifer and is likely to raise the position of the saltwater interface by an average of 16 m.
- Sustainable yield in this study is governed by climatic conditions and supply bore characteristics (location, depth and hydraulic capacity).
- The sustainable yield of the greywacke aquifer based on the existing bore configuration is approximately 255 m^3/day.

The following aquifer management options were assessed and are available for discussion with the main stakeholders in the town:

- **Option 1 – Maintain the status quo in terms of abstraction quantities.** Back this up with information to the community that indicates there is no guarantee that saline water will not occur in their bore during dry periods. Secondly provide an alert service notifying the community when a potential saltwater intrusion event is about to occur based on groundwater levels in a sentinel monitoring bore.
- **Option 2 – Limit the depth of bores along the foreshore to a predetermined level that is above the position of the saltwater interface during dry times for current abstraction rates.** Bores within 50 m of the coast should be backfilled

to 20 mBMSL and bores located between 100 m and 350 m from the coast should be backfilled to 35 mBMSL.

- **Option 3 – No pumping within 350 m of the coast and use a community pumping scheme to supply water to this area.** The Far North District Council supply bore or alternative supply bores could be used to supplement coastal bore consent holders during dry periods or on a continual basis. The bores could abstract a total of approximately 255 m^3/day if drilled to depths similar to the Far North District Council bore and still be within sustainable yield.

7. References

Auckland Regional Council, 1994. On-site Wastewater Disposal from Households and Institutions. Technical Publication No. 58, Second Edition, November 1994.

Freeze, R.A., Cherry, J.A., 1979. Groundwater. Prentice-Hall, Inc., New Jersey.

Northland Catchment Commission, 1987. Russell Water Resources. Technical Publication No. 1987/3.

Pitman, W.V., 1976. A Mathematical Model for Generating River Flows from Meteorological Data in South Africa. Hydrological Research Unit, Department of Civil Engineering, University of Witwatersrand.

Sinclair Knight Merz Ltd, 2001. Russell Hydrogeology Update Report. Final Revision B. Report prepared for Northland Regional Council, June 2001.

Sinclair Knight Merz Ltd, 2002. Russell Aquifer Test Pumping Results. Memo to Northland Regional Council, September 2002.

Todd, D.K., 1980. Groundwater Hydrology. Second Edition. John Wiley & Sons, Inc., Canada.

Appendix A SMWBM Description

The soil moisture water balance model (SMWBM) is a deterministic lumped conceptual parameter model, originally developed by Pitman (1976) to simulate river flows in South Africa. Modification of these algorithms and reworking of the code into a Windows environment now permits soil moisture accounting and assessment of the various components of the catchment water balance. In this study the SMWBM is employed as a preconditioner for assigning groundwater recharge to the MODFLOW model.

Soil moisture accounting on a daily basis model ensures that antecedent soil moisture conditions are considered in a realistic manner. The model utilises daily rainfall and mean-monthly evaporation data to calculate soil moisture conditions and estimate percolation to the aquifer. The model incorporates parameters that characterise the catchment in terms of:

- interception storage,
- evaporation losses,
- soil moisture storage capacity,
- soil moisture infiltration,
- percolation to groundwater, and
- surface runoff.

The fundamental operation of the model is as follows:

Daily rainfall is disaggregated into hourly intervals when a rain day occurs[3] to allow refined accounting of soil infiltration and evaporation losses. Rainfall received must first fill a nominal interception storage (PI – see below) before reaching the soil zone, where the net rainfall is assessed as part of the runoff/infiltration calculation.

Water that penetrates the soil fills a nominal soil moisture storage zone (ST). This zone is subject to evapotranspiration via root uptake and direct evaporation (R) according to the mean monthly evaporation rate and current soil moisture deficits. The soil moisture zone provides a source of water for deeper percolation to the underlying aquifer, which is governed by the parameters FT and POW.

If disaggregated hourly rainfall is of greater intensity than the calculated hourly infiltration rate (ZMAX, ZMIN) surface runoff occurs. Surface runoff is also governed by two other factors, which are the prevailing soil moisture deficit and the proportion of impervious portions of the catchment directly linked to drainage pathways (AI).

Rainfall of sufficient intensity and duration to fill the soil moisture storage results in excess rainfall that is allocated to either surface runoff or groundwater percolation depending on the soakage and slope characteristics of the catchment (DIV).

Finally, the model produces daily summaries of the various components of the catchment water balance and calculates the combined surface runoff/percolation to groundwater to form a total catchment runoff discharge.

3 For days where no rain occurred in the historical record, a one day time step is implemented.

A.1 Model Parameters

Parameters used in the soil moisture accounting model of most significance comprise the following:

ST: Maximum soil moisture capacity

The parameter ST is of major importance in that it is the most significant factor governing the ability of the catchment to regulate runoff for a given rainfall event. The higher the value of ST, potentially the greater the amount of rainfall absorbed during wet periods, and results in more sustained baseflow during dry periods.

The depth of the ST zone basically prescribes an active zone above the water table (vadose zone) within which root uptake through plants can occur. Depending on the vegetative and lithological characteristics this may coincide with the soil zone or may be deeper (i.e., forests and in sands). Russell is assigned a ST depth of 120 mm for the greywacke aquifer and the gravel aquifer was assigned a ST value of 200 mm.

SL: Soil moisture storage capacity below which percolation ceases

There is a definable soil moisture state below which percolation ceases due to soil moisture retention. For practical purposes this has been assigned as zero for both aquifers.

ZMAX & ZMIN: Maximum and minimum soil infiltration rate

ZMAX and ZMIN are nominal maximum and minimum infiltration rates in mm/hr used by the model to calculate the actual infiltration rate ZACT. ZMAX and ZMIN regulate the volume of water entering soil moisture storage and the resulting surface runoff. ZACT is usually nearest to ZMAX when soil moisture is nearing maximum capacity.

A nominal rate of 10 mm/hr has been assigned to ZMAX for the greywacke aquifer and 20 mm/hr for the gravel aquifer.

ZMIN ultimately determines the depth of rainfall required in any period required to initiate surface runoff. A value of 0 mm/hr has been assigned from ZMIN.

FT: Percolation rate from soil moisture storage at full capacity

Together with POW, FT (mm/day) controls the rate of percolation to the underlying aquifer system from the soil moisture storage zone. FT is the maximum rate of percolation and was assigned a value of 0.35 mm/day for the greywacke aquifer and 1.5 mm/day for the gravel aquifer.

POW: Power of the soil moisture-percolation equation

The parameter POW determines the rate at which percolation diminishes as the soil moisture content is decreased. POW has significant effect on both the seasonal distribution and reliability of percolation, as well as the total yield from a catchment. Through previous experience a value of 2 has been assigned to POW.

AI: Impervious portion of catchment

This parameter represents the proportion of impervious zones of the catchment directly linked to drainage pathways (AI) and is assigned 0.1 (10% of the catchment area) for the greywacke and gravel.

R: Evaporation-soil moisture relationship

Together with the soil moisture storage parameters ST and SL, R governs the evaporative process within the model. The rate of evapotranspiration is estimated using a linear relationship relating evaporation to the soil moisture status of the soil. As the soil moisture capacity approaches full, evaporation occurs at a near maximum rate based on the mean monthly pan evaporation rate, and as the soil moisture capacity decreases, evaporation decreases linearly according to the predefined function. A value of 1 has been assigned to R.

Table A-1 summarises the parameter values applied to the SMWBM.

Table A-1. Summary of SMWBM Parameters.

Parameter	Calibrated value - gravel	Calibrated value - greywacke
POW	2	2
SL (mm)	0	0
ST (mm)	200	120
FT (mm/day)	1.5	0.35
ZMIN (mm/hr)	0	0
ZMAX (mm/hr)	20	10
PI (mm/day)	2	2
AI	0.1	0.1
R	1	1
DIV	0.1	0

Appendix B Test Pumping Results