4. Model Calibration

The calibration of a numerical computer model is a trial and error process that requires adjustment of model variables to achieve an equivalent model response to measured field conditions. 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 and coarse discretisation can lead to calibration difficulties and an unrepresentative model.

Two methods were adapted in the calibration process – steady state and transient calibration.

4.1 Steady State Calibration

The steady state calibration process involved generation of a groundwater table as a function of average hydraulic properties and groundwater recharge in the various zones across the whole study area. This process simply verified the conceptual model by indicating that the modelled groundwater levels and flow directions, and the model parameters required to produce these were generally representative of field data.

Steady state simulation of the model attempted to replicate the piezometric surface generated from groundwater levels measured in NRC observation bores during January 1987 and from boreholes at the time of drilling.

The resulting steady state piezometric surface is shown in Figure 10, and provides a rough estimation of the regional water table for January 1987. This will be employed as the initial condition for transient calibration simulations.

4.2 Transient Calibration

Transient (time-varying) simulations are used to analyse time-dependent problems. In order for a model to be employed accurately in a transient sense for predictive purposes, it first must be calibrated to historical conditions.

A transient simulation is divided into a set of discrete stress periods, with each stress period further divided into discrete time steps. Each stress period may have variable boundary conditions (e.g., aquifer recharge, constant heads, pumping wells) in order to simulate the time dependent changes that occur in the natural environment.

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

1. the storage characteristics of the aquifer must be specified;

2. initial conditions giving the head distribution in the aquifer must be given for the particular starting time;

3. imposed stresses for each stress period must be calculated and imported into the model; and

4. time discretisation (i.e., stress periods length and computation of time stepping) must be appropriate for the time scale of the model.

Seven NRC observation bores (206, 207, 208, 209, 211, 81, 226) as indicated in Figure 8, were utilised for the matching process during the transient calibration.

The calibration simulations utilised precondition groundwater recharge, generated from Aupouri Forest rainfall for 1987 to 1999. The preconditioned recharge hydrographs and block-average periods for each zone are shown in Figure 11. Block average time lengths for the recharge zones varied from 66 to 495 days for the dunes zone, 90 to 3.4 years for the forest zone and 90 to 270 days for the plains zone.

4.2.1 Stress Periods and Time Steps

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. In contrast to surface water systems, groundwater responds slowly to changes in imposed stresses. As a results it is reasonable to use average surface processes to drive the model. However, using large stress periods implies that short time scale events will not be observed in the model.

The stress periods in MODFLOW are determined by time changes in boundary conditions and pumping wells. For the transient calibration simulations this consists of the recharge blocks and pumping well times. Each model stress period is discretised into ten time steps by a 1.2 multiplier.

4.2.2 Initial Conditions

Initial conditions refer to the head distribution in the model at the beginning of the simulation. If the initial condition is not representative of conditions that actually occurred at the starting time, then the early-time model response would reflect rapid adjustments in head values to be gain consistency with the model parameters and hydrologic inputs. For this reason, the initial condition for the transient simulation is taken as the model generated head distribution for January 1987 from the steady state calibration as shown in Figure 10, rather than contoured field monitoring data.

4.3 Transient Calibration Results

In excess of eighty transient model simulations, each of approximately fifteen-minute duration, were conducted before the calibration was deemed acceptable given the data and time available. During the calibration procedure recharge, hydraulic conductivity, specific yield and specific storage were adjusted within sensible ranges for the respective parameters.

Four discrete recharge zones within the upper layer were set as shown in Figure 12. These correspond to the three zones as discussed in Section 3.1.4.1, and a fourth zone representing the Motutangi Swamp. The Motutangi Swamp recharge area was fixed at an estimated average condition (120 mm/yr; 10% of rainfall), as little is know of the area and it is outside of the areas of interest.

As modelling progressed adjustments were made to hydraulic properties within layers and also independently within discrete zones of differing characteristics. The number of discrete zones was kept to a minimum, with new zones introduced only when simulation errors could not be minimised without a local change in hydraulic property.

The calibrated model consists of four hydraulic property zones in the upper layer, as identified in Figure 13, and a continuous property distribution within the lower layer. Table 7 summarises the calibrated hydraulic property information and provides a description for each zone.

Table 7. Summary of calibrated model hydraulic properties.

Zone	Layer	Description	K_{xy} (m/s)	K_z (m/s)	Ss (1/m)	Sy (-)
1	1	Dunes Areas – western peninsular and beach front, relatively clean sands.	2.0×10^{-5}	2.0×10^{-6}	-	0.30
2	1	Dune Areas – eastern areas, older sands with higher proportion of silt.	1.0×10^{-5}	1.0×10^{-6}	-	0.25
3	1	Plain Areas – low lying areas in east, high proportion of surficial silts, clays and peat.	1.5×10^{-6}	1.5×10^{-7}	-	0.20
4	1	Lake Areas – wetlands and numerous clay sills (lakebeds).	1.5×10^{-6}	1.5×10^{-7}	-	0.30
5	2	Shellbed – highly permeable.	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-3}	-

Notes:
K_{xy} is lateral hydraulic conductivity in x and y directions.
K_z is vertical hydraulic conductivity.
Ss is specific storage, defined as the storativity divided by the saturated aquifer thickness.
Sy is the specific yield.

Vertical anisotropy is introduced into all hydraulic zones in the upper layer to attenuate groundwater percolation rates or leakage between layers. This is consistent with bore hydrographs and typical for sedimentary lithological sequences where horizontal fluvial and aeolian bedding features retard vertical groundwater movement. The degree of anisotropy is more significant in eastern areas where a higher proportion of silt and clay occurs in the borelogs.

The calibrated model parameters are within the range indicated by hydraulic tests for the Aupouri aquifer as summarised in Table 3. In addition, Table 8 provides a summary table of typical published values for the various hydraulic properties and lithology types employed in the model. Comparison with the published data indicates calibrated model properties are within the typical range.

Table 8. Summary of typical published hydraulic property values.

Lithology	K (m/s)	Ss (1/m)	Sy (-)
Clean sands	4.5×10^{-5} to 3.5×10^{-3}	4.9×10^{-4} to 1.0×10^{-3}	0.30
Silty sands	1.0×10^{-7} to 2.0×10^{-4}	1.3×10^{-4} to 2.0×10^{-4}	0.20

(Adapted from Anderson and Woessner, 1992)

In order to replicate the observed bore hydrographs, numerous combinations of recharge and hydraulic properties were trialled for the differing zones of vegetation cover and lithology. Rarely did the recharge zones exactly overlay the hydraulic property zones, which led to greater complexity when calibrating the model.

In some cases it was possible to reproduce the same hydrographic response with opposite combination extremes. For example, high values for recharge and hydraulic conductivity may result in a similar groundwater response as low recharge and low hydraulic conductivity. This is the problem of non-uniqueness in model parameters and in this particular model is difficult to overcome because of the lack of certainty in any of the model variables.

Through the course of the calibration process a good understanding was developed for the functionality of the groundwater system and sensitivity to the various model parameters. The final calibration gives the most appropriate combinations for each particular zone.

The final calibrated model hydrographs for the key observation bores are provided in Appendix E. Inspection of trends indicates acceptable correlation between model response and field data over most of the calibration period. However, a time when the model response is unilaterally poor occurs during the wet period of 1989 to 1990. In this period calculated groundwater recovery fails to match the magnitude of the observed recovery. Considering that the later time groundwater recoveries match reasonably well, this would indicate that measured rainfall during the period is erroneous or incomplete.

The model response for bores 81 (Ogle Drive) and 226 (Lake Heather) show similar trends in groundwater movement, although the modelled mass in the system is lower than that measured.

As previously noted the hydrographs for these bores show a significantly delayed and attenuated response to rainfall in comparison to the other monitoring bores. This response and the presence of the perched dune lakes in the area suggest that a degree of coupling between the lakes and the underlying aquifer may exist. The lakes may act as a leaky reservoir supplying water through their basal clay and peat sediments. This mechanism would be head driven by levels in the lake, with a time delay due to slow percolation rates through the low permeability lake sediments. As long as the lakes contained water, then even during dry times a source of groundwater recharge would be available, albeit at low rates of supply. This mechanism has not been simulated in the model, as it would require additional investigations and extensive trial model simulations.

4.4 Model Volumetric Budget

An independent water budget calculation for the model provides a check on the acceptability of the solution, and a summary of the flow system. Volumetric budget flux results for the steady state simulation and the total for the transient calibration are summarised in Tables 9 and 10. Review of the discrepancy values indicates acceptable solutions for both simulations.

Table 9. Volumetric budget summary (m^3/day) for the steady state simulation (January 1987 conditions).

Fluxes Into Model	Recharge	184,182
	Total In	**184,182**
Fluxes Out Of Model	Coastline	120,307
	Drainages	63,875
	Total Out	**184,182**
In - Out Discrepancy		-0.0156
% Discrepancy		0.0000

Table 10. Volumetric budget summary (m^3/day) for the transient calibration simulation.

Fluxes Into Model	Recharge	4,735,739
	Accessions from Storage	20,818,848
	Total In	**25,554,588**
Fluxes Out Of Model	Coastline	12,975,163
	Drainages	9,679,989
	Accessions to Storage	2,899,434
	Total Out	**25,554,586**
In - Out Discrepancy		2.0
% Discrepancy		0.0000

Table 10 indicates that during the calibration period (1987 to 1999), the overall volume of water removed from groundwater storage is 7.2 times greater than water replenishing storage. This indicates an overall depletion in the aquifer storage, which is consistent with the response of the aquifer to prolonged dry periods and increased water demand through landuse change (i.e., planting of *Pinus radiata*).

Figure 14 compares the piezometric surfaces for an indicative dry period (July 1995) and wet period (August 1999), while Table 11 summarises the respective water budgets for these times.

Results indicate that during the dry period coastline discharges are 55% of recharge and accessions from storage are 43% of recharge, while for the wet period coastline discharges are approximately 16% and accessions from storage are virtually nil. Although the magnitude of coastline discharges are greater during wet periods, the lower percentage as a proportion of recharge indicates that accessions to storage (groundwater rise) are occurring.

Table 11. Volumetric budget summary (m^3/day) for indicative dry (July 1995) and wet periods (August 1999).

		Dry	Wet
Fluxes Into Model	Recharge	146,144	772,723
	Accessions from Storage	63,292	428
	Total In	209,436	**773,151**
Fluxes Out Of Model	Coastline	79,817	123,438
	Drainages	56,058	95,366
	Accessions to Storage	73,581	554,346
	Total Out	209,456	**773,150**
In - Out Discrepancy		-20.31	0.4375
% Discrepancy		-0.0100	0.0000

4.5 Flow Volume

The quantity of groundwater flow in an aquifer can be estimated using Darcy's law, which requires knowledge of the aquifer hydraulic conductivity, hydraulic gradient (head difference in the direction of flow) and the cross-sectional area of the aquifer. The flow volume has previously been estimated for the Hukatere to Houhora transect by NRC (1991) at 4,000 m^3/day per kilometre coastline on the west coast, assuming a hydraulic conductivity of 10 m/day (1×10^{-4} m/s). The flow to the east coast has been estimated at approximately 400 m^3/day per kilometre of coastline, assuming a hydraulic conductivity of 1 m/day (1×10^{-5} m/s).

Use of a computer model provides a more sophisticated and rapid method for estimating the flow volume for differing climatic conditions. The respective flows to the west and east coast for the dry and wet conditions discussed in the previous section are summarised in Table 12.

Table 12. Indicative flow volumes on the west and east coasts for various climatic phases.

	Dry (m^3/day per km)	Wet (m^3/day per km)
Hukatere-Houhora Area		
West coast	1,825	2,698
East coast	1,166	1,950
Paparore Area		
West coast	925	1,702
East coast	459	610

Table 12 indicates that flow to the west coast is between 1.4 and 1.6 times greater than to the east coast at the Hukatere-Houhora transect, and between 2.0 and 2.8 times greater in the Paparore area. Flows are greater along the Hukatere-Houhora transect due to the greater width of the peninsula, deeper aquifer and more permeable aquifer materials.

5. Model Sensitivity Analysis

A sensitivity analysis has been carried out in order to quantify uncertainty in the calibrated model caused by limitations in estimates of hydraulic conductivity, storage properties, and groundwater recharge. It also indicates the general acceptability of the model for predictive purposes.

The process has involved six additional simulations of the calibrated model, where in each case parameters have been systematically changed within a range of plus or minus 30% of the respective calibrated value. For each run, groundwater elevations corresponding to the calibration observation bores were extracted at yearly intervals. These were compared to historical data for the same time or interpolated data if water levels were not available. The difference in measured and simulated heads at each location and the root mean square (RMS) error for each time was calculated.

Results of the sensitivity analysis are displayed in Figure 15, which shows a graph of RMS error versus time for recharge, hydraulic conductivity, and storage. Analysis of these graphs reveals that for the calibrated model parameters, the RMS error ranges from approximately 0.3 m to 1.0 m. RMS error increases to a maximum during the wet period of 1989 to 1990 and then decreases slowly over the remainder of the simulation. The high RME error during 1989 to 1990 is due to the simulated water levels being lower than observed (as discussed in Section 4.3).

Sensitivity of the Recharge Parameter

Analysis of the graph for recharge sensitivity indicates that with a 30% decrease in recharge, RMS error increases at all times (i.e., groundwater levels are too low across the whole model). However, for the 30% increase in recharge case, RMS error actually improves during the 1989 to 1990 period when simulated groundwater levels were too low in the calibration, but becomes significantly greater after 1995 when the calibrated model response was superior.

Sensitivity of the Hydraulic Conductivity Parameter

Analysis of the graph for hydraulic conductivity sensitivity indicates that with a 30% increase, the RMS error increases at all times because simulate groundwater levels are too low. However, with a 30% decrease in hydraulic conductivity the RMS error is decreased at the beginning of the simulation because this raises groundwater levels to nearer observed levels. RMS errors during the later part of the simulation increase significantly, due to rising groundwater levels, which are greater than field observations.

Sensitivity of the Storage Parameters

Analysis of the graph for sensitivity of the various storage parameters indicates that with a 30% increase, RMS error actually improves, whereas the opposite occurs with a reduction in storage.

Overall the model appears to be most sensitive to changes in recharge and hydraulic conductivity and least sensitive to changes in the storage parameters. The magnitude of RMS error values for the calibrated model (0.3 to 1.0 m) indicates an error as a proportion of the mean groundwater elevation across the aquifer of approximately 3% to 10%.

While these error estimates are reasonably high at some locations, it should be noted that sparse information on recharge processes and hydraulic properties hinders refinement of the model. Field investigations and continued monitoring to improve knowledge of these properties will assist in clarifying model uncertainties.

6. Criteria for Sustainability

The sustainable yield of an aquifer is described as the amount of groundwater that can be withdrawn annually without producing any undesirable results. What constitutes an undesirable result is often difficult to define and varies depending on the area and aquifer concerned. Assessment of the sustainable yield requires consideration of technical, social and economic factors affecting the aquifer, aquifer users and the surrounding environment.

Various issues have been identified as criteria that require consideration when assessing the sustainable yield of the Aupouri aquifer. These include:

- **Climate and landuse change** – Both issues will effect aquifer recharge in the long-term. The growing and felling cycles of exotic forest plantation will have differing water requirements. It is difficult to assess the effects of these changes.

- **Salt-water intrusion** – Depletion of groundwater pressures in aquifers that are in hydraulic connection with the sea may induce inland advances of the salt-water interface. This has the potential to effect the quality of water in groundwater bores at the coast.

- **Artesian flow** – Groundwater pressures that result in free flowing conditions when tapped with a bore. Consideration needs to be given as to whether any ecosystems are dependent on the maintenance of artesian heads. If there are not, is the maintenance of artesian flow an effective use of the resource?

- **Sensitive surface areas** (i.e., wetlands, lakes etc.) – Depressurisation of groundwater tables through over pumping in areas with sensitive surface areas can result in drying of lakes and wetlands if they are coupled with the underlying aquifer. The degree of coupling and hydrological significance of the sensitive areas needs to be considered.

- **Maintenance of environmental flows** - Environmental flows are considered to be the minimal volume of water flowing in a river, stream or aquifer system that are required to sustain dependent ecosystems and aesthetic qualities. Environmental flow volumes are often difficult to determine.

- **Efficient use of the resource** – Determining efficient use of the resource requires a comprehensive understanding of the water balance of the aquifer or area under consideration, and the impact on the water balance through groundwater development (i.e., what quantity of total groundwater storage will be effected by pumping?).

- **Impacts on downstream users** – Groundwater abstraction in the headwaters of a catchment may effect the quality and quantity available to downstream users.

- **Land subsidence** – Will depressurisation of the aquifer induce land subsidence through reduction in pore pressures and subsequent compaction of sediments? If so, who and what will be effected and to what degree.

7. Assessment of Sustainable Yields

Predictive groundwater modelling is required to assess the performance of the aquifer in the two high abstraction areas and provide estimates of the sustainable yields for each area. In particular, the model will consider the impacts on groundwater levels and flux balances under incrementally increasing abstraction loadings over a 105.7-year (38,622 day) simulation period.

The predictive simulations utilise preconditioned groundwater recharge histories for January 1894 to September 1999 calculated by the SMWBM for the three recharge zones, as previously identified in Section 3.1.4. The use of a longterm historical data set provides a window into the climatic variability and likely extremes that can be anticipated for the region.

Groundwater abstractions for predictive simulations utilise abstraction consent allocations as detailed in Section 3.1.5, with the amount of abstraction varying depending on the scenario under analysis. Five abstraction scenarios have been conducted. These include:

- 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 of predictive simulations are shown in Figures 16 and 17, which display hydrographs for the observation bores used during calibration. Piezometric surface plots for the end times of each simulation are provided in Figure 18 for comparative purposes.

Analysis of hydrographs for the no pumping scenario (upper-most line on graphs) indicates that groundwater levels during the first 80 years of the simulation fluctuate due to cycles in climate, but generally maintain relatively equivalent mass in the system overall. However, from 80 to 100 years model-time, groundwater pressures drop dramatically. This is due to a reduction in the frequency of extreme wet periods, which had previously occurred at least once every decade during the 1920's to 1950's, coupled with a greater frequency of below average rainfall years and landuse change (i.e., planting of *Pinus radiata*). The marked increase in groundwater levels occurring at the end of the simulation appear to be as significant as any other recovery phase during the simulation. This indicates that the cyclic pattern of groundwater depressurisation and recovery is continuing.

Comparison of bore hydrographs for each simulation indicates incremental increases in groundwater depressurisation with increasing groundwater abstraction. Careful analysis of the early-time model response indicates that initially the aquifer depressurises in response to the imposed pumpage, then stabilises after a certain period of time. From this point, the difference in groundwater level relative to the zero pumping response remain roughly equal, although the time required for stabilisation to occur increases with increasing groundwater abstraction.

The following sections provide a summary of results for each abstraction area.

Houhora Area

Comparison of the zero to 500% abstraction scenarios indicates bores furthest from the abstraction area show the least impact. For example, bore 206 shows only a 1.25 m reduction in groundwater level at the end of the simulation. In comparison, bore 208 located in the middle of the pumping area shows over 10 m of drawdown after 105 years. The other bores in the forest transect showing a lesser intermediary response.

The modelled aquifer response for the 100% abstraction scenario indicates that in the middle of the pumping field (bore 208), after 105 years of pumping the groundwater table is just over 2 m below the zero pumping scenario. Groundwater pressures remain at approximately 12 mAMSL, indicating a significant hydraulic gradient to the coast still exists. Sufficient groundwater storage is still available, considering that the saturated thickness of the aquifer remains at approximately 100 m.

Analysis of the 500% abstraction scenario indicates that a cone of depressurisation is occurring adjacent to bore 208, as up gradient and down gradient groundwater levels are greater. Groundwater levels at bore 208 are also approaching sea level for this scenario. However, saltwater intrusion would not occur if down gradient water levels remained higher.

Figure 19 shows the throughflow hydrographs for the respective coastlines adjacent to the Hukatere-Houhora transect and Paparore-Lake Heather area. Throughflow rates for the no pumping abstraction scenario adjacent to the pumping field are estimated to vary from approximately 1,500 to 4,000 m^3/day/km at the west coast compared with 1,000 to 3,000 m^3/day/km at the east coast. With the 500% abstraction scenario, these rates are reduced by approximately 6–15% and 12–35% for the west and east coasts, respectively.

Paparore-Sweetwaters Area

Bore 211, which is located within a pumping field shows very little response to 50% and 100% pumping, with approximately 1.5 and 3 m drawdowns for 250% and 500% pumping, respectively. Bore 81 at Ogle Drive shows a similar result, while Bore 226 at Lake Heather indicates virtually no effect of simulated pumping.

As the normal groundwater pressures at bore 211 are around 6 mAMSL, this bore has only minimal storage available before pressures are reduced to such a level that salt water intrusions may start occurring. The 500% pumpage scenario indicates groundwater pressures are close to this level after 105 years, although this will vary with climatic fluctuations.

Throughflow rates, as shown in Figure 19, for the no groundwater abstraction scenario adjacent to the pumping field are 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 at 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.

8. Limitations of the Model

The non-uniqueness problem, defined by Anderson and Woessner (1992) occurs when different combinations of parameters yield essentially the same head distribution. This is likely in this model due to the limited number of data inputs with a high degree of certainty.

During model calibration, parameters with a high degree of certainty are held relatively constant, while parameters with less certainty are defined through trial and error adjustments. This model required significant adjustments of every model parameter because of the numerous uncertainties. For example;

- aquifer geometry was estimated from only sparse borehole data,
- preconditioned aquifer recharge was maintained within a range of estimated or ballpark longterm average recharge coefficients for each landuse type,
- aquifer hydraulic properties was maintained within a broad range defined by test pumping, and
- groundwater abstractions were based on allocated consents and don't consider that water requirements vary depending on prevailing climatic cycles during each season.

In particular the recharge parameter, being one of the most sensitive within the model, has the least degree of certainty. Variations in the recharge characteristics for a particular zone have significant impacts on the simulated hydrographs.

The variability in recharge dynamics over time through the effects of landuse changes is extremely difficult to account for in predictive simulations of the model and has not been considered here. In terms of the longterm recharge patterns in the pine plantation areas, there are obviously going to be cycles in forest water use that correspond to the growing and felling stages of the trees.

Due to the simplified structure of the model's vertical discretisation, which required using bulk hydraulic properties rather than numerous discrete layers, the artesian characteristics of the aquifer are not considered in great detail.

Predictive simulations have used a recharge history generated from long-term historical rainfall records. The assessment of sustainability is based on the assumption that historical extremes in rainfall are more than likely to reoccur in the future. However, there is no guarantee that the rainfall patterns over the next 100 years will not vary significantly.

When assessing the implications of modelling results the above limitations need to be considered.

9. Summary

Findings from this study indicate current groundwater allocations are having negligible impact on the regional water table over the long term. Localised impacts may be experienced during below average rainfall periods, but the high susceptibility of the aquifer to rainfall recharge indicates that the aquifer recovers rapidly during subsequent wet periods.

The fact that the vast majority of groundwater abstractions occur during the summer months when rainfall is generally is lowest unfortunately results in rapid localised depressurisations, as observed in some monitoring bores. However, given that only minor groundwater abstractions occur during winter and rainfall is greatest, rapid groundwater recovery usually occurs.

Over the long-term groundwater levels were shown to fluctuate significantly depending on prevailing climatic conditions.

The effects the planting of *Pinus radiata* have had a marked effect on water levels in the middle of the forest over the last 20 years in the Hukatere-Houhora transect. It is likely that a similar adjustment to the new imposed hydrological conditions occurred adjacent to Paparore during the 60's when planting began there. However, the absence of monitoring data during this time makes this difficult to preclude. Groundwater recharge in the forest part of aquifer is likely to increase once the felling operation commences.

10. Recommendations

Given the limitations of the model and findings of this study, the following recommendations are provided:

- Conduct a regional bore survey to provide accurate co-ordinates, and ground and collar elevations. This will increase the accuracy of interpolated piezometric surface and base of aquifer geometry.
- Investigative drilling coupled with possibly geophysical surveying to enhance the aquifer geometry in terms of delineating the extent and thickness of the shellbeds (i.e., where it pinches out onto hardrock), sands and silt/clays/peat layers, and provide some information in areas where it is currently sparse.
- Assessment of hydrological significance of perched lakes and in particular the degree of coupling with the underlying aquifer.
- Initiate soil moisture monitoring to enhance understanding of recharge dynamics and predict the effects of different land use (e.g., compare recharge for *Pinus radiata,* avocados, and pasture).
- Borehole Infiltration testing to determine infiltration characteristics of vadose (unsaturated) zone.
- Hydraulic testing of discrete lithological units (i.e., shellbed, semi-confining layers, sands).
- Understorey raingauges in the Aupouri Forest to provide indication of interception losses.
- Uncapped bores in artesian flow areas require immediate capping to prevent waste.
- Continue to monitor groundwater on a monthly basis. Installation of additional observation locations would be advantageous.
- Increase community knowledge of the aquifer dynamics and effects of pumping on the system, so that they can make informed decisions and minimise waste.
- Provide training for drilling contractors so that the standard of lithological borelogs increases. Every piece of information helps.
- Identify any major streams in the dune country (if any) and determine if gauging can be implemented. This will provide value information for the areas water balance.

Using results of the above recommendations, the model may be refined and then extensive numerical simulation to more accurately establish the aquifer sustainable yields may be conducted.

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