3. 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. 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., hydraulic conductivity, specific yield and specific storage;
- regional groundwater pressure distributions - e.g., flow directions and boundary fluxes; and
- recharge processes.

3.1 Model Design

Several numerical modelling strategies are available. For this particular study, NRC requested the modular finite difference groundwater flow model, MODFLOW developed by the United States Geological Survey. The model simulates three-dimensional flow of constant density groundwater through porous earth materials using the finite difference method, which provides an approximate solution to the partial-differential equation that describes the three-dimensional flow of groundwater[6].

The finite difference 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., pumpage). A compromise between accuracy and computing efficiency results in different sized cells. Small cells are used in areas where steep or complex gradients are expected, while larger cells are employed to represent areas where shallow gradients occur or where changes in groundwater flow are not extreme.

[6] For a full description of the MODFLOW code refer to McDonald and Harbaugh (1988).

3.1.1 Model Domain

A two-layer model comprising 7,192 active cells (3,596 in each layer), representing an area of 428 square kilometres has been developed (Figure 8). Cell size varies from about 5.6 hectares (198×283 m) in the area of interest (Paparore-Sweetwaters and Houhora) to approximately 92 hectares (935×983 m) in the northern extremity of the model.

The northern extremity of the model coincides with the approximate location of surface outcropping of underlying basement rocks (i.e., where the sand aquifer pinches out or becomes unsaturated). The southern boundary is roughly defined by the change in land surface gradient on the southern plains adjacent to Kaitaia (i.e., where the aquifer pinches out on the hills). The respective coastlines define the western and eastern boundaries of the model.

3.1.2 Boundary Conditions

Boundary and initial conditions are those features applied to numerical models that act to constrain the solution process and determine the way in which the model domain communicates with outside areas. Boundaries of a model impose hydraulic conditions through such features as defined pressure head, specified flux and recharge.

The boundary conditions of the model were chosen to coincide with known or assumed natural boundaries such as coastlines, rivers, streams and major drainage features. All other boundaries either align parallel to the dominant groundwater flow direction so that flow is only permitted to travel along the boundary, or are located sufficient distances from areas of special interest to ensure simulation errors are minimised.

Key features of this model include:

- ***Constant heads*** - define the west and east coasts. The coastline head elevation will vary depending on the tide, prevailing wind and wave setup. In this model the constant head was set at 0 mAMSL, as on the time scale of this model, errors associated with the coast elevation will be insignificant.

- ***Drain cells*** - assigned an elevation marginally below interpolated ground level for the following features; Whagatane Spillway, Awanui River, Waipapakauri Outfall, Pukepoto Main Outfall, Tangonge Drain, Waiparera Stream, Motutangi Steam, Kaikatia Stream, Waihopo Stream, and an unnamed stream in the vicinity of Paparore.

- ***No-flow cells*** – are located on all other boundaries of the model and this indicates that flow is only permitted parallel to these boundaries.

3.1.3 Layer Geometry

Model discretisation in the vertical direction is handled by specifying a number of layers and their respective hydraulic properties that contain or embody the layer thickness. As the model equations are based on the assumption that hydraulic properties are uniform within individual cells, this condition is more likely to be met when model layers conform to hydrogeologic units. However, in practice a compromise is usually made between the number of layers, thus accuracy of the model, and computational time as each additional layer adds proportionately to the simulation time.

Assigning a separate layer to a discontinuous hydrogeological unit that is significant in only a small proportion of the model generally results in a considerable waste of computational time. Different hydrogeologic units with similar aquifer characteristics may be handled in a single layer with bulk aquifer properties, and without significant loss of model accuracy.

The model constructed consists of two layers, with the respective characteristics of each layer summarised below:

Upper Layer – Extends to the top of the shell bed, and is assigned bulk aquifer characteristics representative of the entire lithological sequence above the shellbed. The base of the layer has been interpolated from 38 borelogs that penetrate the shellbed.

Various borelogs have identified distinct units of lower permeability, generally consisting of silty sand, silt, clay or peat, which may impart some degree of semi-confinement on lower aquifer materials. These units occur more frequently in the east and southern plains. However, the spatial distribution of borelogs is not adequate to accurately delineate the extent and depths of these units. In addition, aquifer tests conducted in the area have typically resolved hydraulic characteristics for bulk lithologies and not discrete units.

Zones of varying hydraulic properties have been delineated across the upper layer through review of bore hydrographic responses, borelog information and analysis of surface characteristics. These zones broadly reflect the higher permeability fine aeolian sands in the west, prograding into lower surface permeability silty sand and peat in the eastern and southern plain.

Vertical anisotropy is introduced into all zones to attenuate groundwater percolation velocities, as is demonstrated in NRC bore hydrographs. Anisotropy is more significant in eastern areas where higher proportions of silt occur.

Lower Layer - Represents the shellbed aquifer, which sits unconformably on regional basement rocks. The shellbed is easily identifiable in the field and for this reason can be considered a regional lithological marker. It is also of high importance as a significant aquifer for groundwater supply. Consequently, there is greater information available regarding the lateral extents and thickness of the shellbed, and thus has been more accurately represented in the model.

Since pump test information in the region generally indicates bulk transmissivity (i.e., reflects the combined hydraulic characteristics of the entire sequence), the shellbed unit has been assigned a hydraulic conductivity marginally higher than most pump tests indicate.

When additional comprehensive borelog data becomes available, the vertical discretisation in the model may be improved to provide a more accurate representation of the discrete units rather than the bulk aquifer properties employed here. This will enable improved simulation of such features as vertical hydraulic gradients and artesian heads.

3.1.4 Aquifer Recharge

The variability in groundwater recharge results from a combination of features in an area, as discussed in Section 2.6.

Short duration low intensity rainfall will be consumed satisfying soil moisture deficits without percolation to the groundwater system, while high intensity events will overcome surface moisture deficits and contribute to the groundwater system or result in surface runoff if the rainfall is of high enough intensity. During prolonged dry periods when soil moisture deficits are greatest, a larger proportion of rainfall is consumed satisfying soil moisture deficits, resulting in lower than normal recharge. Conversely, rainfall occurring when soil moisture deficits are minimal (i.e., wet period) results in a greater proportion available for groundwater recharge or surface runoff.

Employing a fixed recharge coefficient fails to adequately account for the extremes in recharge, which are most apparent during prolonged dry or prolonged wet periods when the resulting recharge is significantly lower or greater than normal, respectively. This has important implications for transient water balance assessments of an area.

3.1.4.1 Soil Moisture Water Balance Model

In order to refine the recharge estimates given in Section 2.6.1 and to create a preconditioned recharge data set for transient simulations of the MODFLOW model, a soil moisture water balance accounting model (SMWBM) was utilised. Mackie and Williamson (1998) and HydroGeo Solutions (1998) have previously used variations of the model successfully to predict groundwater recharge in coastal environments.

The SMWBM is adapted from algorithms developed by Pitman (1976) for the simulation of river flows in South Africa. SMWBM utilises daily rainfall data and mean-monthly pan evaporation to calculate catchment soil moisture conditions, percolation to the groundwater table, and various other water balance components, which are less relevant to this study. The model is described in more detail in Appendix D.

Following the preliminary recharge analysis, review of bore hydrographs, topographic and vegetation data, and to necessarily simplify the conceptual groundwater model, three recharge zones with differing landuse and physical characteristics were identified. These zones include:

1. ***Dune Zone*** - Surrounds the forest zone on the western and eastern side. Typically displays an assortment of vegetation types consisting of pasture, bush and orchards of low to medium height and density (moderate interception losses), smaller active root zone than forest (moderate interception and ET), and high infiltration capacity (low surface runoff).

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

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

Appendix D also contains a description of the model parameters and respective values for each of the above zones.

Simulations of the SMWBM utilised the continuous rainfall record from January 1894 to September 1999 (see Appendix A for details). Model parameters were adjusted until the resulting water balance seemed appropriate for the vegetation and soil types, while maintaining groundwater recharge within the range determined in the preliminary analysis.

Table 5 provides a long-term average water balance summary for each zone following analysis of SMWBM simulation results.

Table 5. Long-term average water balance summary for recharge zones.

Zone	Description	Recharge	Evap.	Runoff	Characteristics
1	Dune Zone	18.1%	81.7%	0.2%	High infiltration capacity, medium soil moisture storage capacity, smaller active root zone, moderate evapotranspiration, low surface runoff.
2	Forested Dune Zone	10.4%	89.5%	0.1%	High infiltration capacity, high soil moisture storage capacity, large active root zone, high evapotranspiration, low surface runoff.
3	Plains Zone	12.0%	64.2%	23.8%	Reduced infiltration capacity, medium soil moisture storage capacity, smaller active root zone, lower evapotranspiration, greater surface runoff (interflow drainage).

Notes:
Values indicate the long-term average as a percentage of rainfall from the 1874 to 1999 record.
Evap. refers to total evaporation losses including interception, evaporation and transpiration.

The long-term average groundwater recharge coefficients indicated in Table 5, reflect the aquifer, drainage and vegetation cover characteristics at each site. For example,

- the forested dune sites display high interception and ET due to the influence of the dense canopy cover and extensive root zone of the *Pinus Radiata* trees, and very low surface runoff due to the high absorptivity of the surficial sand deposits.

- The dune zone displays similar physical aquifer hydraulic characteristics, but lacks the high interception and ET demand of the trees, thus recharge is greater in this zone.

- The plains zone has a slightly higher recharge coefficient than for the forested dunes, although the aquifer hydraulic properties are generally less permeable at the surface with frequent peat, silt, and clay layers present. This results in a susceptibility to surface water logging, which results in surface runoff. The presence of a complex network of surface drains intercepts soil moisture further reducing the amount of water available for recharge.

Figure 9 provides the resulting groundwater recharge hydrographs for each zone and consolidated blocks of time where the preconditioned recharge is considered uniform enough to assign as a single stress period within the MODFLOW model. Equivalent mass transfer has been maintained in calculating these block averages, which range in length from 102 days to greater almost 17 years.

Examination and comparison of each recharge hydrographs shows the more oscillatory nature of the dune and plain zones. This is a reflection of lower interception and ET loses, high infiltration in the dune zone and low soil storage capacity in the plains zone resulting in rapid wetting and drying of the unsaturated zone. The forest zone displays longer blocks of consistent recharge, reflecting the attenuating effect on recharge of the deeper active soil zone.

3.1.5 Groundwater Abstraction

For the purpose of model calibration and predictive simulations, groundwater abstraction bores within the high intensity usage areas of Paparore-Sweetwaters and Houhora were combined into groups to enable simulation within a single model cell. Seven pumping groups were identified as shown in Figure 7. Their respective current groundwater allocations have been summed to give the total allowable abstraction for each group. This is summarised in Table 6.

Table 6. Summary of groundwater abstraction groups used for model simulation.

Group	Location	Area	Application Numbers	Take Volume (m^3/day)	Total Volume (m^3/day)	Total per Area (m^3/day)
1	Paparore Road, Paparore	Paparore-Sweetwaters	3580, 3968, 4564	45, 200, 748	993	
2	Far North Road, near Forest Headquarters	Paparore-Sweetwaters	4350, 8177	240, 365	605	
3	Far North Road, near Ogle Drive	Paparore-Sweetwaters	3788, 2459, 3798	216, 315, 100	631	2229
4	Hukatere Road, south of road	Houhora	3372, 3527, 4903, 7108	170, 200, 200, 100	670	
5	Hukatere Road	Houhora	3888, 8605	170, 160	330	
6	Hukatere Road, north of road	Houhora	3726, 7735	600, 800	1400	
7	Burnage Road	Houhora	3841, 3883, 7115, 7524	90, 120, 25, 70	305	2705

Groundwater abstractions were simulated in the model via six-month cycles corresponding to summer high and winter low abstractions. The winter abstractions were maintained at 5% of the total allocation, while the summer abstractions varied depending on the modelling scenario.