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Waimea Plains aquifer structure as determined by three-dimensional computer modelling

P. A. White, R. R. Reeves

Institute of Geological & Nuclear Sciences Limited
Wairakei, New Zealand
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Abstract

Three-dimensional computer modelling of 274 lithological logs in the Waimea Plains identifies three major aquifer structures. The first is a near-surface structure that covers most of the Waimea Plains and estuary and is consistent with the Appleby Gravel Unconfined Aquifer, the Hope Gravel Unconfined Aquifer and parts of the Upper Confined Aquifer. The second occurs in the vicinity of the Wairoa and Wai-iti rivers and is consistent with part of the Upper Confined Aquifer. The third is a deeper structure that occurs east of the Waimea River and under the estuary and is consistent with the Lower Confined Aquifer.

The computer model indicates that the near-surface aquifer is possibly linked to the deeper aquifer to the east of the Waimea River and by two permeable zones to the west and south-west of Richmond Township. Elevated nitrate concentrations in the Lower Confined Aquifer west and south-west of Richmond could be explained by recharge and chemical transport through these zones between the Unconfined Aquifer and the Lower Confined Aquifer.

Introduction

The Waimea Plains consist of about 75 km^2 of productive agricultural land in the northwest of the South Island, New Zealand (Fig. 1). Tasman Bay, and the Waimea Inlet, bound the Waimea Plains to the north. To the west are the Moutere Hills and to the east is the Barnicoat Range. Flowing across the Waimea Plains are the Wai-iti, Wairoa, and Waimea rivers. These rivers have deposited flood plain gravels and formed terraces. Streams and creeks with catchments in the Moutere Hills and Barnicoat Range have deposited a series of gently sloping fans on the western and eastern edges of

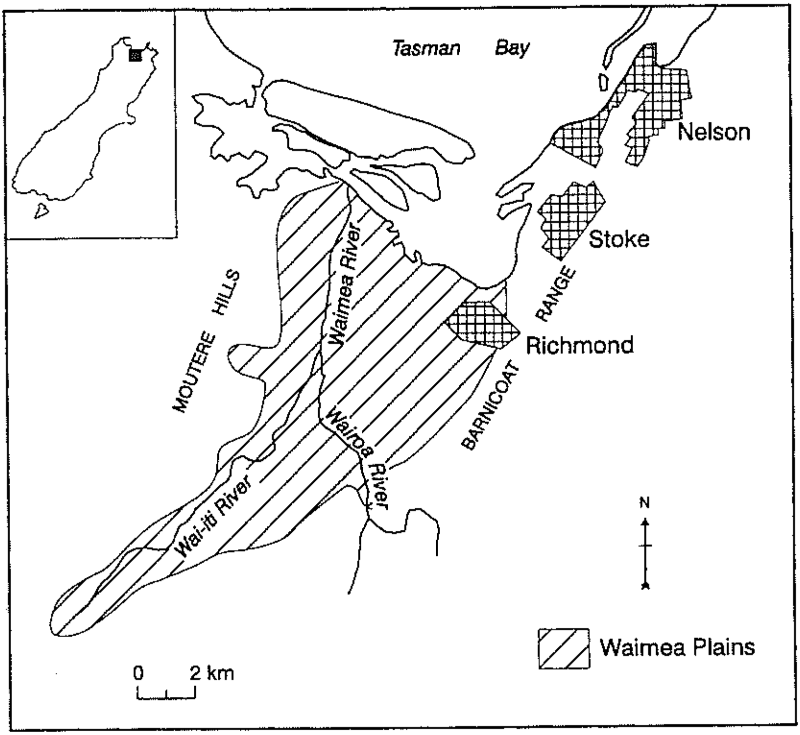

FIGURE 1 – The Waimea Plains, South Island, New Zealand.

the plains. Dicker *et al.* (1992) report the results of hydrogeological investigations of the Waimea Plains aquifers begun by the Department of Scientific and Industrial Research, and the Nelson Catchment Board, in the 1970's.

Groundwater is the primary irrigation water supply for the diverse agricultural and horticultural production of the Waimea Plains. Groundwater is also the main source of water for the approximately 18 000 inhabitants of the Waimea Plains (1996 census) and for local industry.

The area of arable land in the Waimea Plains has increased since European settlement following the establishment of Nelson in 1841. Water tables in the plains have been lowered as a result of the drainage of arable land, the construction of flood protection stopbanks, and the lowering of riverbeds by gravel extraction (Dicker *et al.*, 1992). Increasing groundwater withdrawals have caused lower summer groundwater levels and led to concerns about environmental effects such as sea water intrusion to the coastal aquifers and reduced river flow. Intensive land use has caused groundwater nitrate concentrations to increase.

Late Quaternary sediments of the Waimea Plains are considered by Dicker (1980) and Dicker *et al.*, (1992) to contain four aquifers. Structural contour maps of the top and base of the aquifers were determined from drillers' logs. These aquifer boundary definitions were used by Fenemor (1989) in a groundwater flow model which aimed to quantify the relationships between groundwater and recharge, assess the potential for sea water intrusion, determine the effects of increased pumpage, and examine the impact of community irrigation schemes. The predictions of Fenemor (1989) have been integrated into a Waimea Catchment Water Management Plan on the Waimea Plains (Tasman District Council, 1991). Nine water-use zones have been defined by aquifer and topographic boundaries. Water allocation limits within these zones are based on some of the model predictions (Fenemor, 1989).

The aim of this paper is to reassess the complex structure of the Waimea Plains aquifers using three-dimensional computer modelling techniques. This model will be compared with the findings of Dicker *et al.*, (1992).

Improvements in the representation and understanding of the geological structure of the Waimea Plains will lead to improved management of the groundwater system.

The "classic" model of the Waimea Plains aquifers

Dicker *et al.*, (1992) identified four aquifers in the Quaternary sediments underlying the Waimea Plains.

Appleby Gravel Unconfined Aquifer

The Appleby Gravel Unconfined Aquifer underlies the flood plains of the Wai-iti, Wairoa, and Waimea rivers and the delta of the Waimea River. This fluvial gravel aquifer is up to 17 m thick. The base of the aquifer (Fig. 2) is at the contact with the Hope Gravel and is readily recognisable in drillholes because of the claybound nature of the Hope Gravel. The contact with the Hope Gravel is less recognisable in the Wai-iti Valley, where the Appleby Gravel Unconfined Aquifer is less permeable, than in other areas of the Waimea Plains. The Appleby Gravel Unconfined Aquifer is in contact with the Upper Confined Aquifer, and in lateral contact with marine gravel and sand, in the Waimea River delta region. Groundwater storage volume is estimated as 21 million m^3 in winter and 17 million m^3 in summer (Dicker *et al.*, 1992).

Hope Gravel Unconfined and Confined Aquifers

Water-bearing river channel gravels, up to 0.5 m thick, form aquifers in the Hope Gravel to the east of the Appleby Gravel deposits. The gravel lenses are within 15 m of the ground surface. They are not laterally continuous and are therefore difficult to delineate and map. These aquifers, both unconfined and confined, can supply appreciable quantities of water, par-

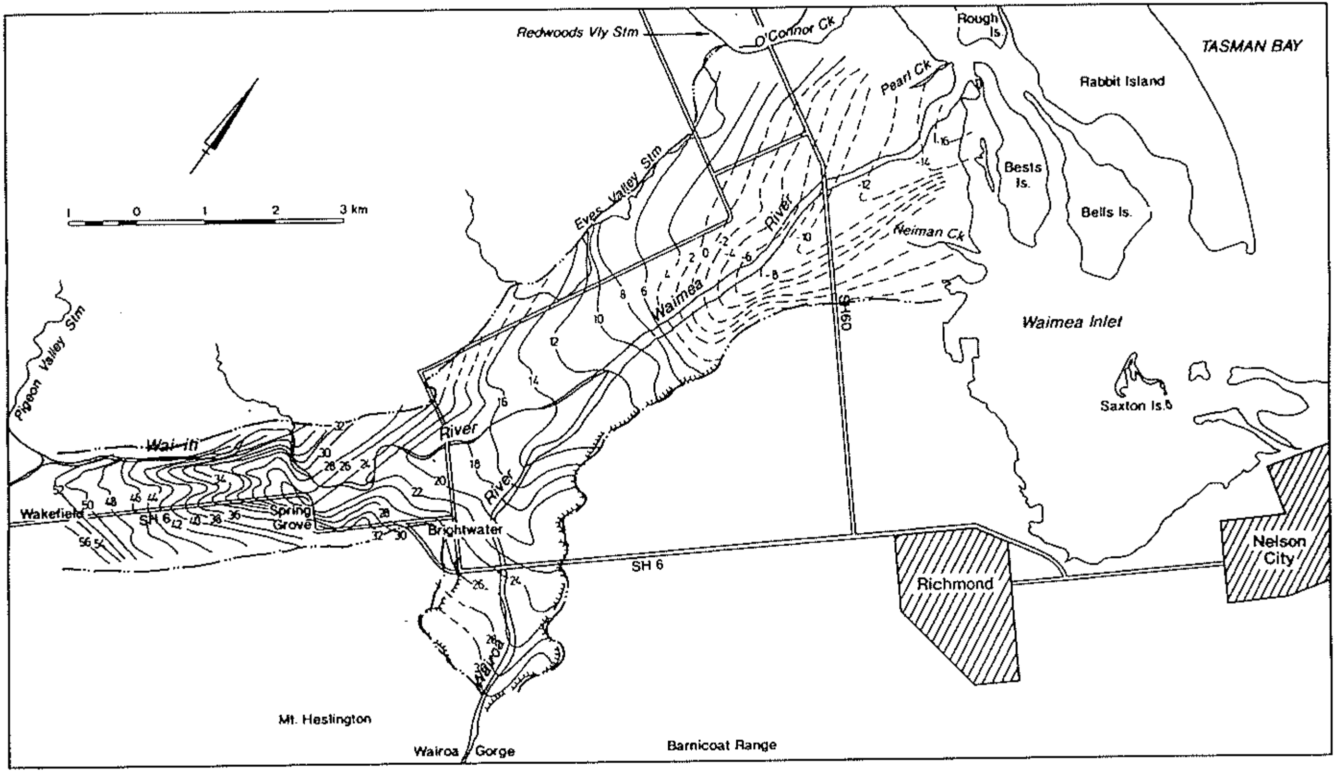

FIGURE 2 – Base of the Appleby Gravel Unconfined Aquifer, metres above mean sea level (after Dicker *et al.*, 1992).

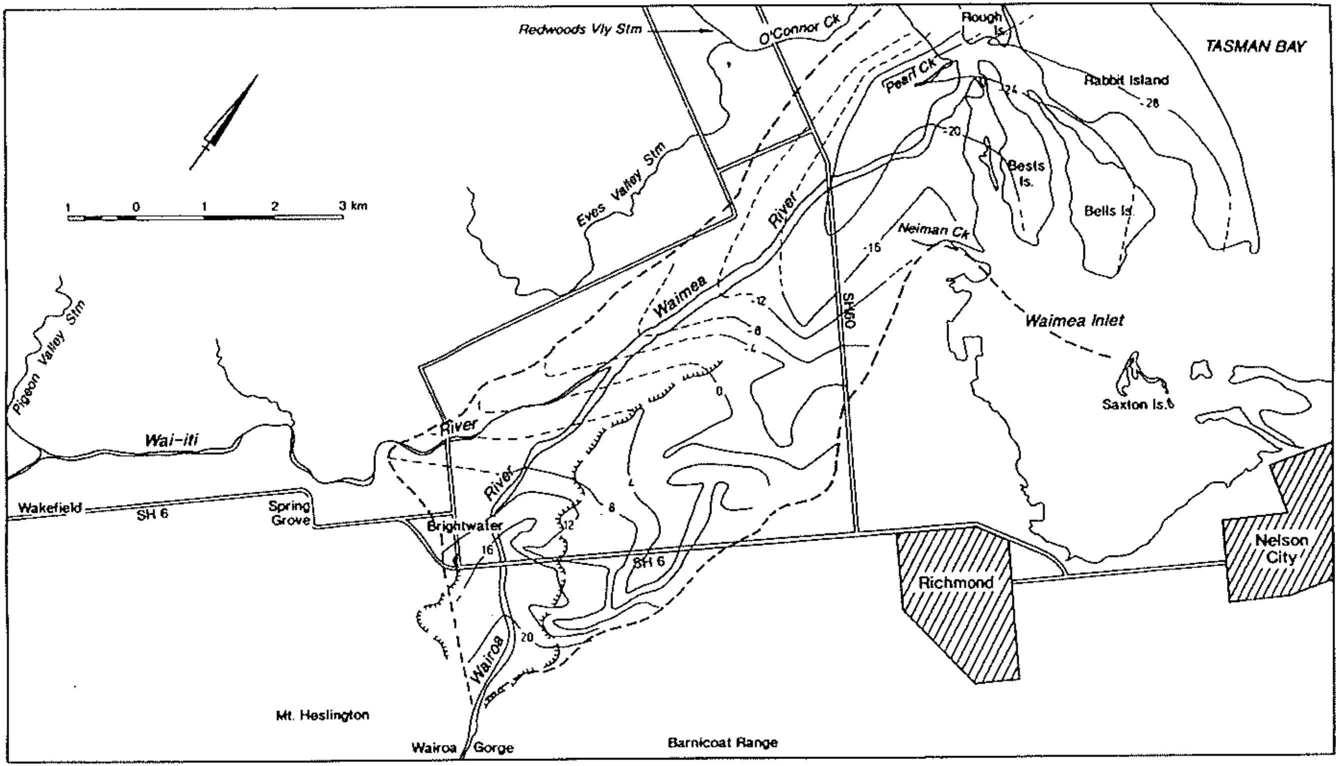

FIGURE 3 – Base of the Upper Confined Aquifer, metres above mean sea level (after Dicker *et al.*, 1992).

ticularly in the vicinity of State Highway 60 (Fig. 2). Water levels and yields decline markedly in summer.

Upper Confined Aquifer

The Upper Confined Aquifer is a fluvial gravel riverbed deposit within the clay-bound Hope Gravel, and accumulated on a degradation surface in the valleys of the Wairoa and Waimea rivers (Fig. 3). Gravels of the Upper Confined Aquifer are better-sorted, with less clay matrix, than the surrounding Hope Gravel. Boundaries are poorly defined to the west of the Waimea River, due to a lack of wells, and the aquifer is of low permeability under the lower reaches of the Wai-iti River. For these reasons Fenemor (1989) modelled the Upper Confined Aquifer as a hydraulic unit that is much smaller than the geological unit. The Upper Confined Aquifer broadens below the Waimea Inlet. The upper surface of the Upper Confined Aquifer is difficult to define because of erosion, and the deposition of the Appleby Gravel deposits. The basal contact of the Upper Confined Aquifer is not strongly defined, as the contact is transitional, marked by a downward change in the gravel matrix from better-sorted gravel to grey and yellow clay. The Upper Confined Aquifer is in contact with the Appleby Gravel Unconfined Aquifer in the vicinity of State Highway 60 (Johnston, 1979). Groundwater flows vertically upward from the Upper Confined Aquifer to the Appleby Gravel Unconfined Aquifer in this region. Well logs suggest that the confining layer of the Upper Confined Aquifer thickens towards the Wairoa Gorge. Recharge from the Wairoa River to the east of State Highway 6 (Fig. 3) is suggested by groundwater level variations. Groundwater storage volume is estimated to be 37 million m^3 (Dicker, *et al.*, 1992).

Lower Confined Aquifer

The Lower Confined Aquifer extends from the Wairoa Gorge (Fig. 4) to the Waimea Inlet. Drillholes on islands in the Waimea Inlet intersect this aquifer. The aquifer is a well-sorted gravel that was deposited on a degradation surface in the Hope Gravel. A sharp lithological change from sorted gravel to clay-bound gravel characterises the base of the aquifer. However, the upper surface of the Lower Confined Aquifer is difficult to identify in many localities, with the better-sorted aquifer gravel grading into the overlying clay-bound Hope Gravel. Gravel fans from the eastern hills are in lateral contact with the Lower Confined Aquifer in the vicinity of State Highway 6. The aquifer thins towards the Wairoa River gorge, and is largely absent in the Wai-iti Valley. The aquifer has a maximum thickness of 14 m approximately 2 km west of Richmond. Dicker *et al.*, (1992) suggest the aquifer has been displaced, subsequent to deposition, by movement on the Waimea Fault. The aquifer was flowing artesian near the coast prior to

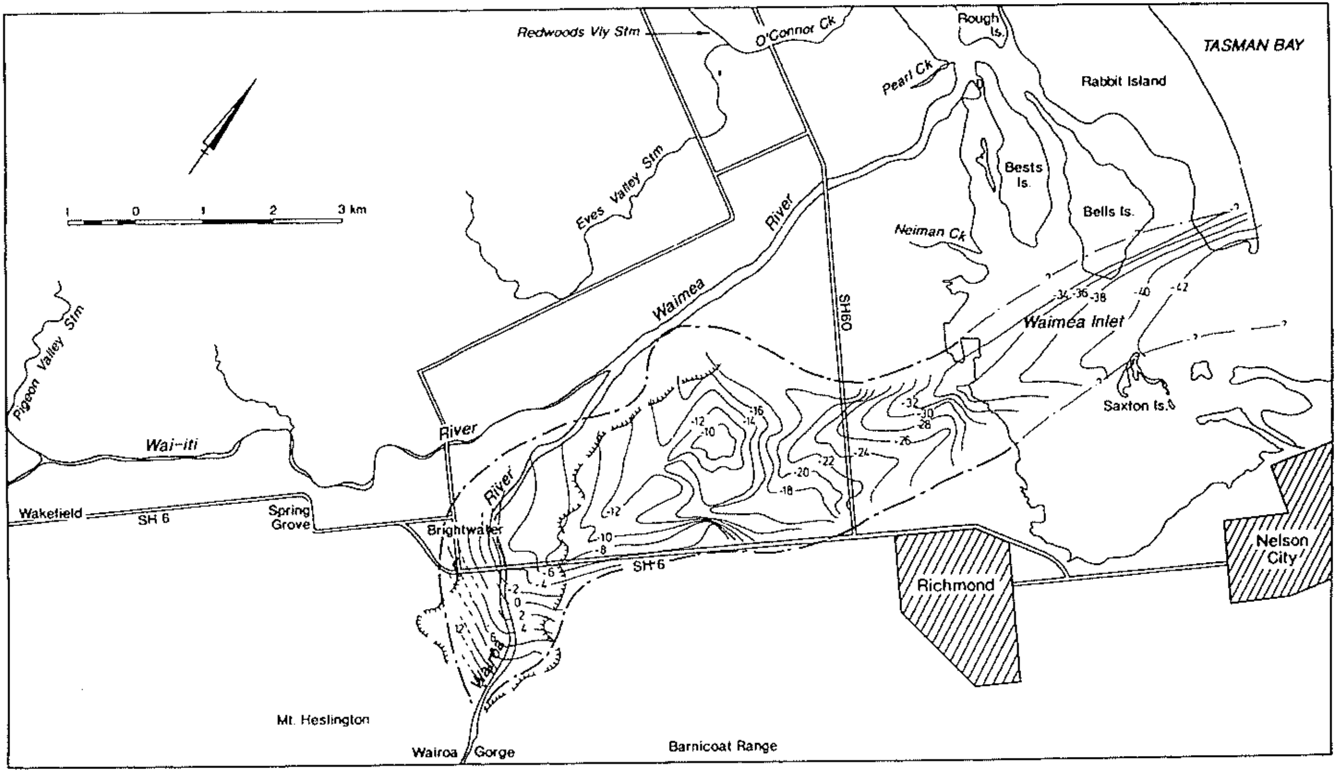

FIGURE 4 – Base of the Lower Confined Aquifer, metres above mean sea level (after Dicker *et al.*, 1992).

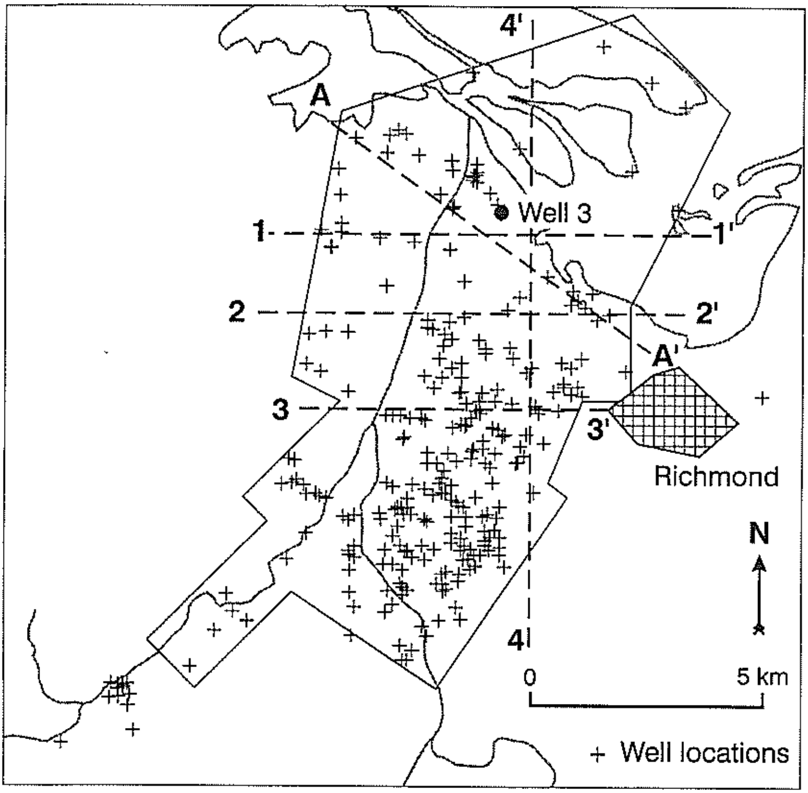

FIGURE 5 – Locations of 274 wells with geological logs in the Waimea Plains and locations of cross-sections

significant development. Summer pumping from wells supplying Richmond and industrial users is the main cause of a pressure decline in the aquifer. Sea water intrusion is a potential problem, and there is some debate whether sea water intrusion actually occurred in the summer of 1977/78 (Fenemor, pers.comm.). Groundwater storage volume is estimated as 20 million m^3 (Dicker *et al.*, 1992).

Three-dimensional computer model of the permeability of the Waimea Plains aquifer

Model derivation

The Tasman District Council well data file recorded a total of 250 wells with lithological logs as of the end of January 1996 in the Waimea Plains

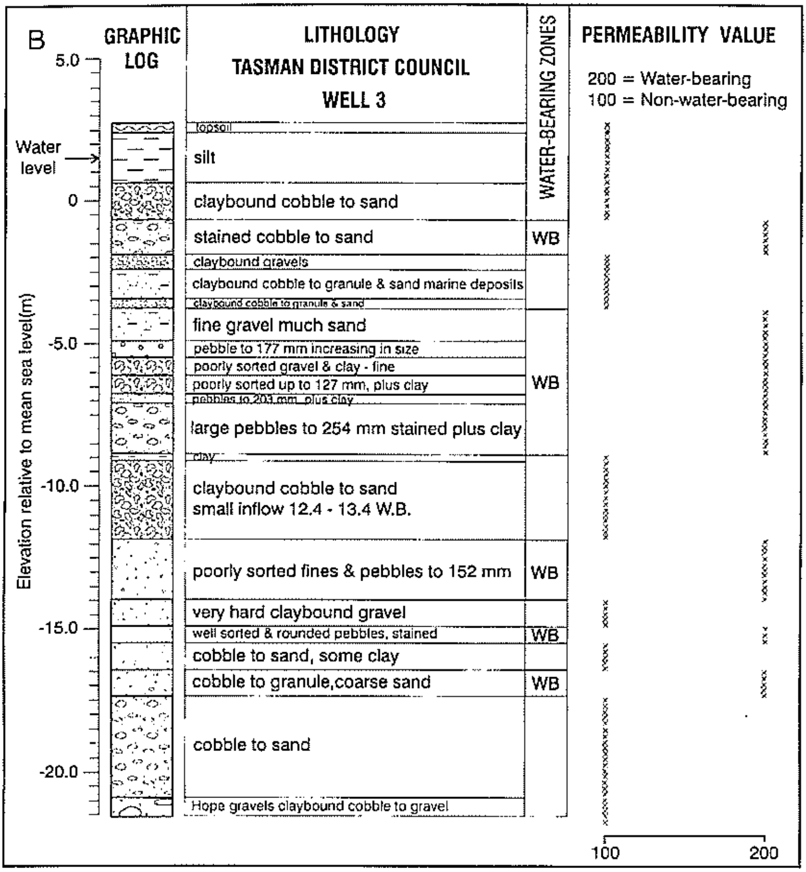

FIGURE 6 – Geological log of Well 3 and permeability value log.

(White and Reeves, 1996) and a total of 274 wells (Fig. 5) with lithological logs as of the end of March 1998. The model described in this paper updates the model of White and Reeves (1996) with new well data. Well log information has been recorded predominantly by local drillers, with some holes logged by geologists. A typical well log, of Tasman District Council Well Number 3 (Fig. 6), records alluvial sediments in the size range clay to cobble. The Tasman District Council encourages well drillers to log wells using the conventions and terminology of Brown (1990) and records the drillers' descriptions on the New Zealand Water Well Data Form (Brown and McCammon, 1976). Sediments are also recorded as "clay-bound" if interstitial clay acts to reduce permeability. Well logs all typically report the water-bearing layers on drill logs (e.g. Fig. 6). Permeable layers are often described as "water-bearing", "poor water-bearing", or "good water-bearing". These qualitative descriptions of layer permeability in wells drilled up to 1989 were used by Dicker *et al.*, (1992) to define the aquifer structure of the Waimea Plains.

These descriptions of layer permeability are used to generate a permeability "log" of each of the 274 wells with a lithological log in this study. Permeable layers (Fig. 6) are assigned a value of 200 and non-water bearing layers are assigned a value of 100 in the permeability "log". Permeability values in the "log" are sampled at an interval of 0.2 m, starting at the upper layer boundary. Sediments above the water table are assigned a value of 100 or 200, based on the description of lithology in the well log. For example, sediments above the well water level in Well 3 (Fig. 6) described as 'topsoil' and 'silt' are assigned a permeability value of 100. The boundaries of layers are manually assessed from the drillers' logs. Layers that are thinner than 0.2 m are not considered in the generation of the permeability "log". Well-head elevation data measured by the Tasman District Council, where the data exist, are used to calculate the elevation of each permeability value. Not all wells have surveyed well-head elevations. Elevations of these wells are estimated using interpolation on a topographic model of the Waimea Plains. The topographic model of the Waimea Plains includes digitised contours from the NZMS 1:50 000 map and well-head elevation data measured by the Tasman District Council. The set of data for all 274 wells contains 29 141 points described by well coordinates (NZMS), elevation relative to mean sea level, and permeability "log" values.

Permeability values are modelled in three dimensions with the minimum tension technique on a conformal grid using EarthVision software. The minimum tension technique used by the EarthVision software aims to represent 3-D data values as closely as possible and aims to calculate plausible models in areas where no data exist. A two-step process is used to generate a model. This process minimises the second derivative of a cubic-function fit (Briggs, 1974) to the permeability "log" values.

Permeability values are generated at grid nodes positioned in uniform increments of thickness below the ground surface in the conformal gridding process. Estimates of permeability values are made on a 31 by 37 by 151 node model of the Waimea Plains. The size of the cells in this model is: X dimension 400 m, Y dimension 390 m, and Z dimension 1 m. An elliptical weighting is used in the grid calculation to enhance the horizontal continuity of permeability value estimates. The process calculates a continuous distribution of permeability values within the bounds of the model. The average difference between the calculated permeability value and the 29 141 observed permeability values is -0.2. The standard deviation of the difference is 33.

A point-by-point comparison of observed values with model values was made with the aim of identifying wells where the observed permeability is not predicted by the model. Wells were identified where the point-by-point differences, between observed and calculated values, were more than ± 2 standard deviations for thicknesses greater than or equal to 1 m. One hundred and nine wells have zones of 1 m or greater thickness where the observed permeability is different from the modelled permeability. Assessment of the geological logs and site details of these wells indicated three sources of error in the observed permeability values. Correction of errors in the location of the wells, their elevations, and the initial interpretation of permeability layer boundaries, resulted in the adjustment of permeability values in 36 of the wells.

Data from two wells (Tasman District Council Well Numbers WWD 353 and WWD 1021) were removed from the database after examination. The well logs are of poor quality, the wells have sections with significant differences between observed and modelled permeability values, and the well logs differ substantially from those of neighbouring wells.

Permeability values in 71 wells were not adjusted on re-examination. The wells generally have well-head elevations determined by field survey and unequivocal identification of permeable layers.

Permeability values were remodelled, using the process described, with the new database of 28 900 permeability values. The continuous distribution of calculated permeability values was altered to discrete values to aid identification of relatively permeable and relatively impermeable 'units' in the model. A value of 100 was assigned to all cells where the calculated value is less than 150 and a value of 200 was assigned to cells with a calculated value greater than or equal to 150. This model honours 76% of the observed permeability values (Table 1).

TABLE 1 – Comparison of discrete 3-D permeability model values with observed permeability values.

Observed Values	**Discretised Model**	
	100	200
100	12 226	3 535
200	3 421	9 718
Number of wells in dataset = 272 Total number of values = 28 900 The model honours 21 944 (76 %) of observed values		

Results

Contoured surfaces of the 3-D Waimea Plains permeability model represent the complexity of permeability variations in the late Quaternary sediments (Figs. 7, 8, 9, 10 and 11). Modelled water-bearing zones are plotted in blue, and non-water-bearing zones in red; the model has an upper surface which represents ground topography. A topographic map is draped on the upper surface. The lower bound of the model is a smoothed surface which represents the maximum depth of boreholes within each 1 km by 1 km area of the Waimea Plains. A polygon representing the lateral extent of boreholes is used to clip the edges of the model. The bottom and sides of the model are also clipped so that the observed layering is based on 3-D interpolation of the drillhole data.

The complexity of the model, like the complexity of the aquifer structure, means that there are difficulties in representing the model with a simple nomenclature and in representing units in a two-dimensional format. Major trends in permeability units are observed by using 3-D spatial filtering of the permeability property value grid to reduce model complexity. Seven zones represent the majority of water-bearing zones in the filtered 3-D permeability model. The zones are chosen, from the filtered permeability model, that are laterally continuous and larger than 2 km^2 in area. Zones are also vertically separated, except where they connect. These zones also represent the majority of water-bearing sediments in the unfiltered model. Zones A, B, C, D, E, F and G are identified on the unfiltered model in Figures 7, 8, 9, 10 and 11 where they intersect a visible plane. A cross-section of the model (Fig. 12) shows a more complex representation of water-bearing zones than does a cross-section on the same plan (Fig. 13) from Dicker *et al.*, (1992) near the coast.

Each of the seven zones is generally dipping down-valley (Figs. 14, 15, 16 and 17). Zones A, C and G appear to be the three major water-bearing units in the model.

Zone A

Zone A occurs over most of the Waimea Plains. The zone varies in depth from 25 m below sea level under Rabbit Island to over 30 m above sea level in the Wai-iti Valley (Fig. 14). Zones A, B and D coalesce under Rabbit Island (Figs. 7, 15 and 16). Layer A is not connected to Layer G in cross-sections across the south of the Waimea Inlet (Figs. 8, 12). A possible palaeochannel is modelled on the bottom surface of Zone A (Fig. 14). The possible palaeochannel, indicated by the –5 m contour due west of Richmond, trends in the direction of the Waimea Inlet. Zone A is connected to Zone G under the Waimea River west of Richmond (Figs. 9, 17) by what appears to be a lobe of Zone G. The base of this lobe is in the depth range –20 m to –25 m (Fig. 17).

Zone A is relatively thin on the Hope Gravel surface south west of Richmond (Fig. 10) and thins to the south. The zone appears to connect with Zone E in the vicinity of Richmond (Fig. 17), and possibly with Zone F south of Richmond.

The zone is generally modelled as permeable at the ground surface (e.g. Fig. 10 east of the Waimea River) but there are areas where the zone is blanketed by low permeability material (e.g. Fig. 8). Zone A is modelled as being very thin in the vicinity of the confluence of the Wairoa and Wai-iti Rivers (Fig. 10). Zone C appears to connect with Zone A north of, and east of, the confluence (Fig. 15).

Zone A also connects with Zone C in the section of Wairoa River above Brightwater (Fig. 15). A north-south section of the model (Fig. 11) shows Zone A to be separated from Zone G, between Brightwater and the Waimea Inlet, by low permeability layers.

Zone C

This zone appears to consist of two lobes (Fig. 15). The eastern lobe dips from under the Wairoa River and joins Zone A north of the confluence of the Wairoa and Wai-iti Rivers at depths between –5 m and –10 m. The western lobe does not dip as steeply as the eastern lobe, and connects with Zone A to the north of the Wairoa River. This lobe occupies a similar lateral position to Zone G. Both lobes are connected underneath the Wairoa River, and connected to Zone A. The upper surface of Zone C is generally bounded by low permeability sediments (Fig. 15) where it is unconnected with Zone A.

Zone G

The base of Zone G is at an elevation of approximately –55 m on the seaward side of the Waimea Inlet. This zone is connected to Zone A under the Waimea River west of Richmond. Two zones, E and F (in Fig. 17) coalesce with Zone G west and south-west of Richmond. Both these zones dip more steeply than G. Zone E connects with Zone A, and Zone F is possibly connected with Zone A. The base of Zone G is approximately 5 m below sea level east of the Wairoa River.

Comparison of the "classic" model of the Waimea Plains with the 3-D permeability computer model

Aquifers identified in the "Classic" Model of the Waimea Plains (Dicker *et al.*, 1992) are consistent with some of the zones identified in the 3-D permeability computer model (Table 2).

Comparisons in Table 2 show a reasonable consistency, given the two different approaches to determining the structure of the Waimea Plains aquifers. The identification of aquifers by Dicker *et al.*, (1992) was not made

TABLE 2 – Comparison of aquifers identified by the "Classic" Waimea Plains model with water-bearing zones identified in the 3-D permeability computer model.

"Classic" Model Aquifer	3D Computer Model Zone
Appleby Gravel Unconfined	A
Hope Gravel	A, E, F
Upper Confined	A (part), C (part)
Lower Confined	G
-	B, C, D

on geological grounds alone. The distribution of groundwater pressure heads, patterns of summer drawdowns and groundwater quality were also considered in determining the aquifer boundaries. Zones A, B, C, D, E, F, and G are simplifications of the 3-D permeability computer model.

Appleby Gravel Unconfined Aquifer

The Appleby Gravel Unconfined Aquifer (Fig. 2) is mapped by Dicker *et al.* (1992) as underlying the flood plain of the Wai-iti, Wairoa and Waimea rivers. Base contours for the aquifer are broadly consistent with those for Zone A north to a location on the Waimea River due west of Richmond. North of this location the Appleby Gravel is modelled as a unit that is at its thickest due east of the Waimea River. The elevation of the base of the Appleby Gravel is estimated at -15 m where the Waimea River enters the Waimea Inlet. The base of Zone A is estimated as -15 m at the Waimea Inlet boundary and Zone A modelled as extending under the inlet to Rabbit Island. The Dicker *et al.*, (1992) model does not contour the Appleby Gravel Unconfined Aquifer north of the Waimea Inlet, as they consider that the unconfined aquifer merges with the Upper Confined Aquifer. They therefore contour the base of the Upper Confined Aquifer (Fig. 3) as the shallow permeable unit under Rabbit, Bells and Best islands. Zone A appears to be consistent with the Upper Confined Aquifer under the inlet.

Contours of the base of Zone A indicate a possible palaeochannel with an eastwards dip. This possible channel is not modelled by Dicker *et al.*, (1992) as part of the Appleby Gravels Unconfined Aquifer. Stewart *et al.*, (1981) note that "the Pugh Gravel member permeability and consequently water yield decreases rapidly in the easterly direction". The 3-D permeability model predicts (Fig. 12) that the Pugh Gravel member is water-bearing in the west and non-water-bearing in the east.

Hope Gravel Unconfined and Confined Aquifers

The contours of the base of Zone A identify the base of water-bearing or potential water-bearing zones within the Hope Gravels as a surface between 30 m above sea level near Wakefield and sea level due west of Richmond. Water-bearing lithologies in Zone A generally thicken northwards. They are sporadic, in agreement with the description by Dicker *et al.*, (1992) of the Hope Gravels. Dicker *et al.*, (1992) found that it was not possible to delineate aquifers within the Hope Gravels. They note that a possible path for recharge to the Lower Confined Aquifer is through gravel fans in the area southwest of Richmond. The 3-D permeability computer model indicates that at least two zones (E and F, Fig. 17) are in possible contact with the base of Zone A (in the Hope Gravels) and the top of Zone G (the Lower Confined Aquifer). Another zone which is in possible contact with Zone A and Zone G in the region south of Richmond occurs between Zone A and Zone F (Fig. 11). It is possible that these zones are a conduit for recharge through the Hope Gravel aquifers.

Upper Confined Aquifer

Interpretation of the 3-D permeability computer model did not identify a zone that is as consistent as the Upper Confined Aquifer defined by Dicker *et al.* (1992). The base of the Upper Confined Aquifer under the inlet is consistent with the base of Zone A. The cross-section at the coast (Fig. 12), while broadly in agreement with the model of Dicker *et al.*, (1992) does not indicate water-bearing zones in the depth range of the Upper Confined Aquifer (Fig. 13). The eastern lobe of Zone C (Fig. 15) is consistent with the occurrence of the Upper Confined Aquifer north of the Wairoa River and basal depths are similar. This lobe merges with Zone A north of the Wairoa River, unlike the Dicker *et al.*, (1992) model which has the Upper Confined Aquifer merging with the unconfined aquifer in the Waimea River delta area. The eastern lobe appears to be located vertically above Zone G. The western lobe of Zone C does not correlate with the Upper Confined Aquifer.

Lower Confined Aquifer

The Lower Confined Aquifer of Dicker *et al.*, (1992) is consistent with Zone G of the 3-D permeability computer model. Dicker *et al.*, (1992) extend the Lower Confined Aquifer a little further up the Wairoa River than Zone G extends. This is because their model represents the geological extent of the Lower Confined Aquifer, whereas the 3-D permeability computer model represents the water-bearing extent. The Lower Confined Aquifer near the Wairoa Gorge is identified from marker beds, but not as a water-bearing unit (Fenemor, pers. comm.).

Elevations of the base of the Lower Confined Aquifer (Fig. 4) are broadly consistent with those of layer G (Fig. 17). The Lower Confined Aquifer is modelled by Dicker *et al.*, (1992) with a base elevation of -34 m to -36 m at the coast. The elevation of the base of Zone G is -30 m to -35 m at the Waimea Inlet. Zone G, with a base elevation in the range -40 m to -55 m below the Waimea Inlet appears to be deeper than the Dicker *et al.*, (1992) estimate of -40 m to -42 m in the same region.

Potential pathways for recharge from shallow aquifers to the Lower Confined Aquifer are identified as Zones E and F in the Hope area. These zones would probably allow groundwater with elevated nitrate concentrations to enter the Lower Confined Aquifer, giving rise to the concentrations of nitrate (Fig. 18) reported by Dicker *et al.*, (1992). Stewart *et al.*, (1981) interpret oxygen isotope values as indicating recharge from shallow groundwater to the Lower Confined Aquifer in the vicinity of Hope. The mechanism for this recharge was suggested as intermixing of water through multiple screened wells in the two confined aquifers. The 3-D permeability computer model also suggests recharge through permeable units represented by Zones E and F.

Summary

Tasman District Council's well database of 274 wells on the Waimea Plains with lithological logs was modelled in three dimensions by a computer visualisation technique, to reassess the aquifer structure of the Waimea Plains. Lithological logs and drillers' records were converted into a three-dimensional data set of 29 141 values based on the stated, or implied, permeability of sedimentary units encountered in each well. A three-dimensional grid of these points was calculated, which was then compared to the input data. This allowed the identification of wells whose logs were markedly different from the logs of neighbouring wells, wells with errors in estimates of well-head elevations and wells with errors in location data. Two wells were removed from the data set because of their poor quality.

Three-dimensional plots of the final model represent the complexity of the permeability variation in the sediments in the Waimea Plains. Seven zones were used to represent potential aquifers in the 3-D model. These zones are a simplification that is useful for representational purposes. Three major water-bearing zones are identified.

The first zone, a shallow zone in the elevation range 40 m to -25 m, is consistent with the Appleby Gravel Unconfined Aquifer and the Hope Gravels Aquifers. This unit appears to be connected to the Upper Confined Aquifer north of the Wairoa River and connected to the Lower Confined Aquifer

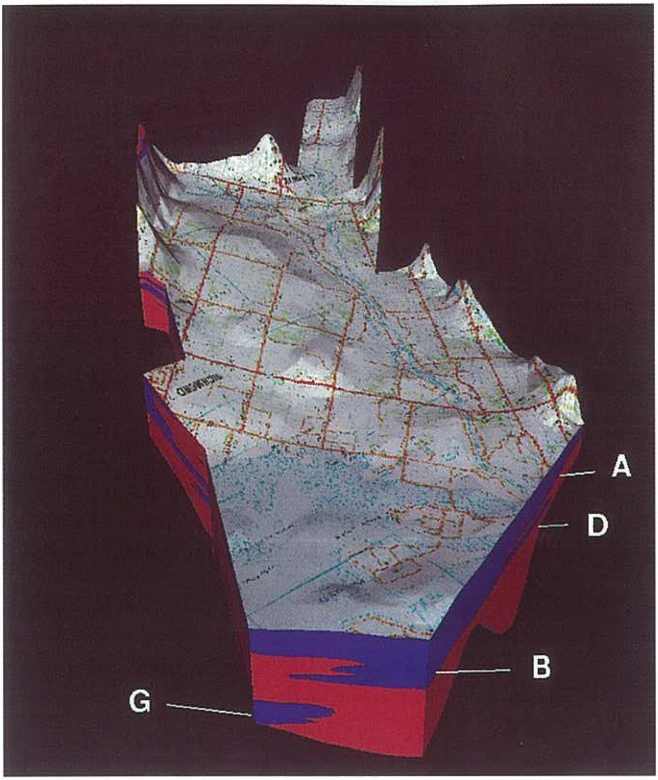

FIGURE 7 – 3-D permeability computer model of the Waimea Plains. Blue = water-bearing layers. Red = non-water-bearing layers.

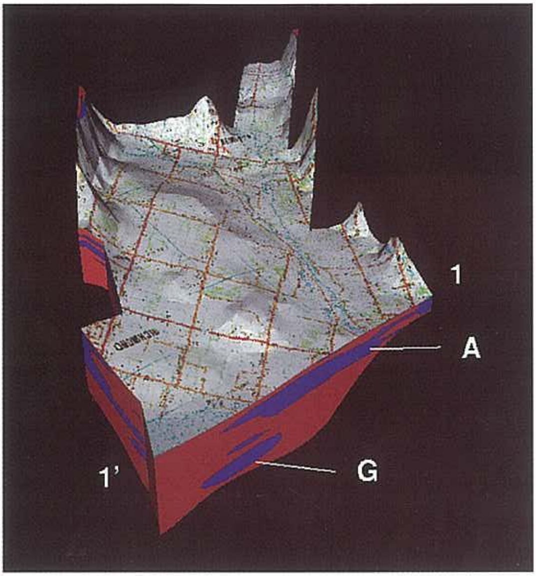

FIGURE 8 – 3-D permeability computer model of the Waimea Plains with west-east section (1-1'on Figure 5) near the estuary.

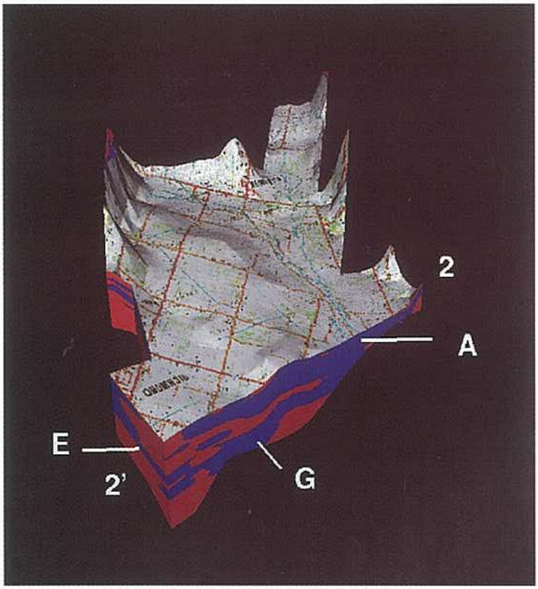

FIGURE 9 – 3-D permeability computer model of the Waimea Plains with west-east section (2-2' on Figure 5) near Richmond.

FIGURE 10 – 3-D permeability computer model of the Waimea Plains with west-east section (3-3' on Figure 5) west of Richmond.

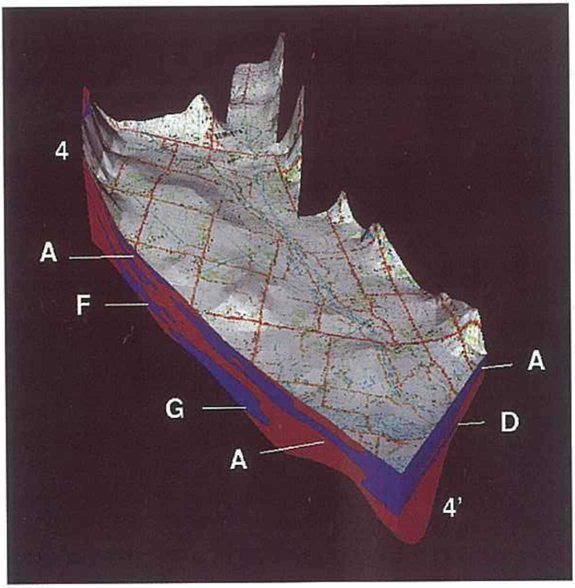

FIGURE 11 – 3-D permeability computer model of the Waimea Plains with south-north section (4-4' on Figure 5) to the west of Richmond.

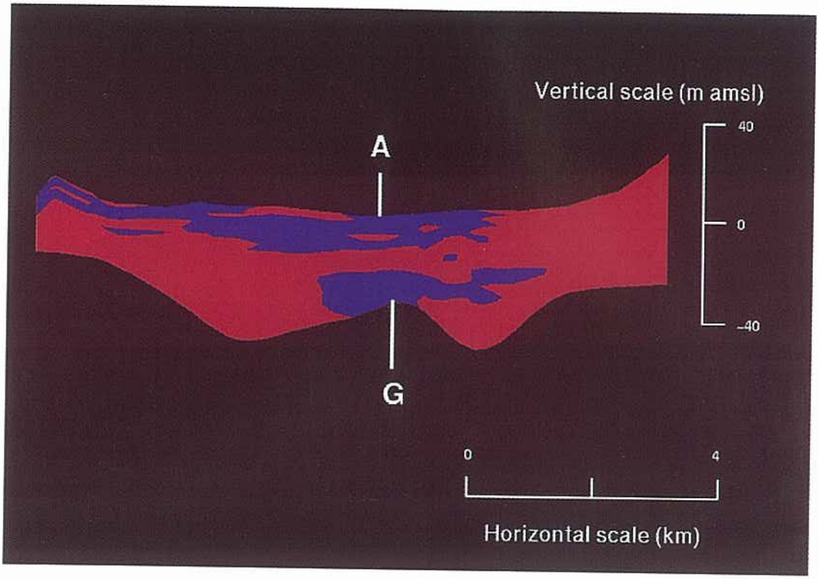

FIGURE 12 – Cross-section of the 3-D permeability computer model on section A-A' (Figure 5).

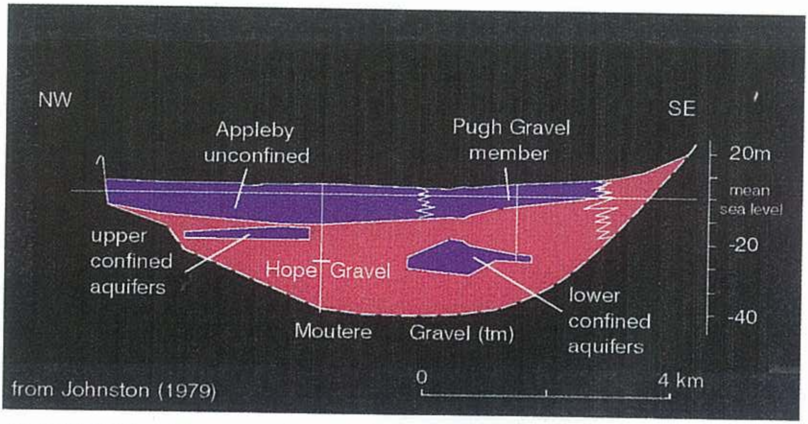

FIGURE 13 – Cross-section of the geology on section A-A' (Figure 5), after Dicker *et al.*, (1992)

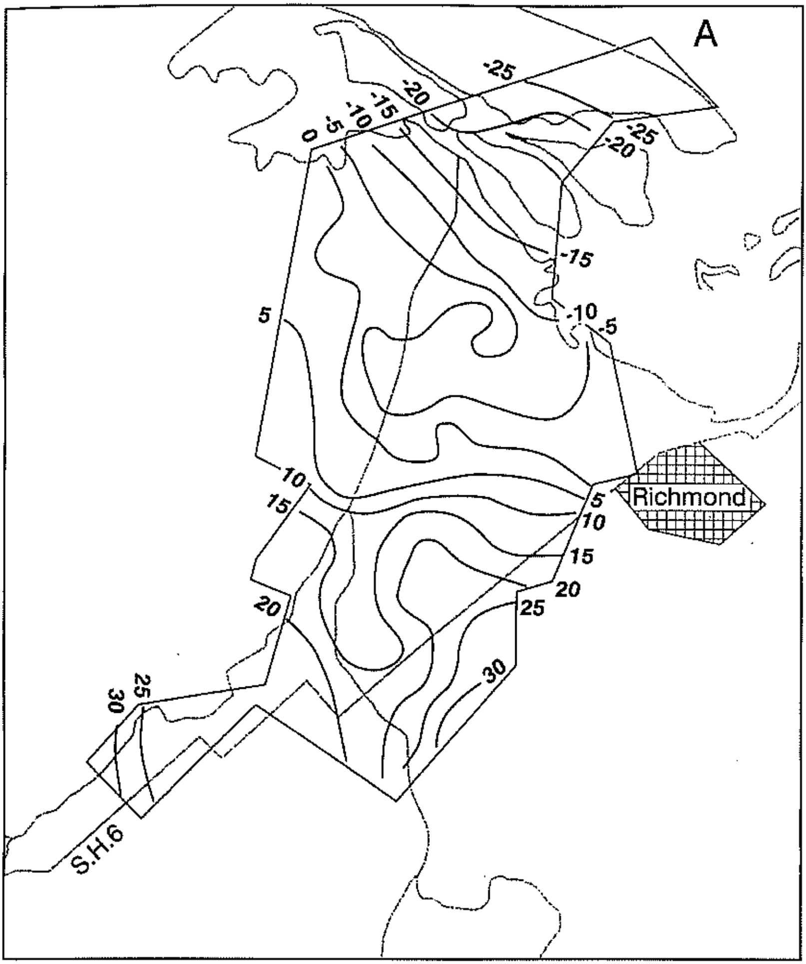

FIGURE 14 – Contours on the base of Zone A (m).

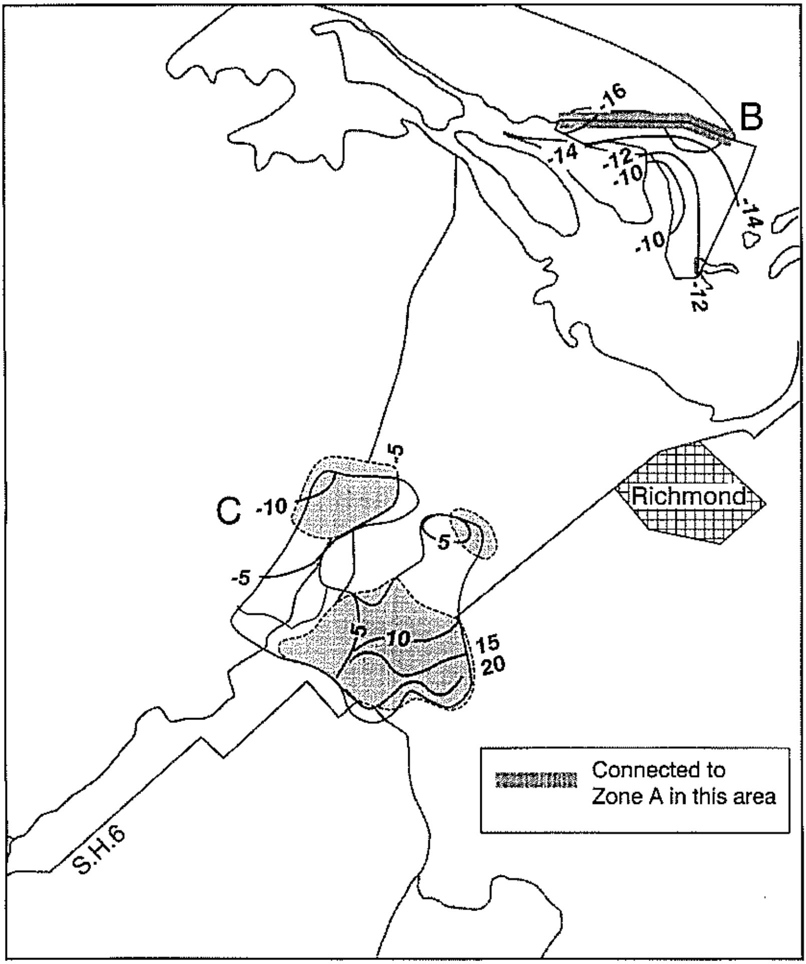

FIGURE 15 – Contours on the base of zones B and C (m).

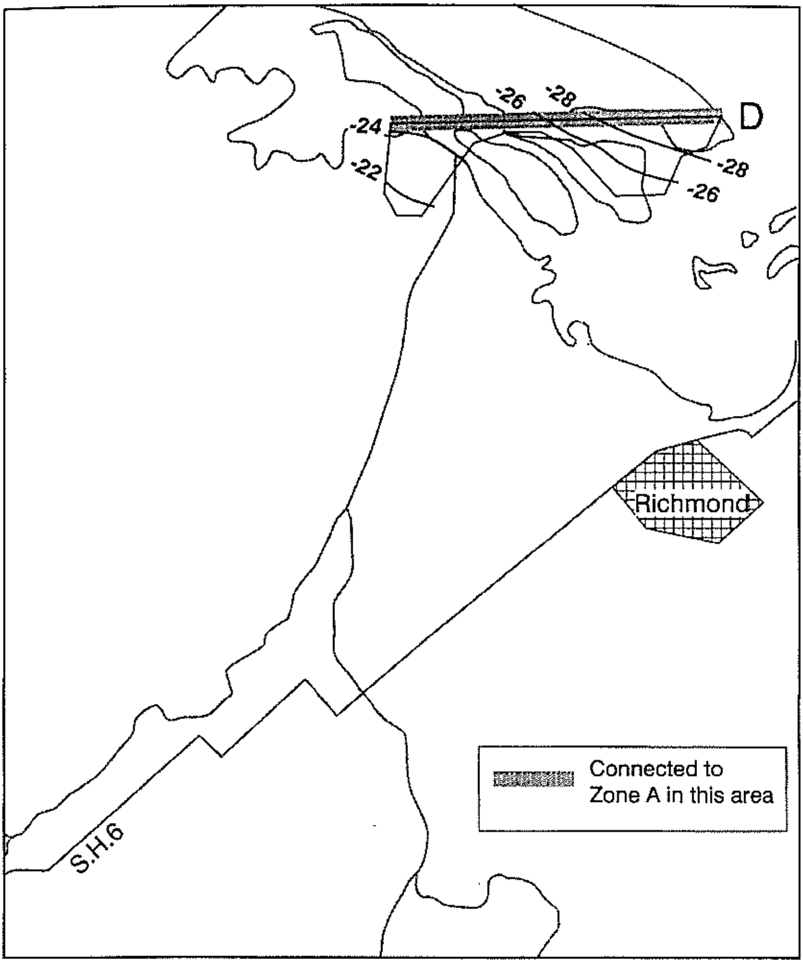

FIGURE 16 – Contours on the base of Zone D(m).

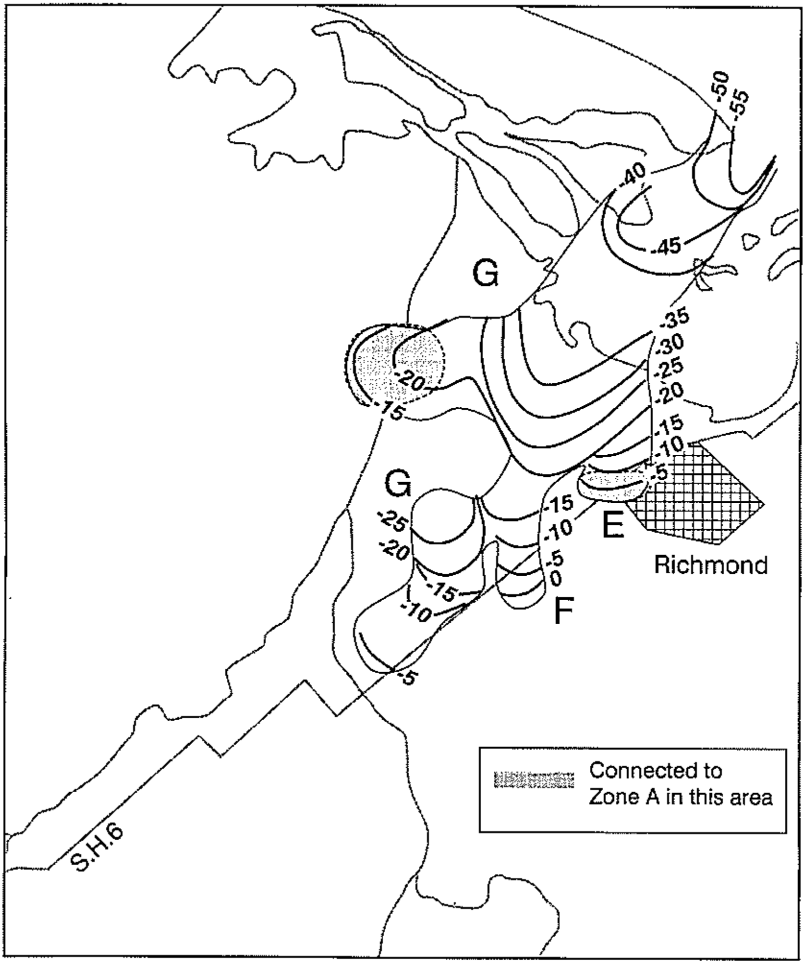

FIGURE 17 – Contours on the base of zones E, F and G (m).

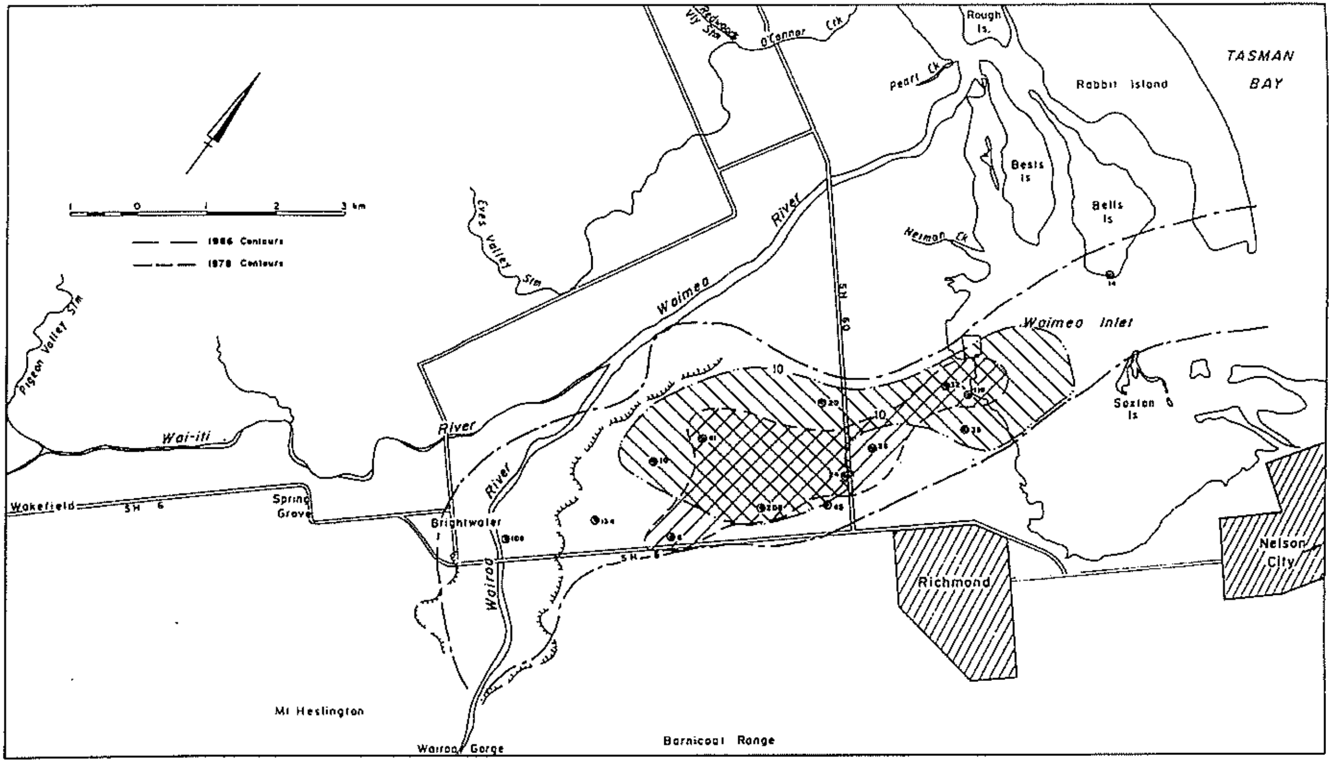

FIGURE 18 – Nitrate-nitrogen concentrations in the Lower Continued Aquifer in 1978 and 1986, g/m^3, after Dicker *et al.*, (1992).

east of the Waimea River. It also appears connected to the Lower Confined Aquifer by two permeable zones west and south-west of Richmond. The base of this unit is consistent with the base of the Upper Confined Aquifer under the Waimea Estuary. The second zone occupies an area in the vicinity of the Wairoa and Wai-iti Rivers. It consists of two lobes, and the eastern lobe appears to be related to the Upper Confined Aquifer north of the Wairoa River. The zone is linked to the first Zone southwest of Richmond. The third zone is in the depth range 0 to -55 m and is consistent with the Lower Confined Aquifer. The depth and extent of the unit is consistent with that interpreted by previous researchers. Potential connections to the Lower Confined Aquifer from shallower layers are more explicit in the 3-D permeability computer model than the existing hydrogeological model.

Connections between aquifer zones are shown on the 3-D permeability computer model. These connections may be potential pathways for both recharge and the movement of contaminants. Two potential pathways from the Unconfined Aquifer to the Lower Confined Aquifer have been identified to the west and south-west of Richmond. Elevated nitrate concentrations, and oxygen isotope measurements, in the Lower Confined Aquifer to the west and south-west of Richmond are consistent with recharge pathways from the near-surface aquifers.

The 3-D permeability computer model represents water-bearing structures in a more complex way than usual hydrogeological interpretations of aquifer structure. The 3-D computer model of the Waimea Plains aquifers gives results that are similar to the established hydrogeological model, but the complexity of structures in the 3-D permeability computer model can enhance the understanding of a system. Modelling of groundwater hydraulic heads, water quality, and chemical and isotopic tracers is presently being undertaken for the Waimea Plains to test the application of new methods to understanding groundwater resources and quality.

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