GROUNDWATER FLOW MODELLING FOR GROUNDWATER QUALITY ASSESSMENTS IN CHRISTCHURCH CITY

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ABSTRACT

The current draft of the Drinking Water Standards for New Zealand 2005 indicates that groundwater models can contribute to demonstrating the security status of groundwater supplies where other methods involving age determinations and chemical variation prove to be inappropriate. Groundwater models are also recommended as a means of identifying key wells for compliance monitoring in supplies that are sourced from multiple wells.

A numerical groundwater flow model of the Christchurch City hydrogeologic system has been developed to aid in the understanding and management of the aquifers, using the Visual MODFLOW software. This numerical model allows a co-ordinated consideration of a range of independently determined hydrogeologic parameters and enables an excellent visualisation of groundwater flow paths. Particle tracking modules allow an assessment of the origin of water that reaches particular wells and the distribution of water ages. This information enables wells to be ranked according to their relative risk of contamination from surface processes.

KEYWORDS

Groundwater, Hydrogeology, Drinking Water Standards, Modelling

1 INTRODUCTION

The Drinking-Water Standards of New Zealand 2000 define groundwater sources as either “secure” or “unsecure” depending on whether they are directly affected by surface or climatic influences. This must be demonstrated by a groundwater sampling programme that shows an absence of *E. coli*, as well as an absence of water less than one year old or limited fluctuations in conductivity, chloride and nitrate. It must also be demonstrated by a regular inspection programme that proves the groundwater is being abstracted via a secure well head structure.

The Ministry of Health established this approach to defining a secure groundwater supply for the most common situation where only one or two wells abstract from an aquifer. However, in Christchurch City the water supply system utilises 172 wells, drawing water from 5 separate aquifers. The mixing of water from such a large number of abstraction points spread both laterally and vertically makes it impractical to rigorously apply the Drinking Water Standards “secure” assessment methodologies at every individual well. Because of this situation, the Christchurch City Council (CCC) has been working with Pattle Delamore Partners Ltd (PDP) to develop an investigation methodology that can be applied to the Christchurch situation to achieve the objectives of the Drinking Water Standards in a pragmatic manner.

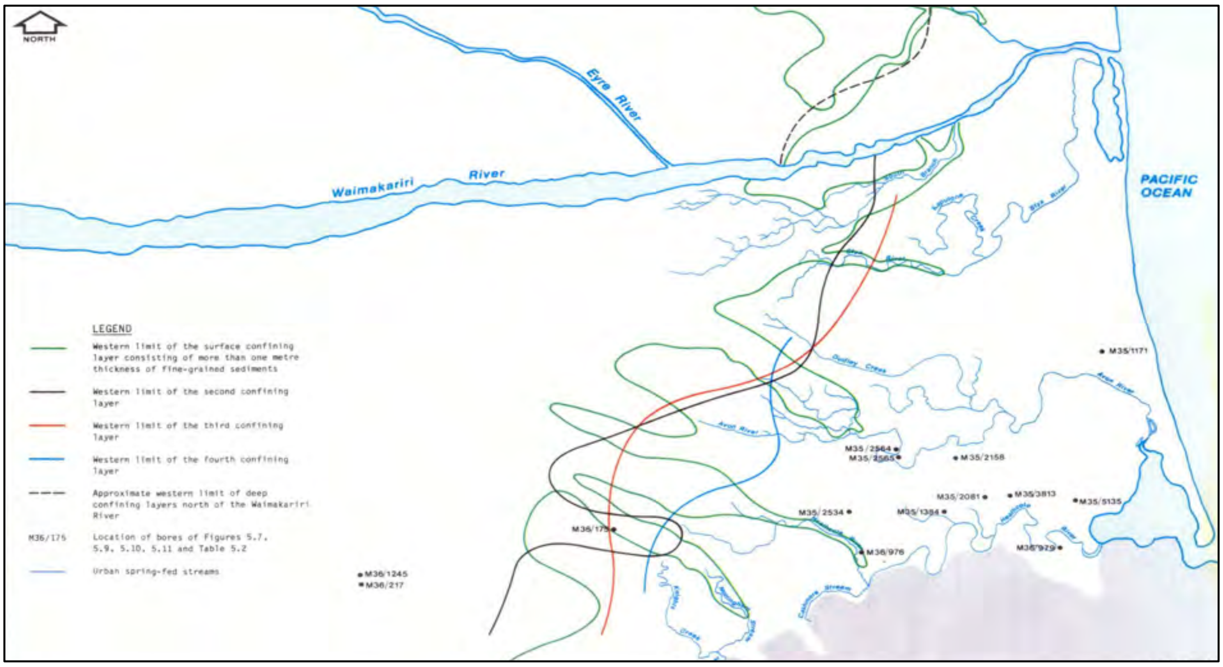
One of the tools that has been used to achieve this objective is the development of a groundwater flow model for the Christchurch aquifer system. This paper describes the geological setting of the Christchurch aquifers and the issues that arise from the use of multiple wells in light of the requirements of the Drinking Water Standards. The modelling process is then described and the application of the model output is discussed.

2 GEOLOGICAL SETTING

The Christchurch aquifer system has been formed from glacial and river derived gravels, deposited during the alternating glacial and inter-glacial periods over the last 500 000 years. Deposition of gravels during ice advances (glaciations) formed fans of unsorted outwash on the inland Canterbury Plains. During the warmer interglacial periods, rivers reworked these outwash deposits and deposited them further down the Plains as more permeable gravel strata, including deposits within the Christchurch area.

During the same time period, along the coastline, rises in sea level during interglacial periods have resulted in the deposition of finer grained (clay, silt and sand) marine and estuarine deposits. These deposits are thickest at the coast and become progressively thinner inland. The inland extent of these low permeability layers is mapped in Figure 1. The surface low permeability layer is referred to as the Christchurch Formation.

Figure 1: Inland extent of confining layers above aquifers – modified from NCCB 1986

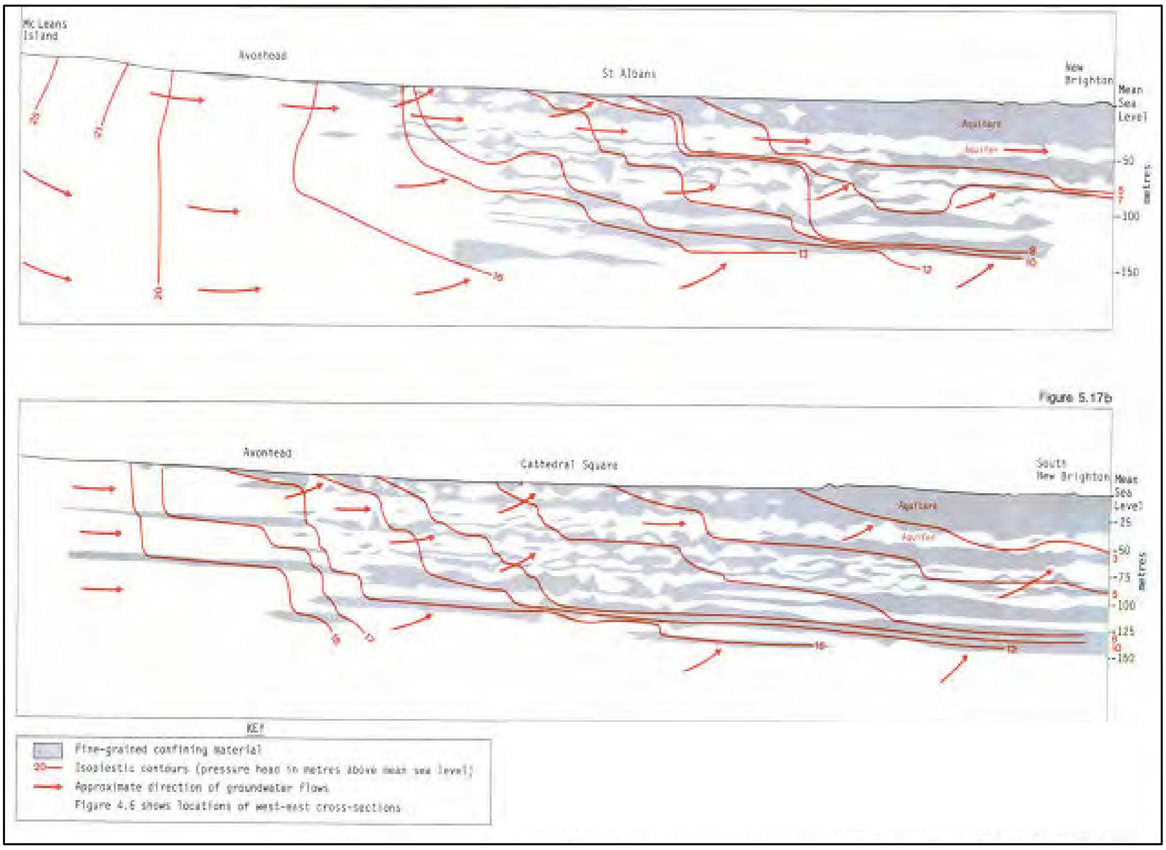


This sequence of glacial and interglacial periods in the Christchurch area has resulted in the formation of permeable glacial and river derived gravel layers originating from the inland area to the west, inter-fingered with low permeability marine and estuarine sediments which thicken in an eastwards direction. This is shown graphically in the west-east cross-sections of strata through Christchurch City presented in Figure 2 (overleaf).

Groundwater is likely to be "secure" where there is at least a 5 m thickness of low permeability strata overlying the shallowest water supply aquifer and at least a 1000 m lateral separation from the 1 m thick edge of the surface confining layer. Based on field tests, the average hydraulic gradient, hydraulic conductivity and porosity for Aquifer 1 are estimated at 0.001, 150 m/day and 0.3 respectively. This gives an average groundwater flow velocity of less than 200 m/year for Aquifer 1. Consequently, a 1000 m lateral buffer from the 1 m thick surface confining layer is expected to indicate an area where there is a significant degree of geological strata separating the aquifer from surface influences.

For Aquifer 2, the western limit of the second confining layer (Figure 1) is an appropriate geological boundary to define the extent to which surface factors have no significant influence on the strata. To the east of the Aquifer 2 confining layer limit (Figure 1) there is unlikely to be any significant influence of surface or climatic influences. All other deeper strata, i.e. Aquifer 3, 4 and 5, are of sufficient depth that they are unlikely to be directly affected by surface or climatic influences at all locations throughout the City.

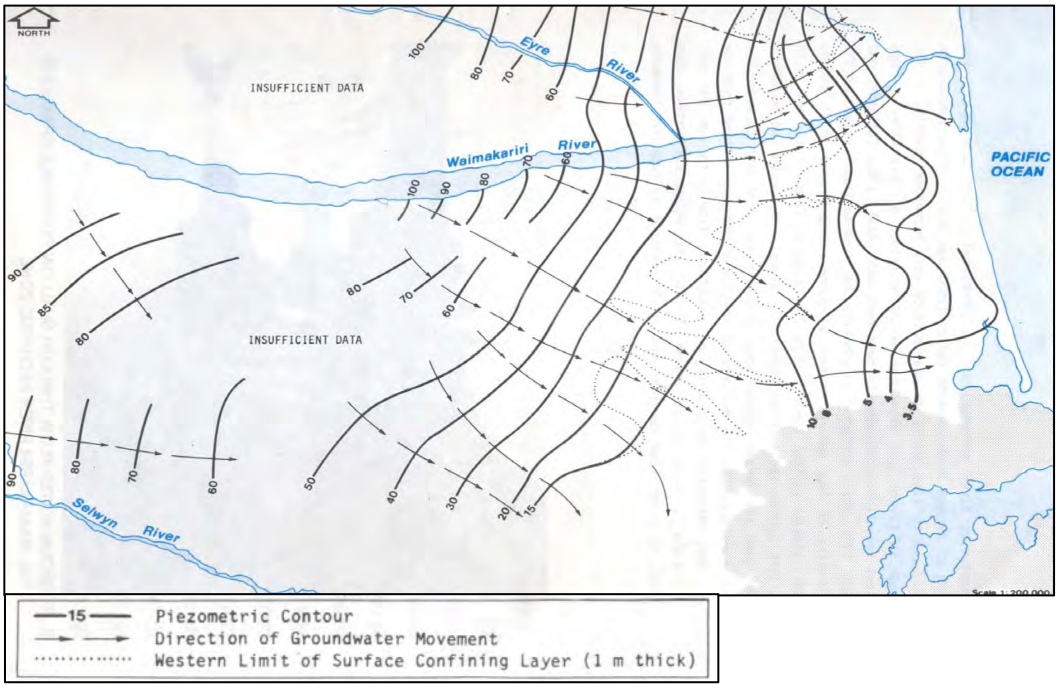
Figure 2: Isopiestic cross section showing lateral and vertical components of groundwater flow through the confined aquifers – from NCCB 1986.



3 GROUNDWATER FLOW PATTERNS

The gravel aquifers are primarily recharged by seepage from the Waimakariri River in the area to the north-west of the City and by infiltrating rainfall on the Plains to the west (beyond the inland edge of the low permeability Christchurch Formation surface strata). The resulting pattern of lateral groundwater flow in the shallowest aquifer is plotted in Figure 3.

Figure 3: Contours of piezometric surface in metres above mean sea level and direction of groundwater flow (May 1985) – from NCCB 1986



Contours of groundwater flow between the aquifers at differing depths are plotted in the cross-sections in Figure 2. This indicates a generally horizontal flow to the west of the City, changing to a strong upward gradient as the coastline is approached.

Information from drillers logs and the plotting of groundwater pressures indicates that none of the groundwater flowing laterally through the gravel aquifers discharges directly offshore through the aquifer. The deeper gravel aquifers are all expected to be closed off by the thickening low permeability marine sediments. In contrast, the Riccarton Gravel deposits (Aquifer 1) are expected to extend offshore and outcrop on the sea floor around 40 km beyond the coastline. However, in Aquifer 1, the pressure of seawater within the gravel aquifer is expected to restrict any direct fresh water discharge through the gravel strata. Therefore, most offshore seepage is expected to occur via diffuse upward seepage through the low permeability confining layers.

Shallow groundwater to the west of the City is a source of water supply to the spring-fed streams of the Heathcote, Avon, Styx and Otukaikino river systems. However, groundwater occurring to the east of spring headwaters, and deeper groundwater beneath the whole of the City area does not have such a permeable discharge flow path, as it moves slowly eastwards into the closed confined aquifers. From these aquifers, discharge primarily occurs via abstraction wells, or by seepage upward through the confining layers, as shown in Figure 2.

The general flow pattern indicates that the youngest groundwater is expected to occur near the water table in the western City area where groundwater can discharge to the spring-fed streams. With increasing depth and moving further to the east (towards the coast) the groundwater will be older and less affected by surface influences. In each aquifer there is a division at which the vertical component of groundwater flow changes from downwards to upward flow. It is considered that by the time groundwater reaches this upward trending flow, the groundwater in the aquifer is likely to meet the Drinking Water Standards definition of no surface or climatic influences.

4 THE CHRISTCHURCH WATER SUPPLY SYSTEM

The Christchurch City water supply system is sourced entirely from groundwater that is abstracted from the five gravel aquifers that occur beneath the City.

The distribution network is organized into eight pressure zones:

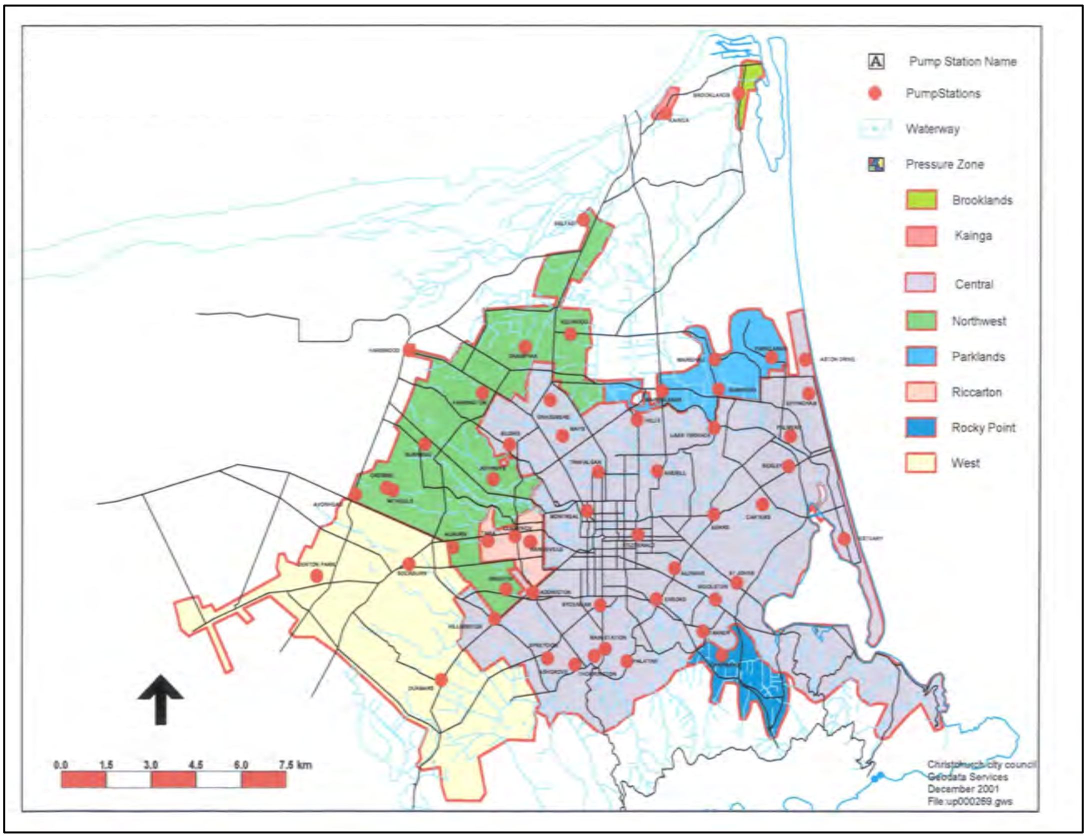
- Central
- North-West
- Parklands
- Riccarton
- Rocky Point
- West
- Brooklands
- Kainga

The pressure zones are supplied from 95 pumping stations that source their water from 172 wells ranging in depth from 16 to 220 m. The location of the pressure zones and pumping stations is shown in Figure 4 (overleaf).

Brooklands and Kainga operate as separate stand-alone systems serving the small communities of Brooklands/Spencerville and Kainga/Stewarts Gully respectively. The remaining supply zones are more extensive and operated at different pressures, based on the historical development of the city's water supply, prior to Local Government amalgamation. However, in an emergency these different zones can be interconnected by opening valves that have been installed at zone boundaries.

The CCC Asset Management Plan (2002) for the water supply system notes that each pressure zone "*is fed by primary pumping stations that pump from a well, or a well-field comprising as many as six wells*."

Figure 4: Christchurch City Council pumping stations supplied by wells; pressure zones supplied by these pumping stations



At many pumping stations, it is not possible to independently sample individual wells, as they are piped directly into the base of a suction tank.

Due to this configuration, water from different wells and different aquifers is mixed at many of the pumping stations. Further mixing occurs within the distribution system where, with the exception of Brooklands and Kainga, water from several pumping stations is spread laterally across the City.

The mixing of water from so many wells, aquifers and pumping stations makes it impractical to rigorously apply the Drinking Water Standards testing regime to the Christchurch water supply system. Therefore a rational approach to developing a refined monitoring programme that is consistent with the Drinking Water Standards is required.

5 DRINKING WATER STANDARDS FOR NEW ZEALAND 2005

Section 4.5.2 of draft 25 of the Drinking Water Standards for New Zealand 2005 addresses the situation of drinking-water supplies that are sourced from multiple bores. It acknowledges that in those situations a large number of samples would need to be collected and analysed for *E. Coli*. It helpfully suggests that this issue can be resolved by the following approach:

"*Where it can be demonstrated that bores supplying a single pumping station draw from the same aquifer, reduced monitoring may be justified. A **groundwater model** must be used to support an application for reduced monitoring.*

To justify reduced monitoring of several bores in these circumstances, the water supplier must show:

- *The bores draw from the same aquifer under similar conditions*
- *Any aquitard protecting the sources is continuous at the bore field*
- *The chemical character of the water from each bore is similar.*

The identified representative bore must be the one that is most vulnerable to contamination of the bores it represents."

In Section 4.5 of the Drinking Water Standards for New Zealand 2005, there is discussion of the methods by which a secure supply may be demonstrated. Parameters that may be used to define a lack of surface or climate influences include: estimation of residence time of water in the aquifer; and lack of significant and rapid shifts in chemical determinands that are linked to surface effects. The standards suggest this should be achieved by determining the residence time from water age determination (tritium, chlorofluorocarbon (CFC) or sulphur hexafluoride (SF_6)) or variations in electrical conductivity, chloride and nitrate over a prolonged monitoring period. However these methods do not provide the necessary definition in all situations. Where they do not work appropriately, the Drinking Water Standards state that the following method may be considered:

- "*A verified* ***hydrogeological*** *model demonstrating that the bore is extracting from a secure aquifer may be acceptable. The model must be derived from a conservative evaluation of hydrogeologic parameters. Such a model must provide information about potential contaminant pathways and must indicate that contamination by pathogens is very unlikely taking into account predictive uncertainty, to satisfaction of a person or persons deemed qualified by the Ministry of Health.*"

The remainder of this paper describes the initial stages of development of a groundwater model that can be utilised to contribute to the classification of groundwater resources in a manner that is consistent with the Drinking Water Standards for New Zealand 2005.

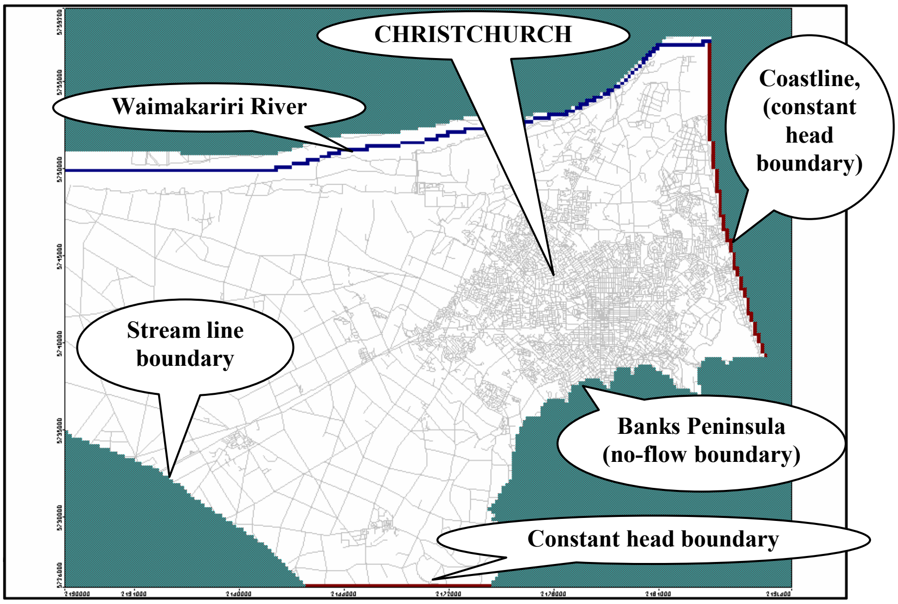
6 THE MODEL SOFTWARE

The numerical groundwater flow model for the Christchurch aquifer system has been developed using the USGS finite-difference code MODFLOW and the Waterloo Hydrogeologic pre-and post-processor Visual MODFLOW 4.1. The numerical model allows a three-dimensional representation of hydrogeologic parameters and groundwater flow paths. Particle tracking modules allow an assessment of the origin of water that reaches a particular well and the distribution of pathways.

7 MODEL CHARACTERISATION OF THE CHRISTCHURCH AQUIFER SYSTEM

The model area is shown in Figure 5; the external boundaries to the model are described in the following points.

Figure 5: Model Outline



- The Waimakariri River to the north provides a flux boundary which provides recharge to the aquifer system;
- The Pacific Ocean to the east and Lake Ellesmere to the south provide a constant head boundary at the downgradient margins of the groundwater flow system;
- Banks Peninsula to the south-east is designated as a no-flow barrier to groundwater flow;
- A groundwater stream-line to the south-west is set as a no-flow boundary;
- The western boundary occurs within the alluvial gravel strata although the model was able to be calibrated with no through-flow occurring across that boundary.

Within the model domain, recharge is provided both from Waimakariri River seepage and from infiltrating rainfall. Discharge occurs via offshore flow to the east; through-flow to the south-east; into spring-fed streams such as the Avon and Heathcote Rivers; and via pumping wells.

The surface topography for the model was derived from the detailed LIDAR (Light detection and ranging) database provided by Christchurch City Council. Outside the City limits, a Digital Elevation Model derived from NZMS 260 series was used, provided by Environment Canterbury.

Coding of geological information from drillers logs established the layering of aquifers and intervening aquitards. In the model, lateral hydraulic conductivities of aquifers have been set at values ranging from 50 to 400 m/day, with intervening aquitards ranging from 0.05 to 10 m/day. Vertical hydraulic conductivities have been set at one-tenth of the lateral values. Zones of hydraulic conductivity are shown in plan view in Figure 6 and in cross-section in Figure 7.

Figure 6: Hydraulic conductivity (K) zones in upper layers

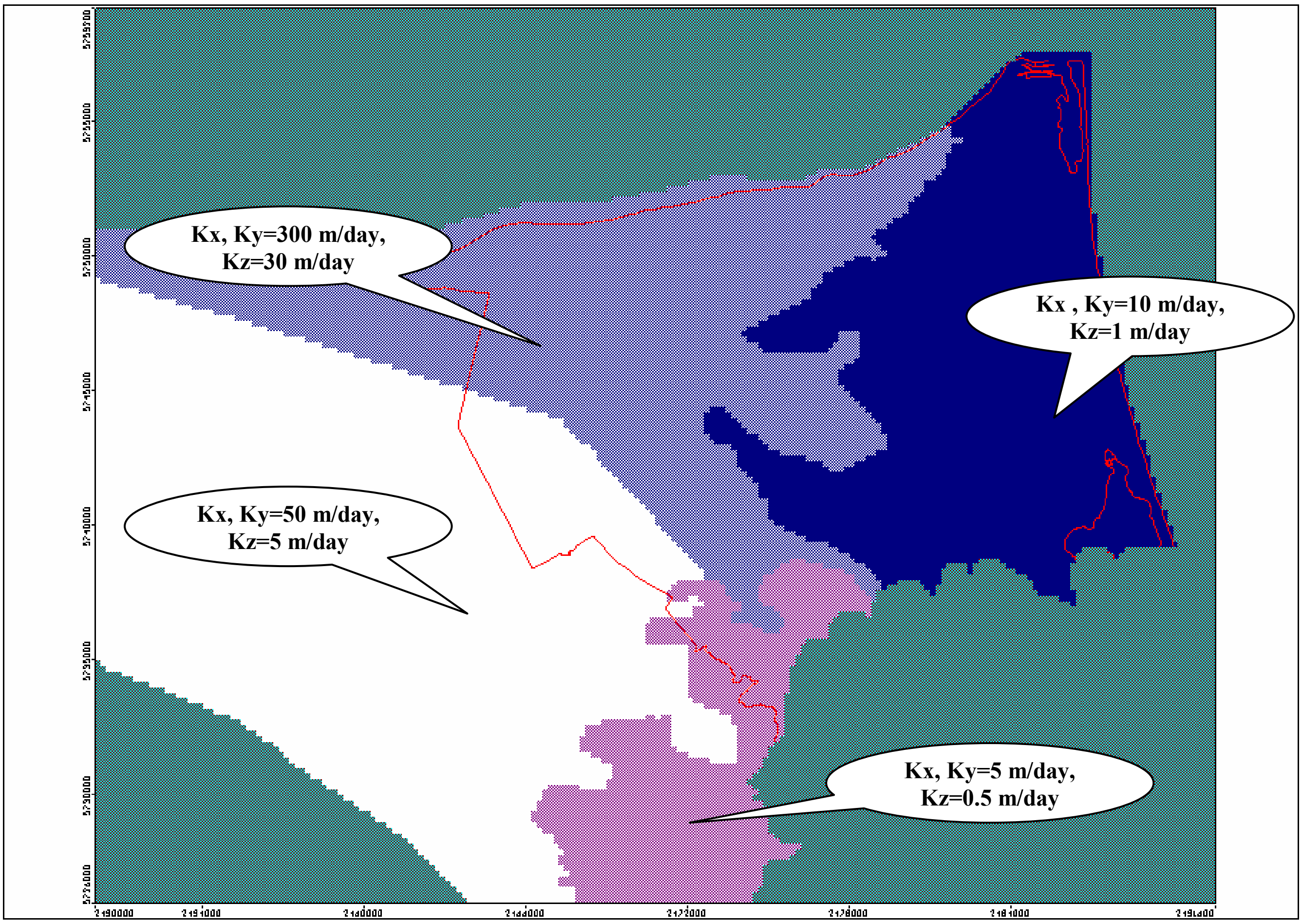
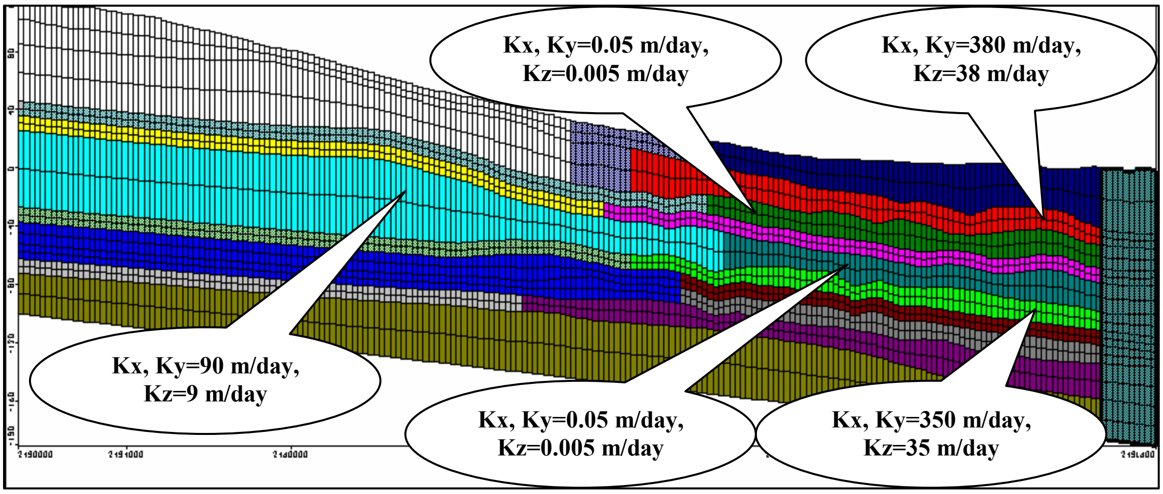


Figure 7: Hydraulic conductivity zones (cross-section view)



MODEL CALIBRATION

The model has been calibrated to average groundwater level elevations across all aquifers with a root mean squared error of 3.98%, which is well within an acceptable calibration target of 10%. Generalised transient simulations using theoretical high and low rainfall inputs have produced simulated fluctuations in groundwater pressures of the same order as seasonal water level fluctuations observed in monitoring wells.

Figure 8 shows the steady-state modelled water balance for the aquifer system, with units of flow shown in m^3/day. As recharge and pumping rates were adjusted in the model, corresponding changes in spring-fed stream flows and offshore discharges were observed. The resulting groundwater level contour and flow pattern across the model area is shown in Figure 9 and in cross-section from west to east in Figure 10.

Figure 8: Steady state water balance

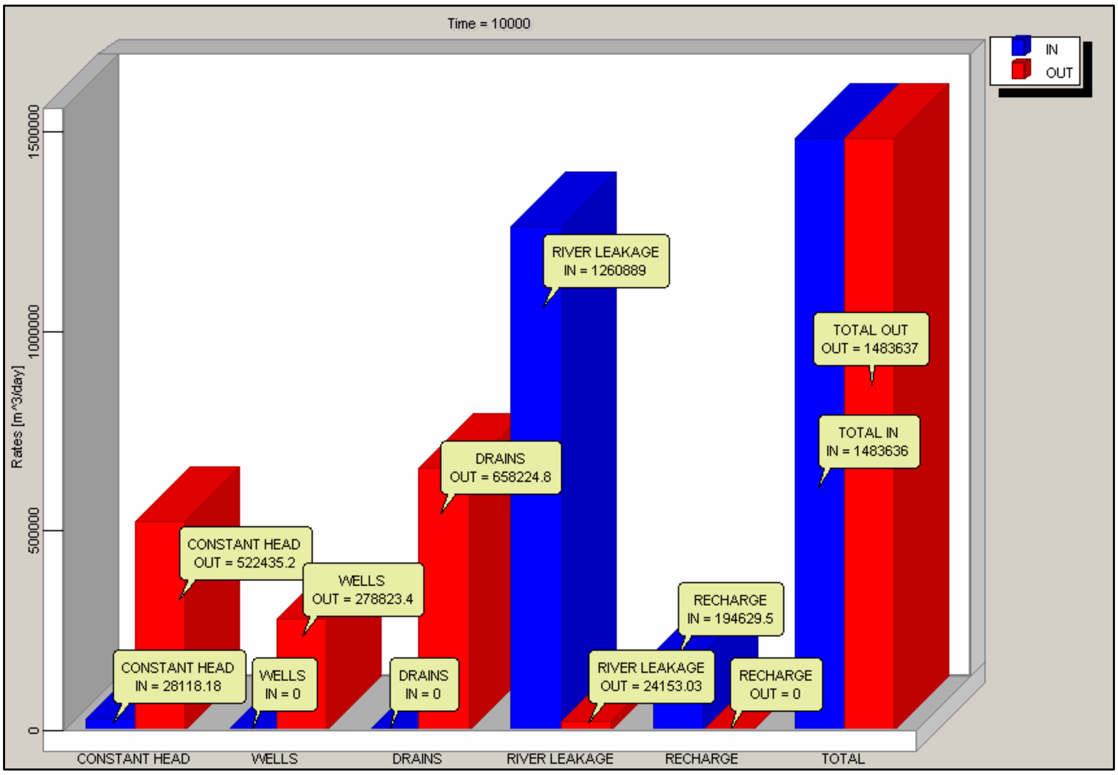


Figure 9: Simulated piezometric head contours – 5 m intervals (plan view)

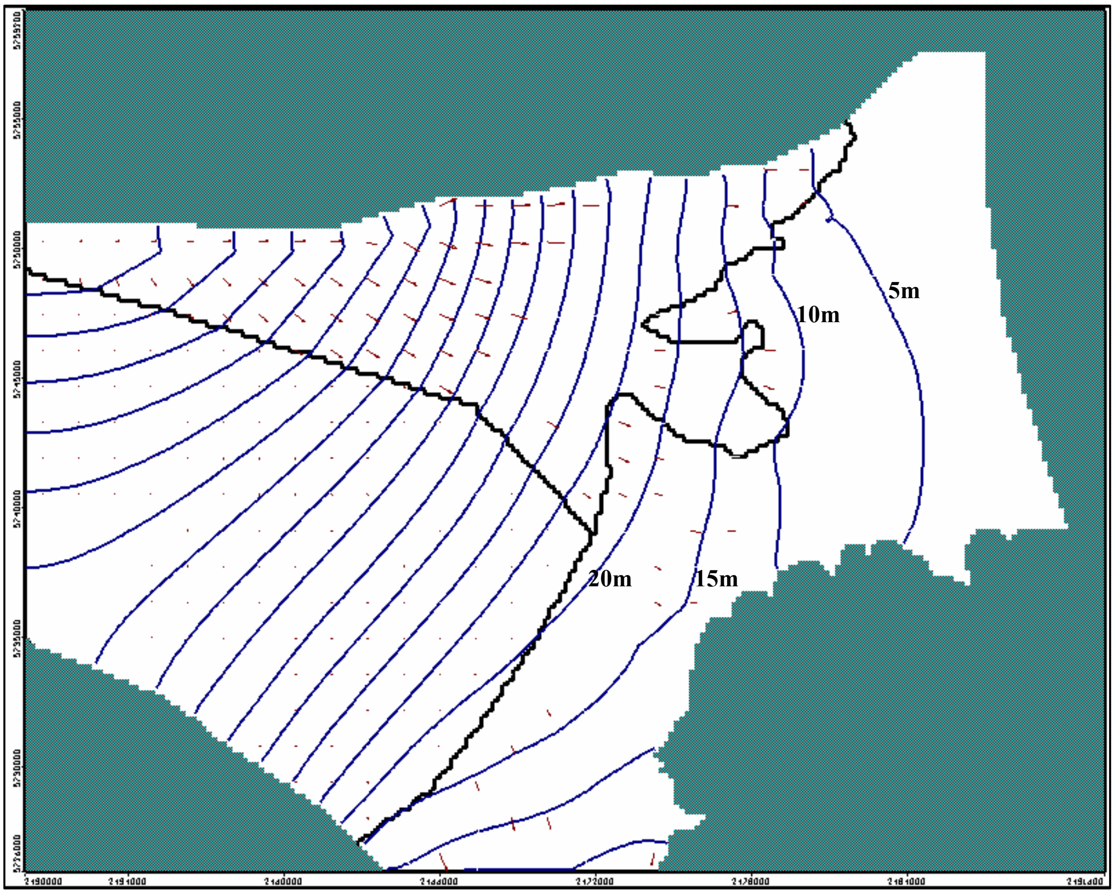
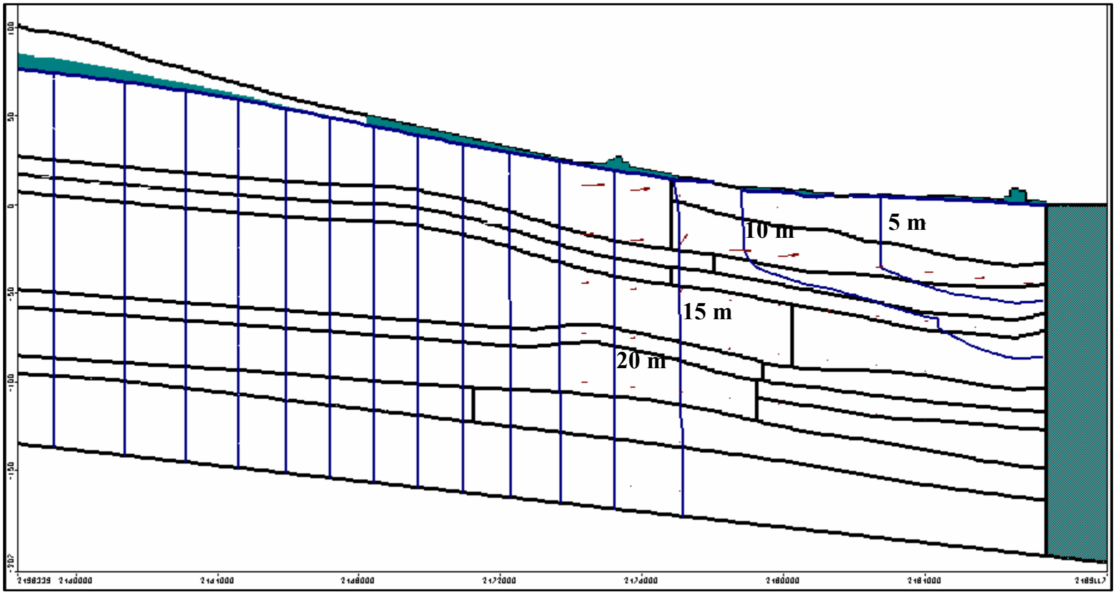


Figure 10: Simulated piezometric head contours – 5 m intervals (cross-section view)



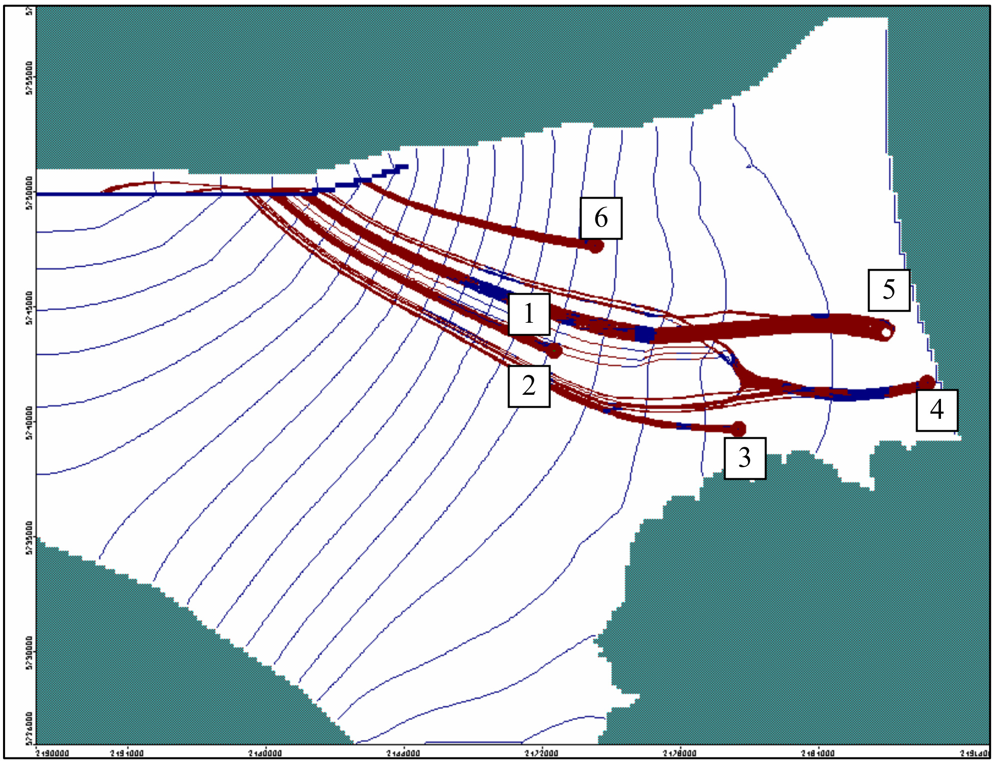
8 PARTICLE TRACKING AND AQUIFER VISUALISATION

To understand the groundwater movement to any particular water supply well Visual MODFLOW has a particle tracking package that allows particles to be set at a particular well screen and then tracked backwards through the groundwater flow system to indicate the path the water took to reach the well and the time taken. Pathlines

Table 1: Comparison of Water Ages (Model ages from steady state average conditions, with pumping)

CCC Water Supply Well	Location code for (Figure 11)	Well depth (m)	Average Groundwater Age (years)	
			From model	From water age determinations
Avonhead 2	1	26	6 (6 to 20)	19
Avonhead 4	2	195	173 (153 to 184)	77
Sydenham 4	3	40	6 (6 to 28)	11
Estuary 4	4	48	34 (34 to 66)	78
Bexley 2	5	148	86 (86 to 384)	60
Harewood 1	6	26	3 (3 to 5)	10

Figure 11: Pathlines showing particle tracking (plan view)



for a selection of public supply wells are shown in Figure 11 and the average age determined by the model compared to isotope and trace chemical age determinations is set out in Table 1.

A cross-sectional view of the particle tracking is presented in Figure 12 (overleaf). It shows how multiple pathlines, travelling through a variety of aquifers and aquitards, can reach a single pumping well.

3-D visualization of the aquifer system (Figures 13 and 14, overleaf) allows representation of the hydrogeologic system and the way in which water movement occurs toward water supply wells.

9 IMPLICATIONS FOR FUTURE MANAGEMENT OF THE CHRISTCHURCH DRINKING WATER SUPPLY SYSTEM

Natural variability of groundwater flow systems means that numerical flow models cannot reliably define groundwater flow paths and travel times in a unique and accurate manner. However, when a verified numerical flow model utilised in combination with a wide range of other hydrogeologic information provides a consistent explanation of observed groundwater characteristics, then the model makes a significant contribution to the understanding of the groundwater flow system. Alongside the model, other sources of hydrogeologic information that contribute to this understanding are: geologic mapping; aquifer testing; groundwater level monitoring; and water quality analyses, including bacteriological determinations.

Figure 12: Pathlines showing particle tracking (cross-section view) for Estuary 4 well

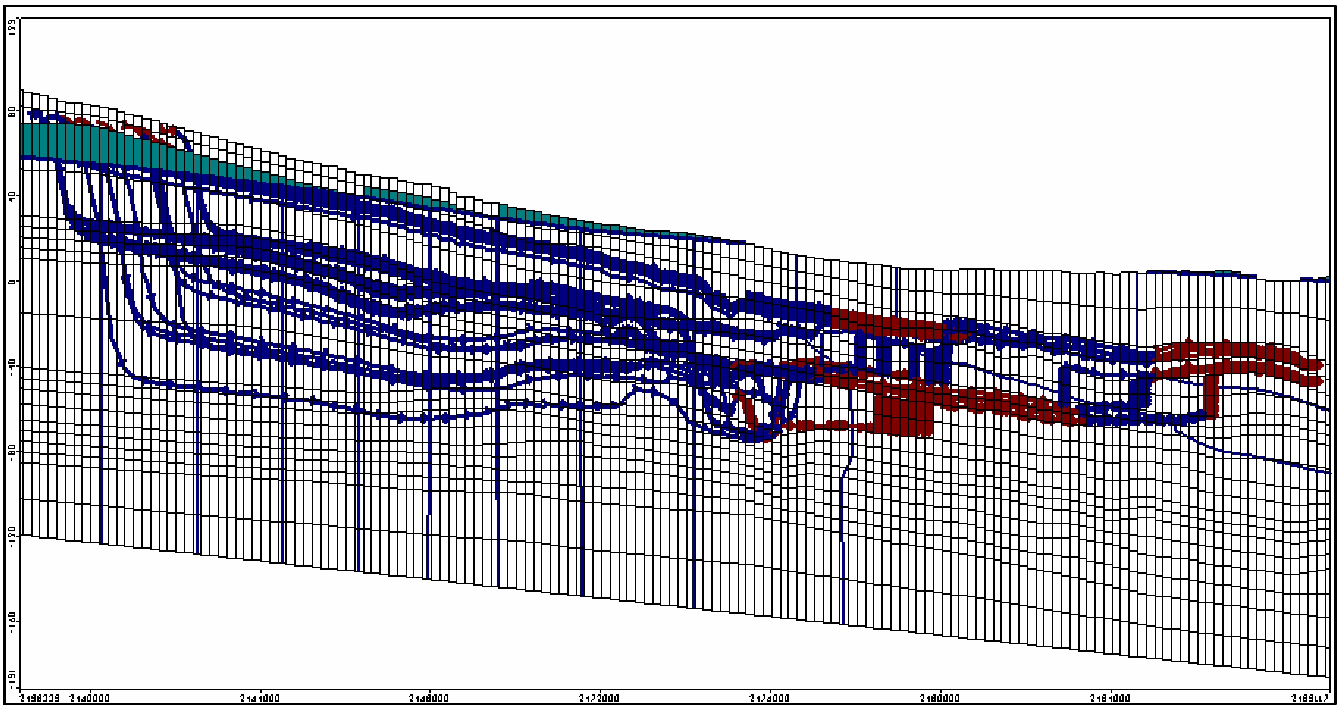


Figure 13: Three dimensional plan view

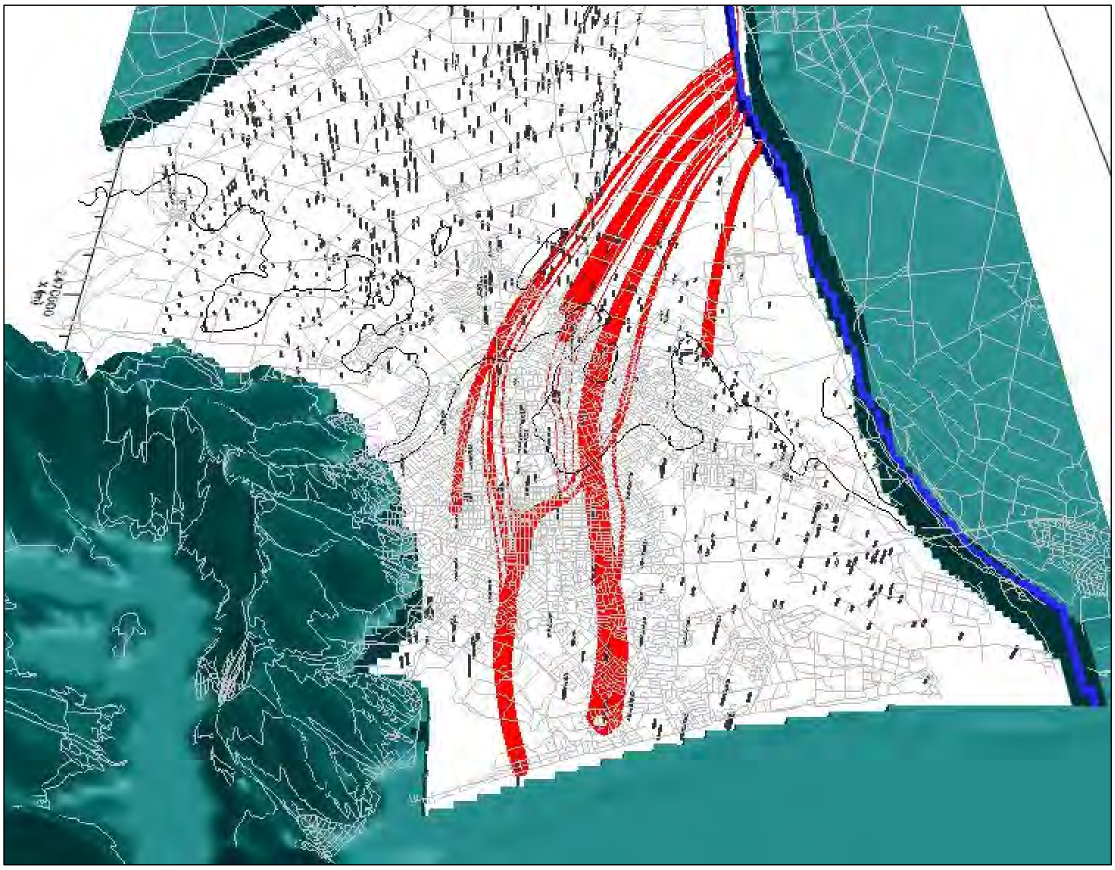
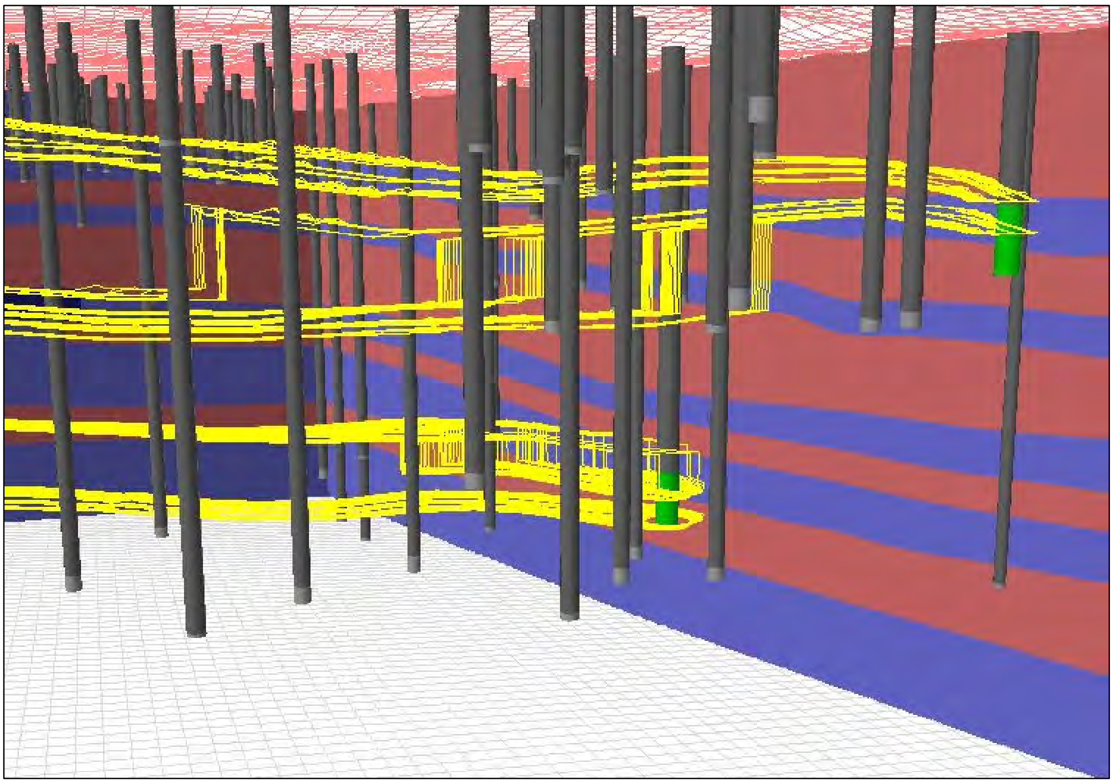


Figure 14: Three dimensional cross-section view



The model is also particularly useful for determining relative contributions of shallow and deep groundwaters, using flow paths to particular wells. In that regard it is possible to rank the wells within the Christchurch City system to identify which ones are more at risk from various contamination sources than others. In this way it can directly achieve the objective in section 4.5.2 of the Drinking Water Standards for New Zealand 2005 by allowing monitoring to be focused on representative wells that are most vulnerable to contamination relative to other groups of wells further down the flow pathlines.

From a water supply management perspective this allows for a refinement of the water supply monitoring budget in a way that more accurately targets key indicator wells. It also provides a more robust rationale for the selection of representative monitoring wells and the definition of the larger grouping of wells that they represent.

10 CONCLUSIONS

Christchurch City draws its water supply from a large network of wells that abstract water from a variety of aquifers beneath the City. Strict application of the monitoring requirements in the Drinking Water Standards would be an unrealistically onerous and unnecessary requirement.

The development of the groundwater flow model helps to demonstrate, along with other hydrogeological information, how groundwater moves towards specific wells and the relative time taken to reach those points. It provides an excellent visualization of these flow paths that helps to rank wells in terms of their vulnerability to contamination. This smaller group of key monitored wells provide a representative coverage of a much larger number of wells within the aquifer system.

11 REFERENCES

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