Chapter 13 - Modelling Groundwater Behaviour

Introduction

Groundwater models are tools that scientists use to understand how a groundwater system works and to predict future behaviour. Over the past 30 years they have become a valuable aid for understanding aquifer processes and assisting with groundwater management. In some cases they are used to forecast aquifer behaviour, while in others they are simply used to test theories or ideas and advance our knowledge.

Natural groundwater systems are complex and have a large number of parameters that are highly variable throughout time and space. In order to understand or describe how an aquifer functions, we need to simplify these parameters, and this is essentially what a groundwater model is, a simplification of a natural system.

Groundwater models range in their simplicity from conceptual pictures or basic descriptions, to complex computer programs that run a large number of mathematical equations simultaneously. The process of modelling is an evolving one, with each new generation of model superseding the previous version.

Models are improved as technology evolves and we gain more information and understanding of the systems we are studying. This section is an introduction to the kinds of groundwater models that have been used by the MDC, and how they have been applied in Marlborough to study local aquifers.

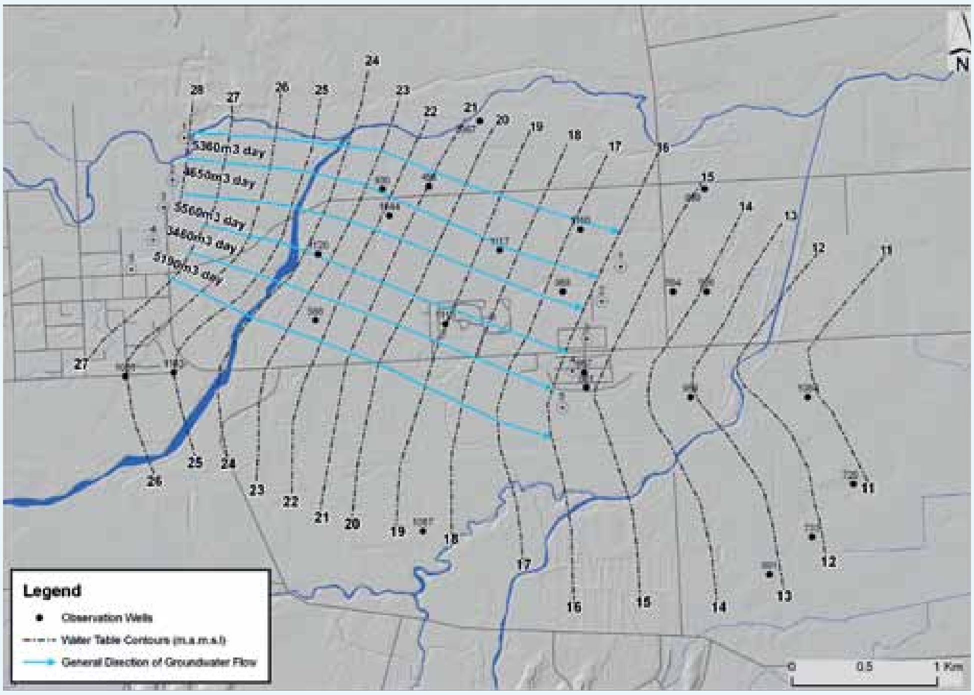

Figure 13.1: Piezometric survey for Woodbourne March 1981. The volumetric rates in m^3/day have been derived from the slope, and aquifer transmissivity. The blue lines indicate the direction of groundwater flow for that particular period.

Basic principles

The flow of water through the earth is governed by the laws of physics, and these laws are the foundation for groundwater studies. The equations that describe the flow are similar to those for heat diffusion. The first law of thermodynamics, or principle of continuity, applies to groundwater in that there can be no net change of water mass or energy within a unit volume of aquifer. Any change of inflow to the system must be balanced by a change in either groundwater storage or outflow:

Change in Groundwater Storage = Recharge - Discharge

This principle allows hydrogeologists to generate mass balances or inventories of all the inputs and outputs to an aquifer, which forms the basis for groundwater modelling. The rates of specific inflows and outflows across any surface are known as fluxes. The rate that changes in storage occur is largely determined by the aquifer properties, transmissivity or permeability, and storativity or specific yield.

Groundwater is constantly driven by gravity and flows from higher elevations to lower elevations, and the difference between two water levels is called a hydraulic gradient. If we apply the continuity principle to a section of aquifer we can derive Darcy's Law, which is the fundamental equation for groundwater flow.

The flow of groundwater within an aquifer can be easily understood when the water table is considered as a continuous series of pipes or streamlines controlled by hydraulic gradients. We can show how the aquifer works diagrammatically by drawing water table or piezometric contours on a map (Fig. 13.1).

Streamlines are drawn perpendicular to the piezometric contours to illustrate the direction of groundwater flow. The result is a flownet which represents the groundwater surface, just as a topographic map represents a model of the earth's surface.

The piezometric contours indicate the direction of flow within the aquifer and the convergence or divergence of these contours shows where aquifer losses or recharge is occurring. The distance between piezometric contours indicates the hydraulic gradient, which is greater in areas where the contours are closer.

Conceptual aquifer models

A conceptual model is an idealised description of how an aquifer works. They are fundamental to any groundwater study and form the basis for more complex modelling studies. The development of a conceptual model is the first step towards understanding a groundwater system (Fig. 13.2). These models are constantly being refined as new information or ideas come to hand.

No matter how much information is collected, we could never fully describe a natural system. So by necessity a conceptual model is a simplification of the real world. A conceptual model describes the key physical attributes and dynamics of an aquifer. This knowledge is used to direct the collection of field measurements so that the system can be monitored and our understanding further improved.

Key components of a conceptual model are the nature of boundaries, aquifer properties and flow paths. In Marlborough, recharge comes from rivers, streams and rainfall. Losses occur through pumping, evapotranspiration, aquitard leakage and natural drainage to springs, streams or to the sea. A mass balance for an aquifer is a type of conceptual model that describes all the inputs and outputs to a system (Fig. 13.2).

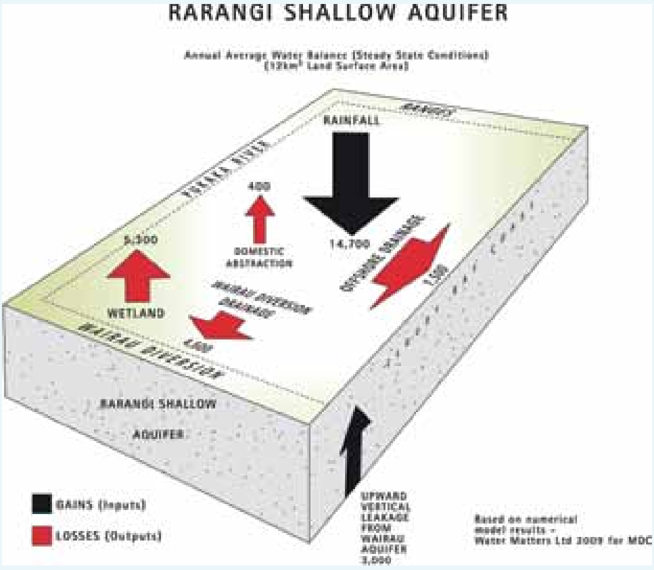

Figure 13.2: Conceptual model for the Rarangi Shallow Aquifer. Computed long-term water inputs are shown in black and outputs in red. These represent average daily rates in m^3/day based on modelling. Aquifer boundaries include the Pukaka Ranges, Wairau Diversion, Pukaka River and Cloudy Bay Coastline.

An important aspect of a conceptual model is that it only describes the static or present day state of an aquifer. To predict how a system will respond to different stresses, it is necessary to develop what is known as a dynamic or transient model. Transient models incorporate changes to a system through time and are either analytical or numerical in nature.

Analytical models

Aquifers lend themselves to mathematical description. Expressions of varying complexity are used on a daily basis by hydrologists to describe aquifer systems, and predict their behaviour. Analytical models consist of simple equations that represent a particular aspect of a groundwater system and they are useful to groundwater scientists because they can be accommodated in a spreadsheet.

Equations are commonly used to predict localised aquifer behaviour such as the impacts of pumping on other wells or streams. For more complex or regional scale problems, a numerical model is the more appropriate tool. Because equations describe complex natural systems, simplifying assumptions are necessary to make them universally applicable.

Ideally the validity of a model will be tested and some parameter values constrained via a process known as calibration. Calibration involves changing parameter values so that the calculated results match independent real world observations. For example, if we are using groundwater equations to estimate the loss of stream flow caused by pumping a well nearby, we could calibrate our model by comparing the calculated results with actual channel losses measured by stream flow gauging.

The fundamental equation for describing groundwater flow to a pumped well was developed by Theis in 1935 and modified by Jacob in 1946 (Fig. 13.3). The equations used by hydrogeologists to estimate aquifer properties are:

$$T = (2.3Q)/(4\pi\Delta s) \quad \text{and} \quad S = (2.25Tt)/r^2$$

Where:
T = transmissivity of the aquifer (m^2/day)
Q = pumping rate of the well (m^3/day)
Δs = drawdown in water level in the aquifer in metres
S= storativity of the aquifer which is dimensionless
t = length of time that the well is pumped in days
r = distance from the pumped well in metres

Some of the key assumptions of the Theis equation are that the aquifer is confined, is of infinite areal extent, homogeneous and isotropic in nature, of uniform thickness and the piezometric surface is flat. Over time, variations of the Theis equation have been developed to cater for different hydrogeological settings.

In Marlborough the real worth of the many models that have been developed by the MDC and its predecessors since 1988, has been in testing theories of aquifer behaviour, or refining understanding of their mechanics and flow processes.

Stream depletion

Groundwater and surfacewater naturally interact and it is necessary to quantify the effect one has on the other to ensure springs aren't dried up by pumping. The first model to be used by hydrogeologists to predict the effect on stream flow of a nearby pumping well was the Jenkins equation. This equation tends to over-estimate depletion rates because it ignores the isolating effect of the sediments lining the channel.

Dr B. Hunt of the Engineering School at the University of Canterbury, developed sets of spreadsheet equations (Hunt - 2004) to more accurately describe scenarios of stream flow losses caused by pumping (Hunt - 1999, 2003). These algorithms have been in use for some time now to estimate the direct impact that pumping is having on surface waterways.

The equations can either be used to analyse stream depletion parameters from pumping test results, or to predict stream depletion rates if the aquifer and stream bed conductance values are known. Incorporating the isolating effect of the stream bed clogging layer represented a significant improvement in the accuracy of the models.

Several pumping tests have been reanalysed for stream depletion using the new algorithms (PDP - 2004). The MDC has also carried out specific stream depletion pumping tests at Mills and Ford Road wells 3958 and 4404.

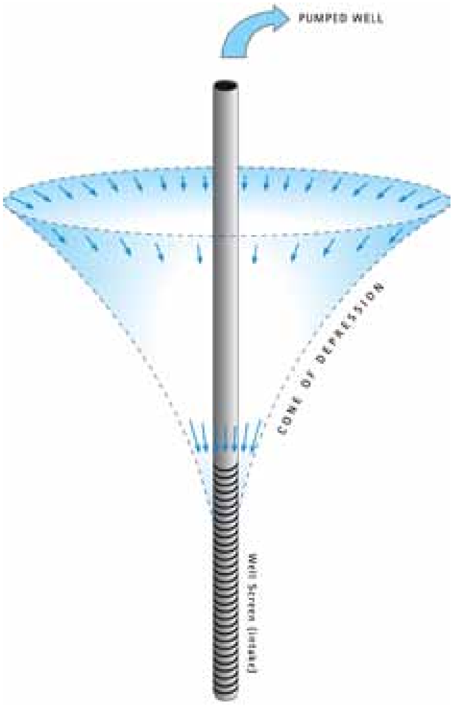

Figure 13.3: Radial flow towards a well

Areas where stream depletion predictions have been carried out are the Southern Springs, Blenheim Urban Springs and the Rapaura area. The Rapaura study was carried out to estimate potential flow loss in the Wairau River caused by pumping in the Wairau Aquifer (Wilson - 2006). These tools allow the sensitivity of groundwater springs to pumping to be assessed.

Seawater interface

Some of Marlborough's aquifers lie adjacent to the coast and the sea acts as an important hydrological boundary and groundwater from the Wairau, Riverlands and Rarangi Shallow Aquifers all border Cloudy Bay.

The interface between fresh groundwater and sea water is known as the saltwater or saline interface. The position of this interface is largely determined by the difference in water levels between the fresh and saltwater bodies, and also the relative difference in density between the two.

Because saltwater is denser than fresh water, a lense of saltwater is often found at the base of an aquifer that may extend inland for some distance. If a coastal aquifer is over-pumped, the water levels will be lowered to a point where the saltwater lense could start moving inland and contaminate coastal wells.

Wairau and Riverlands Confined Aquifers

It is uncertain where the saline interface is located for the confined Wairau and Riverlands Aquifers although it is most likely that the overlying Dillons Point Formation aquitard extends offshore. Because the location of the interface is unknown, the MDC have used sentinel wells to indirectly monitor its position. The Ghyben-Herzberg relationship has been used to set the minimum safe water level required at each well to avoid saltwater interface and it relies on the different densities of freshwater and saltwater.

The Ghyben-Herzberg relationship is used to calculate the depth to the saltwater interface under static conditions where there is a permeable connection between the aquifer and the sea. The assumption of static conditions in the confined aquifers applies at the Cloudy Bay coastline because the dominant component of groundwater flow is upwards, not horizontally offshore. So a groundwater elevation of two metres above sea level corresponds to a depth of 80 metres of fresh water below sea level. It follows that if groundwater level in the well is lowered by 0.1 metres, the seawater interface will rise by four metres and its toe will move further inland.

Rarangi Shallow Aquifer

The problem of describing the interface between seawater and the Rarangi Shallow Aquifer differs from the confined aquifers in that the interface position is known, and there is significant flow offshore. An equation has been developed by Glover (1959) to describe the shape and position of the seawater interface in an unconfined aquifer with offshore flow (Fig. 13.4).

The Glover solution is an advance on the Ghyben-Herzberg approximation in that the position of the freshwater lense is influenced by the hydraulic gradient of the aquifer. The Glover equation has been applied by the MDC at Rarangi to set safe water level thresholds in shallow coastal monitoring wells and avoid seawater intrusion. This is described in detail in the Rarangi Shallow Aquifer chapter.

One limitation of the Glover equation is that the hydraulic gradient needs to be known. The slope of the water table at Rarangi steepens as the coastline is approached, so it is difficult to know what an appropriate hydraulic gradient is.

This problem can be overcome if the position of the seawater interface is known. The interface predicted by the Glover solution can then be fitted to the actual interface position by adjusting values for the hydraulic gradient. This is an example of a rudimentary form of model calibration.

Southern Valleys allocation

Equations can be developed from observations of simple cause and effect relationships. These empirical relationships can be derived from hydrological observations. Through regression analysis we can develop rules of thumb between two variables as well as provide some statistical description of the uncertainty associated with the relationship.

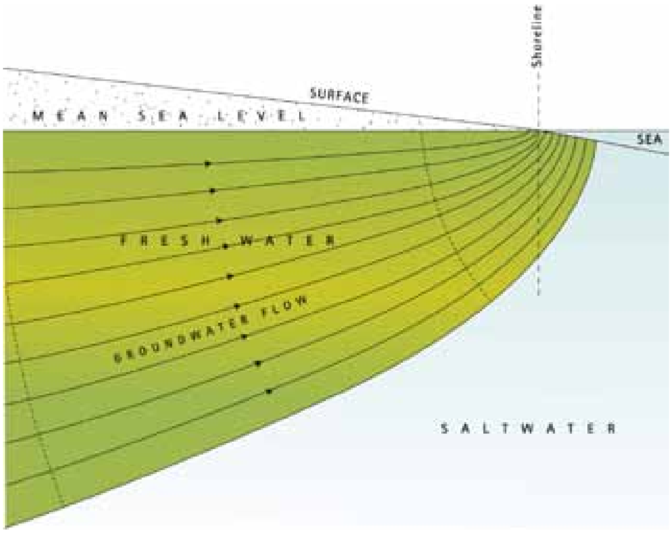

Figure 13.4: Glover model.

An approach developed to determine seasonal allocation in the Southern Valleys aquifers involved matching seasonal irrigation use for each consent holder with seasonal aquifer drawdown. By studying this relationship over the course of a decade, the effect of a certain level of abstraction can be predicted for each summer season.

An analytical approach was also used to look at options for conjunctive management of Deep Southern Valleys Aquifers with the Southern Valleys Irrigation Scheme (Aqualinc - 2004). This involved a water balance of estimated aquifer inputs and outputs to simulate aquifer behaviour. The model was calibrated by comparing the water levels predicted by the water balance model with observations made in wells. The calibrated model was used to run two different scenarios of water demand.

Numerical models

Numerical models are used to assess the cumulative impact of pumping a large number of wells at a regional scale. They are also used to simulate situations where there are multiple or complex hydrological boundaries that would not be adequately described by the simpler analytical models.

Numerical models are the closest approximation to real world conditions that can be made. They consist of a large number of interdependent flow equations that simulate two or sometimes three dimensional groundwater movement. The number of equations involved is well beyond the computational capacity of a spreadsheet.

The most commonly used numerical model is called MODFLOW. More powerful models using finite element numerical methods exist, but these require more processing power and detailed information. MODFLOW was developed by the United States Geological Survey in 1984 and since then a series of commercial interfaces have been developed to make it more user-friendly.

MODFLOW works by simulating groundwater flow between cells which form a regular shaped grid. Flow into and out of each individual cell is then computed using finite difference numerical methods. Equilibrium (steady state), or time-dependant (transient) scenarios such as variable pumping scenarios can be modelled. Contaminant transport can also be modelled, but a prerequisite is knowledge of the groundwater flow.

The actual numerical modelling process usually involves three stages: parameterisation and gridding, calibration and verification or validation. The development phase involves setting up the model to reflect the conceptual understanding. Observations or measurements of hydraulic properties and well levels are imported to characterise aquifer behaviour.

The first step in building a numerical model of an aquifer is to specify a regular grid of cells for calculating changes in water storage. Their geometry will approximate the real aquifer system. Areas near boundaries or where water levels or flows change significantly are assigned a higher density of cells such as where wells are pumping and causing large changes in aquifer levels (Fig. 13.5). The models range from very simple grids to more complex models with multiple layers or boundaries. A slice through the Riverlands Aquifer from west to east shows the varying thickness of the aquifer forming sediments specified by the modeller (Fig. 13.6).

The next step is to build what is known as the steady state version of the model. Its purpose is to test the validity of the conceptual model and quantify volumetrically inputs and outputs of water. A steady state model is generally based on winter conditions when a natural equilibrium exists, and there is limited pumping to disturb the balance. Properties are assigned to each of the cells in the model based on measurements where possible (Fig. 13.7).

Calibration is the name used to describe the process of making sure a model can reproduce reality. It involves adjusting model properties until the predicted values match observed values. During steady state calibration, transmissivity or hydraulic conductivity is adjusted until the observed water levels in monitoring wells match the modelled values. For transient models storativity is also adjusted.

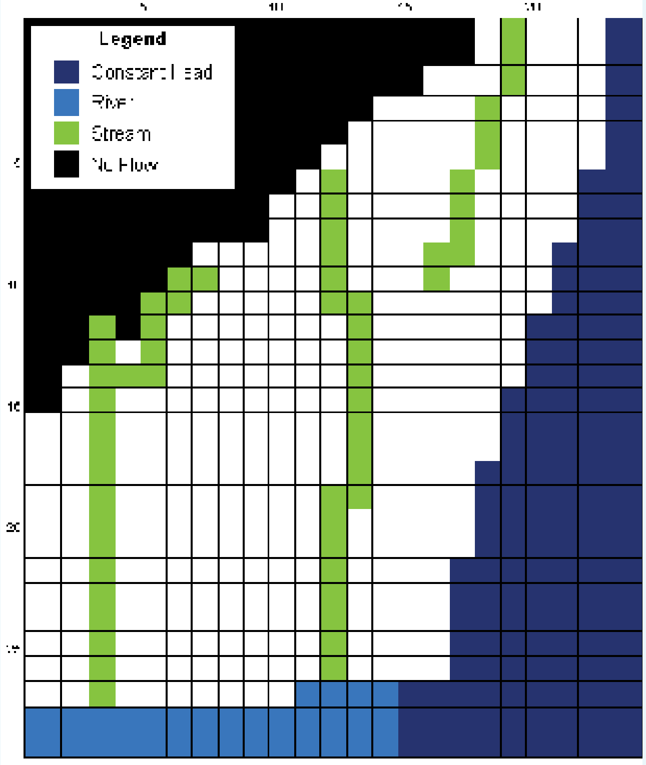

Figure 13.5: Plan view of the grid for a model of the Rarangi Shallow Aquifer (2007). In this case the cell size dimensions are all the same. Green cells represent drains or wetlands, the dark blue is the sea, black show the ranges and the light blue is the Wairau Diversion channel.

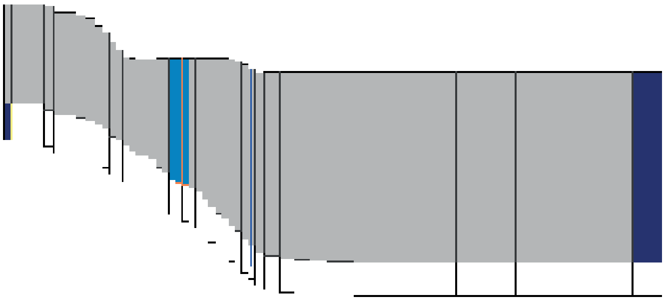

Figure 13.6: Side view of Riverlands Aquifer model structure

A transient model involves significantly more information, processing power and calibration difficulty. The benefits are that once the transient model is calibrated, it can be used for forecasting the impacts of different pumping scenarios. Models are highly dependent on accurate information and are only as reliable as the as the information used to build them.

Model verification is the next stage in the process and tests the accuracy of the calibration. This is done by running the calibrated model over a period of known record that wasn't included in the calibration phase to see if it can faithfully reproduce it. Many recent models do not include the verification process because it is preferable to use the whole dataset for calibration with advanced statistical processes.

The first regional scale numerical model of the Wairau Plain was developed by Mr David Scott of the DSIR and described in Davidson and Scott (1994). This MODFLOW based model characterised the hydraulic link between the Wairau Aquifer and freshwater springs. Model simulations formed the basis for the 4 m^3/s allocation limit for the Wairau Aquifer in the 1998 Wairau-Awatere Resource Management Plan.

This model was further developed by firstly PDP and Aqualinc Research Ltd, with a view to refine the proposed allocation limit. The model has eventually evolved to describe transient (time-variant) conditions with weekly time steps (Aqualinc - 2005).

An integral aspect of this new model involved the dynamic simulation of groundwater interaction with the Wairau River. This model is a work in progress, and will continue to be improved as new monitoring and hydraulic information becomes available.

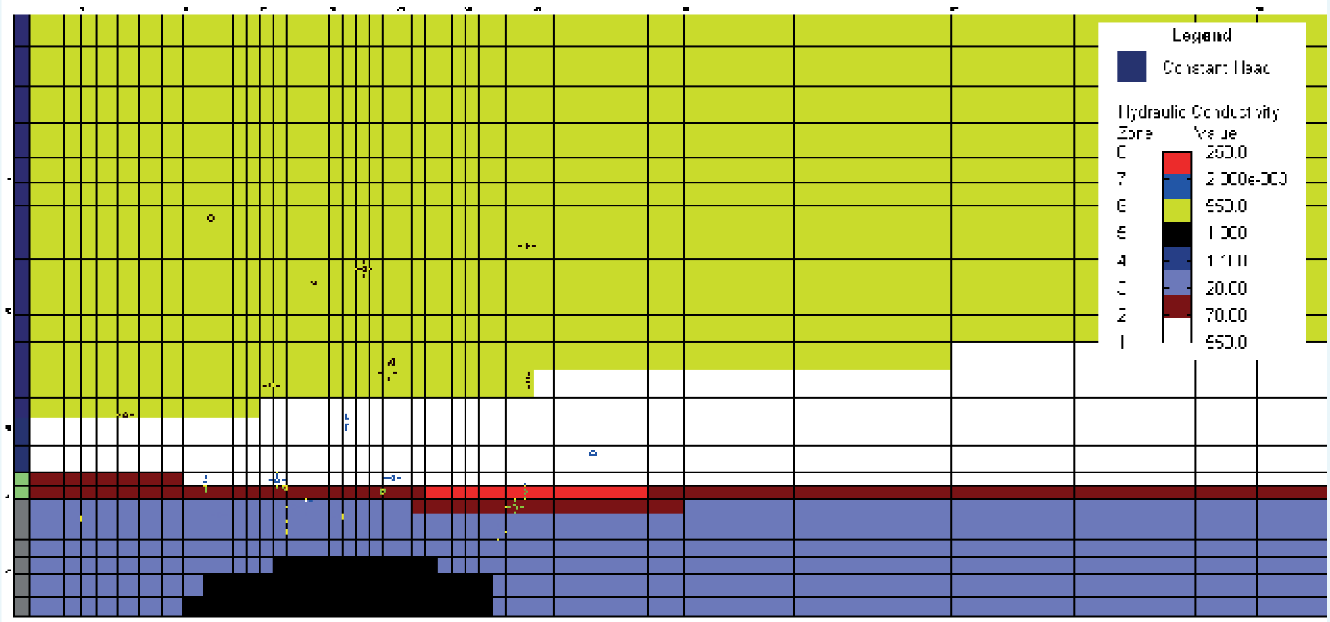

Figure 13.7: Plan view of hydraulic conductivity values for the 2008 MDC Riverlands Aquifer model. North is at the top of the diagram and the Wither Hills at the bottom. The lower yielding areas to the south in blue have lower values of hydraulic conductivity compared to the yellow or white areas, representing areas closer to the centre of the Wairau Plain.

Overall, numerical models are best for testing our understanding of the patterns of groundwater and contaminant movement and the parameters that control that movement. The accuracy of a model can be best judged by the accuracy with which it can reproduce measured results. However, care must be taken when using models for predicting future aquifer responses, particularly when these go beyond the range of the calibration dataset. Such predictions can be quite inaccurate and the model can never replace the need for monitoring the actual groundwater response to various activities. The model can however provide a very useful guide as to the location and frequency of how that monitoring should occur.

References

Aqualinc, 2004. Deep Southern Valley Aquifer Model: Model Documentation. Report prepared for Marlborough District Council. Aqualinc Research Limited, Lincoln.

Aqualinc, 2004. Wairau Aquifer Management Review: Transient Modflow Model. Report prepared for Marlborough District Council. Aqualinc Research Limited, Lincoln. Report No. L05038/1.

Aqualinc, 2005. Wairau Aquifer Management Review: Stage 5. Report prepared for Marlborough District Council. Aqualinc Research Limited, Lincoln. Report No. L05213/1.

Davidson, P.W., and Scott, D., 1994. Wairau Aquifer Resource and Issues. Technical Report Prepared for Marlborough District Council.

Freeze, R.A. and Cherry, J.A. 1979. Groundwater. Prentice Hall, New Jersey, 604 p.

Glover, R.E., 1959. The pattern of fresh-water flow in a coastal aquifer. Journal of Geophysical Research, 64(4): 457-459.

Hunt, B., 1999. Unsteady stream depletion from groundwater pumping. Groundwater 37 (1): 98-102.

Hunt, B., 2003. Unsteady stream depletion when pumping from a semiconfined aquifer. Journal of Hydrologic Engineering (ASCE) 8, 12-19.

Hunt, B., 2004.Groundwater analysis using Function.xls. Workshop notes available online at: www.civil.canterbury.ac.nz/staff/bhunt.asp

Ingham, M., 2004. Measurement of the saline/fresh water interface at Rarangi using DC resistivity traversing. Technical report prepared for Marlborough District Council, 30pp.

Kruseman, G.P. and De Ridder, N.A., 1994. Analysis and Evaluation of Pump Test Data (2nd Ed.). Publication 47, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Pattle Delamore Partners, 2001. Preliminary Development of a Groundwater Flow Model for the Wairau Aquifer. Technical report prepared for Marlborough District Council.

Pattle Delamore Partners, 2004. Stream depletion report. Technical report prepared for Marlborough District Council, 59 pp.

Wilson, S.R. 2004. Sensitivity analysis of the saltwater interface, Rarangi Shallow Aquifer. Marlborough District Council internal report.

Wilson, S.R., 2006. Groundwater-Wairau River interaction on the Wairau Plain. Technical report prepared for Marlborough District Council, 32pp.