

Technical Report  
Investigations and  
Monitoring Group

**Canterbury Plains  
regional groundwater  
model: Project  
overview**

# **Canterbury Plains regional groundwater model: Project overview**

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## Executive Summary

Groundwater use in the Canterbury region has increased significantly over the last decade. This has prompted the development of policies aimed at ensuring sustainable management of groundwater and interconnected surface water. The Natural Resources Regional Plan has proposed interim allocation limits which have been initially established as a proportion of land-surface recharge. The management strategy is to develop more specific management policies as additional information becomes available and as pressure on the resource increases.

Environment Canterbury's regional groundwater modelling project is intended to provide a sound basis for the development of specific management policies for groundwater allocation zones within the Canterbury Plains where pressure on the resource has been greatest. Development of the regional groundwater model reflects the following factors:

- the need for more robust definition of long-term sustainable management policies;
- the significant economic value of groundwater within the region;
- the difficulty of defending interim allocation limits in recent water allocation hearings;
- scientific and policy gags relating to the use and management of groundwater;
- lessons learnt from previous modelling studies.

This report summarises the design of the regional groundwater model including:

- the model extent covering most of the Canterbury Plains;
- the model inputs and outputs;
- the model calibration approach and associated computer methods;
- methods to describe prediction uncertainty.

The report provides an illustration of how the ability to describe prediction uncertainty can be incorporated into the assessment of groundwater management policies. Progress on the development and testing of a prototype model using the adopted calibration methodology is described in a companion technical progress report (Moore and Scott 2008).



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## 1. Introduction

This report provides an overview of Environment Canterbury's regional groundwater modelling project. This project involves the development of a groundwater flow model for the Canterbury Plains groundwater system and is an initiative for Environment Canterbury begun in 2006, prompted by concerns about the sustainability of the region's groundwater resources, the limitations of earlier smaller-scale models and the need to inform policy decisions.

The report provides an introduction to the resource management framework and physical setting of the Canterbury Plains. Previous groundwater modelling studies are outlined with the intention of noting the lessons learnt from that work – both in terms of the insights that have been gained about the nature of the groundwater resource and the limitations of alternative approaches to modelling.

The approach to modelling used in this project is described setting out:

- the objectives of the modelling study;
- the general modelling philosophy adopted;
- the modelling methodology developed for this project, in particular:
  - the application of automated calibration and sensitivity analysis techniques to determine model parameters and to explore the uncertainty of model predictions;
  - the use of regularisation<sup>1</sup> to represent a world that is far more complex than we can identify uniquely in a model;
  - sub-model development – where localised environmental issues of concern lead to the need for customised groundwater management rules;
  - the development of a system to allow the large number of model runs required by distributing the computational load over Environment Canterbury's computer network.
- a summary of groundwater management issues and options;
- an example of the application of the modelling approach.

This report is intended to provide the necessary context for the first technical progress report on regional model development (Moore and Scott 2008).

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<sup>1</sup> The term regularisation is used in a mathematical context to refer to methods which allow for the solution of problems which would otherwise have no unique solution. The use of regularisation in groundwater modelling often involves the introduction of additional information such as a preferred smoothness or value of model parameters.

## **2. Groundwater resources in Canterbury**

This section provides a broad overview to a reader who may be unfamiliar with Environment Canterbury's groundwater management framework and the groundwater resources of the Canterbury Plains. It is largely based on the overview of groundwater resources and management by Scott (2007).

### **2.1 Management framework**

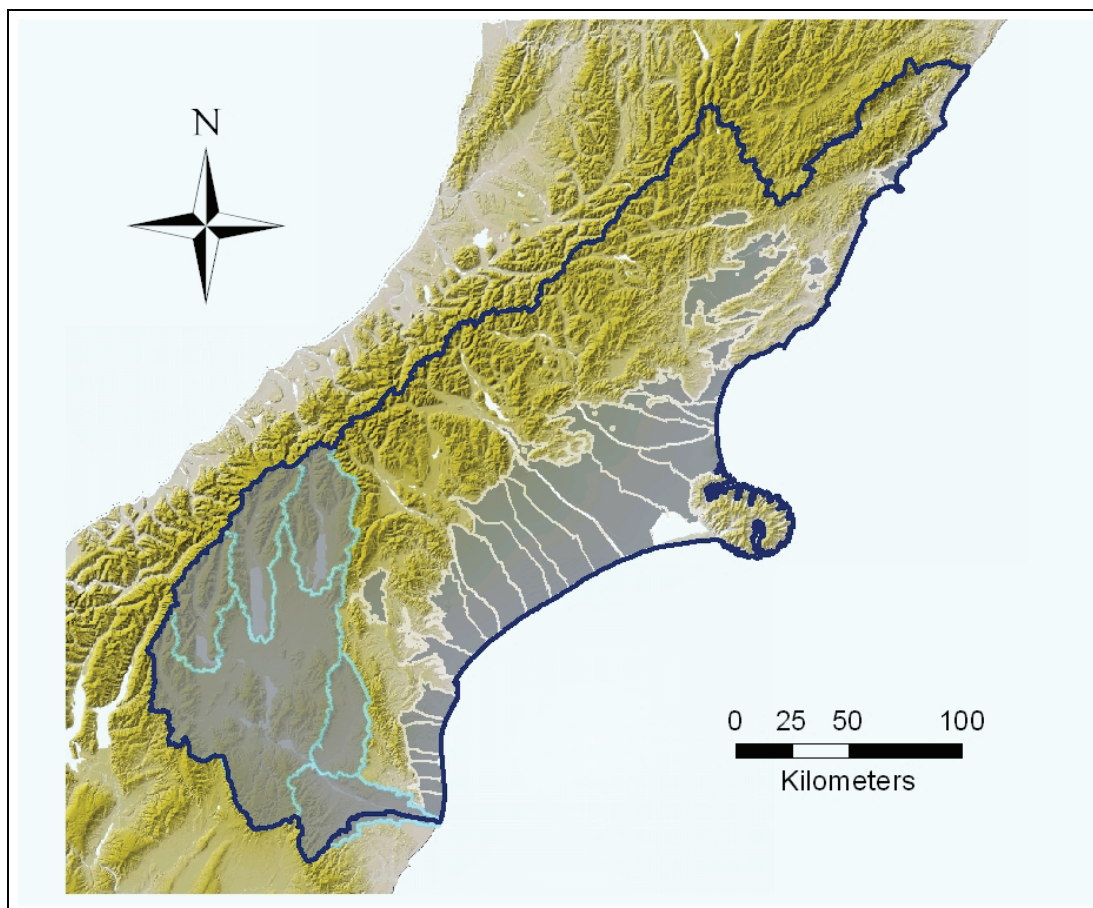
Water resource management in New Zealand is devolved to 16 regional authorities with responsibility for implementing the Resource Management Act 1991 (RMA) which promotes the concept of sustainable development of natural and physical resources and empowers local decision making and community participation in the development of resource management plans. Decisions on resource consent applications or on policies and plans can be appealed to a specialist court - the Environment Court.

The Canterbury region (Figure 2-1) is administered by Environment Canterbury (the Canterbury Regional Council) and covers a diverse landscape ranging from the Southern Alps on the western flank, rolling foothills, expansive alluvial plains and volcanic remnants. It is the largest of New Zealand's regions in terms of land area (45,537 km<sup>2</sup>) and the second largest in terms of population (approximately 500,000). Fifty eight percent of the water allocated in New Zealand is allocated from the Canterbury region and approximately 33% of that is from groundwater (Lincoln Environmental 2000).

Groundwater is available over an extensive part of the region as indicated by the dark gray areas within Figure 2-1. Figure 2-2 shows a close up view of the Canterbury Plains which is the area within which there is the greatest use of groundwater. Environment Canterbury's Natural Resources Regional Plan has established Groundwater Allocation Zones (demarcated by the light gray lines in Figure 2-1) to provide a basis for groundwater management. Interim allocation limits have been established for those zones as a proportion of the average land-surface recharge<sup>2</sup>. Those limits have been exceeded in several of the allocation zones and, as a result, there is a need to more robustly determine the requirements for long-term sustainable management of the groundwater resource. That need is a primary focus of the Canterbury Plains regional groundwater model project.

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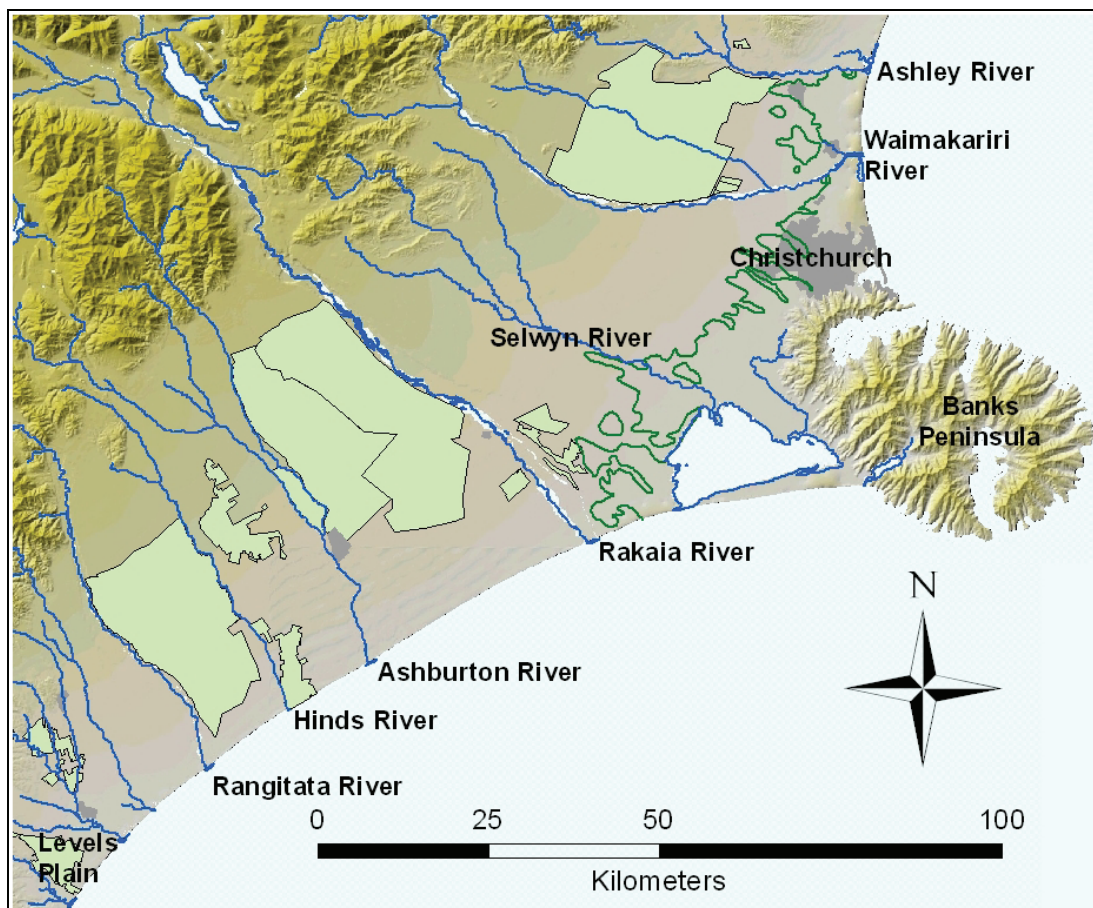
<sup>2</sup> The term "land-surface recharge" includes rainfall recharge and the additional recharge that occurs as a consequence of irrigation.



**Figure 2-1: The Canterbury region (boundary in dark blue) within New Zealand’s South Island and the Groundwater Allocation Zones (shown in dark grey with zone boundaries as light gray lines). The Waitaki Regional Allocation Plan covers the areas within the light blue lines – groundwater is also available throughout much of these areas.**

## **2.2 Brief description of the groundwater resource**

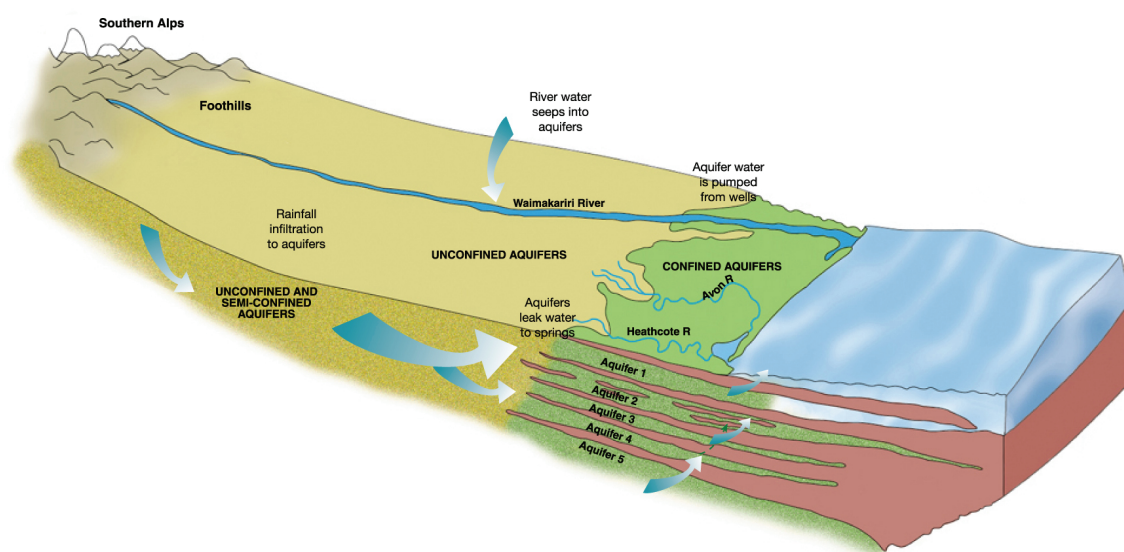
Groundwater resources within the Canterbury region occur predominantly within sedimentary aquifers and are most significant in the extensive Canterbury Plains which cover an area of approximately 8,000 km<sup>2</sup>. These plains are comprised of a mixture of glacial outwash material and inter-glacial/post-glacial reworked material in indistinctly-layered sediments ranging up to 500 m in thickness within which hydraulic conductivity varies significantly. Examination of drillers’ logs has led to the view that hydraulic conductivity generally increases towards the coast and decreases with depth (Scott 1980). Recent, more comprehensive, evaluation of such data (Davey 2006) has highlighted the role of permeable channels within the sandy gravel matrix and interpretation of complementary tracer and pumping tests (Dann et al. 2008) indicates that permeable channels may have a major influence on groundwater flow and may justify the use of a conceptual model which incorporates significant horizontal anisotropy. In the area adjacent to the volcanic Banks Peninsula the aquifers are more clearly confined by a sequence of terrestrially deposited gravels and finer marine sediments.



**Figure 2-2: Canterbury Plains showing major river names, urban areas (gray shading) and surface water-supplied irrigation scheme areas (green shading). The green line shows the extent of fine sediments which create confined aquifer conditions adjacent to Banks Peninsula.**

The groundwater system receives relatively steady recharge inputs from the alpine-sourced rivers traversing the plains and variable recharge from rainfall. Though rainfall is reasonably uniformly distributed throughout the year the high potential evapotranspiration rates in summer largely limit rainfall recharge to the winter season. Widespread irrigation from groundwater and surface water sources modifies this natural pattern and results in significant land-surface recharge during the irrigation season (October to April inclusive). This is clearly discernible in areas that are flood irrigated (with border dyke irrigation) from river-supplied irrigation schemes.

Groundwater sustains the baseflow of many small streams on the coastal margin of the plains particularly in the area where marine sediments have created confining conditions. Figure 2-3 provides a schematic view of one segment of the Canterbury Plains groundwater system highlighting some of the significant hydrological components.



**Figure 2-3: Schematic view of a segment of Canterbury Plains groundwater system in the vicinity of Christchurch City where marine sediments have created confining conditions.**

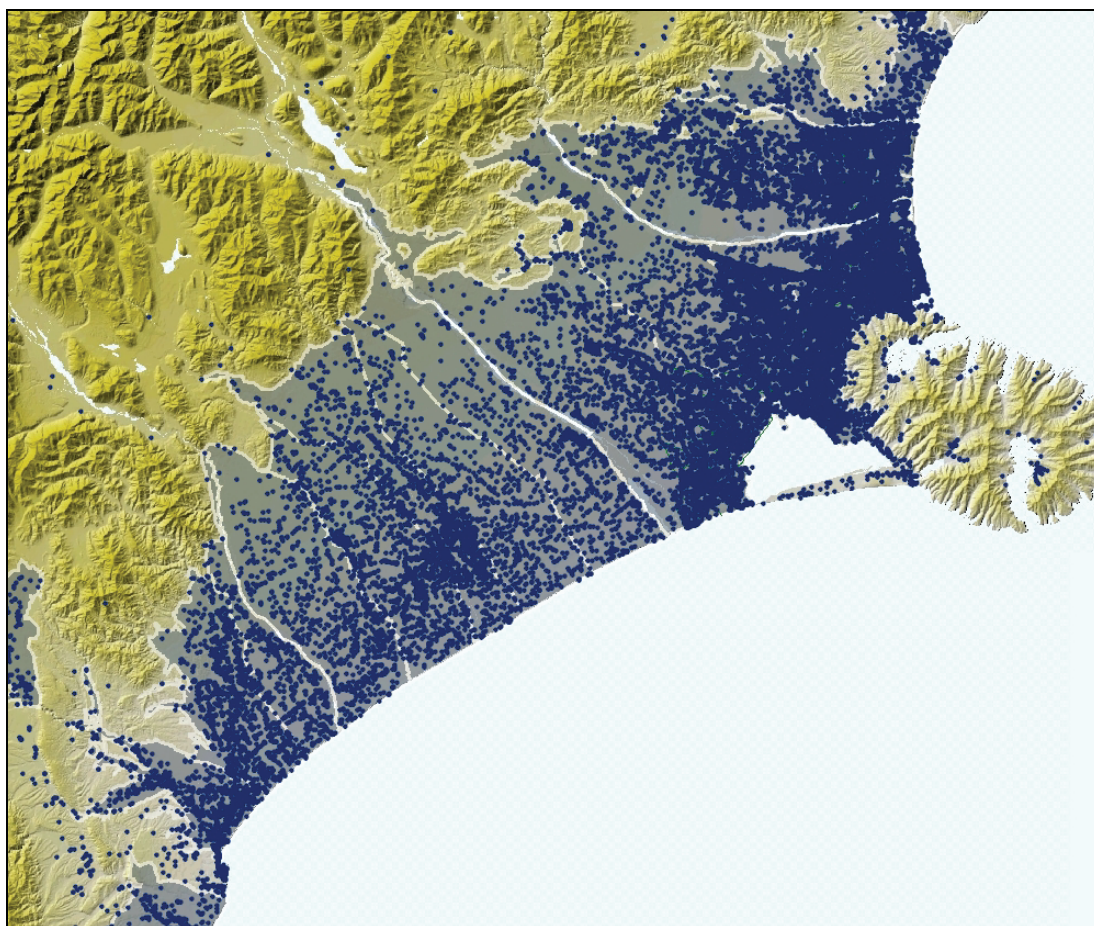
Canterbury groundwater has been the subject of scientific study for many years. Collection and interpretation of borehole information from the many thousand water wells has provided the basic knowledge but this has been supplemented by other hydrogeological investigation methods. Surface and down-hole geophysics have been used to determine aquifer structure but have had limited ability to delineate water-bearing zones within the sedimentary deposits. Environmental tracers have been used to determine groundwater age and source – the relatively high elevation of the alpine river catchments makes  $^{18}\text{O}$  a useful indicator of recharge source and trace atmospheric contaminants (e.g. CFC-11 and CFC-12) have provided useful estimates of groundwater age.

### 2.3 The economic value of groundwater

Groundwater resources in Canterbury are of high economic value. Christchurch, the region's main urban area (population approximately 350,000) relies entirely on groundwater for its potable supply and for industrial uses. Christchurch's groundwater is of such quality that it is able to be reticulated without the need for treatment – a feature greatly valued by Christchurch residents. The economic value of the Christchurch-West Melton groundwater system has been estimated at around NZ\$60 million/year (White et al. 2004).

Groundwater also has very significant economic value for irrigation. Canterbury has 287,000 ha of irrigated land, which contributes NZ\$330 million to national GDP (MAF 2004). Because of the high risk of agricultural drought intensive land uses are critically dependent on irrigation water. MAF (2004) estimates that the net contribution to farm-gate GDP of current irrigation from central Canterbury groundwater is NZ\$963/ha. The recent moves to set interim limits on groundwater allocation from highly allocated zones has led to an apparent "gold-rush" as land owners seek to gain access to the remaining resource. The distribution of wells within the Canterbury Plains as recorded by Environment Canterbury's is shown in Figure 2-4. The rate of development is reflected in the recent history of groundwater

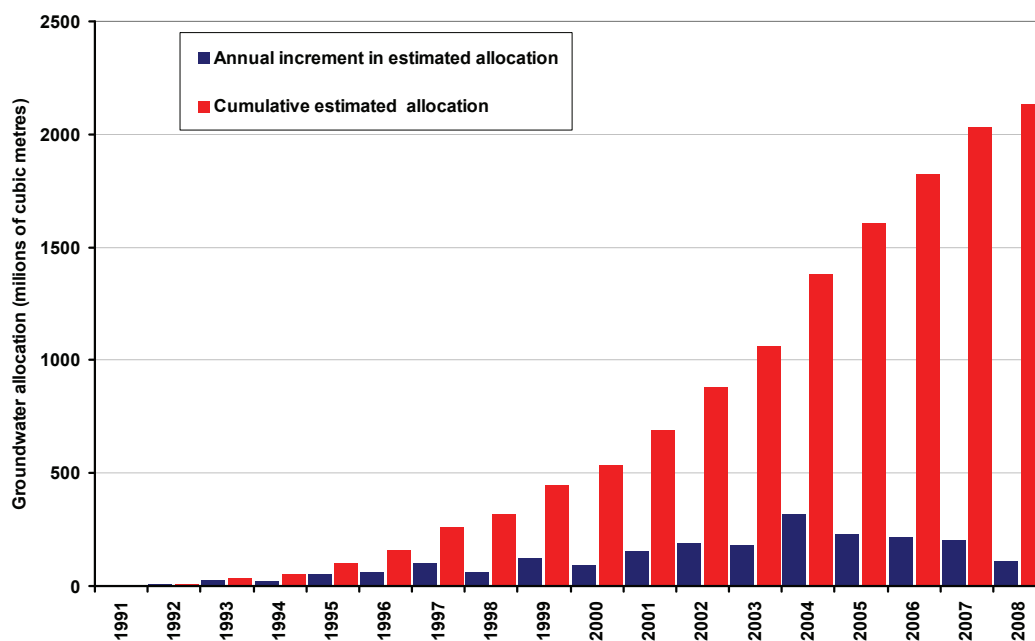
allocation<sup>3</sup> shown in Figure 2-5. Until recently most groundwater use permits (consents) have been issued for the maximum allowable term of 35 years. The establishment of Groundwater Allocation Zones and the associated interim allocation limits have led to greater scrutiny of new applications for groundwater in the more highly developed zones. This has presumably contributed to the reduction in the rate of growth of groundwater allocation since 2005. The term of recently issued permits has typically been limited to 10 years reflecting the increased concern about the effects of increased groundwater use.



**Figure 2-4: Distribution of wells within the Canterbury Plains.**

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<sup>3</sup> Figure 2-5 describes groundwater allocation in terms of “estimated allocation” – a term used to reflect the fact that many groundwater permits have, in the past, not included an explicit annual volume limit. Nevertheless, there are a variety of implicit constraints which effectively limit the total annual volume of water that can legitimately be taken under existing permits.



**Figure 2-5: Annual increments (blue) and cumulative sum (red) of estimated groundwater allocation since 1990.**

## 2.4 Ecological impacts of groundwater use

Any groundwater abstraction can be expected to result in a reduction in natural groundwater discharge. There are urban and rural examples of impacts of that sort within the Canterbury region. In Christchurch city the necessary land-drainage measures required for urban development have presumably contributed to the gradual reduction of flow in the tributaries of groundwater-dependent streams. These relatively subtle effects are difficult to monitor and reflect the cumulative effects of a range of factors that are hard to distinguish. Nevertheless reduction (or loss) of flow in urban streams provokes strong reactions from city residents who value the groundwater-dependent ecosystems. In the rural context the recent rapid development of irrigation to support intensive land-uses, especially dairying, has raised serious concerns about the probable impacts on lowland stream flows and the sustainability of the particular land-use. Because of the variability of the climatic factors it is difficult to demonstrate the extent to which irrigation development is exacerbating a natural condition and this has been, and is likely to continue to be, the subject of argument before the Environment Court.

Groundwater use also has the potential to allow salt-water contamination of the aquifer. This has already occurred in one part of Christchurch where groundwater levels had been allowed to decline to the extent that shallow overlying saline groundwater had begun to be drawn into the aquifer. A programme of water conservation and pumping reductions has been introduced and conditions are beginning to improve.

Groundwater use for irrigation can result in increased nutrient loads coming from the more intensive land-uses. Nitrate levels in shallow groundwater do reflect the effects of land use and more intensive land use is likely to result in further increase in nitrate concentrations. Because of the potential for a long delay between land-

use change and consequent changes in groundwater quality research is currently underway to better understand and anticipate the scale of these effects.

Environment Canterbury has responded to these existing and potential impacts by developing groundwater and land-use management rules that are intended to constrain total groundwater allocation and to limit nutrient leaching. Those rules are part of a comprehensive resource management plan which will become operative after extensive public consultation and may yet be subject to appeals being heard by the Environment Court. Recent decisions for consents to abstract additional groundwater from highly allocated zones have underscored the need to develop more complete understanding of the effects of groundwater development on surface water bodies.

## **2.5 Key scientific and policy gaps related to the use and management of groundwater resources**

The key scientific and policy gaps related to the use and management of groundwater resources are as follows:

- Understanding and predicting the impacts of abstraction on groundwater-dependent ecosystems;
- Understanding and predicting the impacts of land-use intensification on groundwater quality;
- Development of effective adaptive management approaches;
- Development and implementation of guidelines for reasonable use, especially for irrigation;
- Obtaining the staff and funding required for large-scale water resource system simulation;
- Understanding the strengths and limitations of large-scale water resource system simulations;
- Managing the cumulative effects of an increasing number of individual groundwater abstractions;
- Dealing with the pace of groundwater development when it is outstripping the ability to monitor and anticipate the effects of that development.

The regional groundwater model project is expected to contribute to the evaluation of strategies to deal with the above scientific and policy gaps.

### **3. Review of previous modelling studies**

Groundwater models have previously been developed for a number of sub-areas of the Canterbury Plains and there is growing interest in the feasibility of modelling the large-scale interaction of surface water and groundwater to explore water resource development options.

This section provides a brief overview of previous modelling work and summarises the lessons learnt.

#### **3.1 Numerical models**

##### **Sub-regional studies**

###### *Ashburton-Rakaia*

This early groundwater model (Scott and Thorpe 1986) was undertaken by the then Ministry of Works and Development in response to the proposal for irrigation development from surface water and groundwater in the area between the Ashburton and Rakaia rivers. The approximate extent of the model is shown in Figure 3-1. This single layer model was based on the finite difference methods described by Hunt (1976) and explored the use of flow net analysis as a basis for determining the distribution of transmissivity for model calibration. Scott (1992) later demonstrated that the flow net analysis (which essentially provided a type of regularisation) was of somewhat limited value.

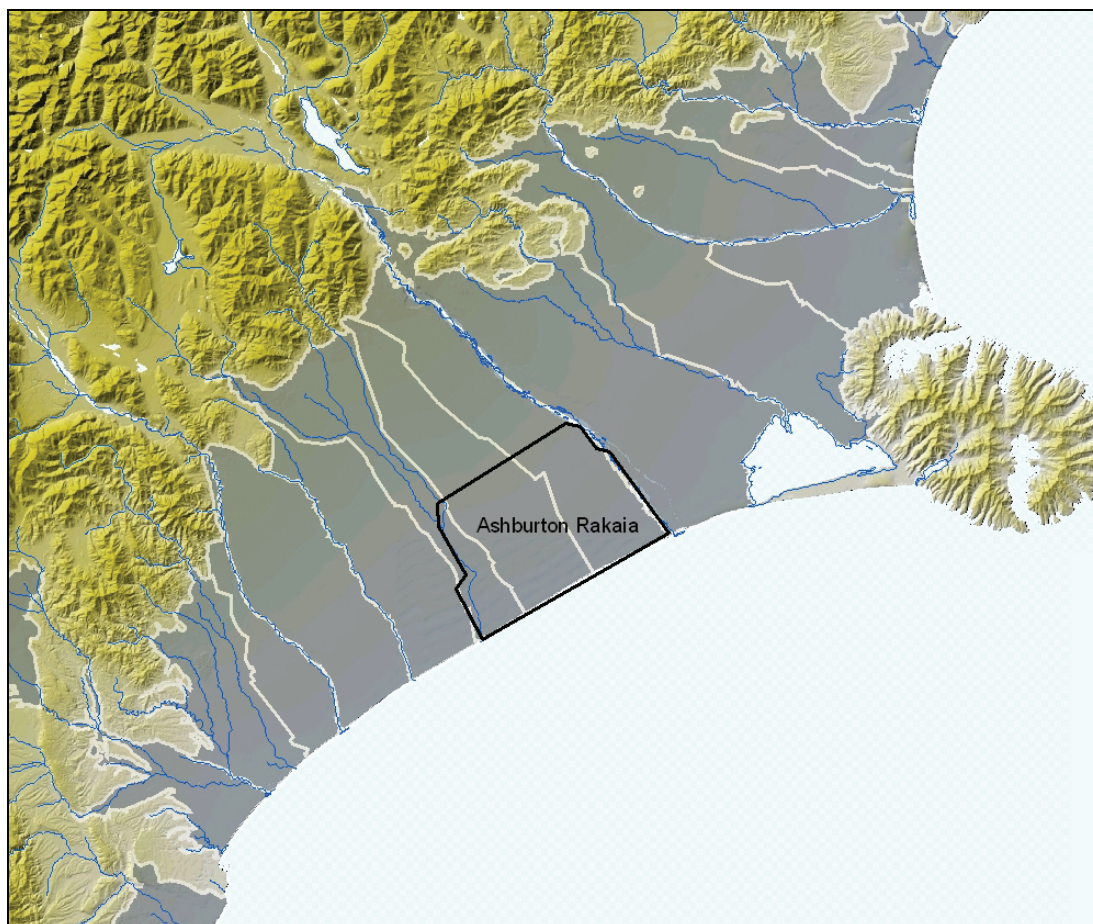
The modelling study used a simple soil moisture budget model to calculate rainfall recharge and estimate potential irrigation demand. Model results were interpreted to provide an indication of the changed reliability of supply for existing bores for various development options. The study results were subsequently subjected to a post-audit by Murray (1989) who attempted to replicate the results using the USGS MODFLOW model (McDonald and Harbaugh 1988) and highlighted the unsatisfactory mass-balance errors in the earlier modelling work. The description of the overall water balance and the description of changes to reliability of supply are arguably the lasting value of this work.

Lessons learned from this study include:

- the difficulty of re-evaluating a model for post-audit (or update) particularly when an alternative model code is involved;
- the advantages of using industry standard methods (e.g. the USGS MODFLOW model)<sup>4</sup>;
- the need to include a third dimension (depth) to represent observed head profiles;
- the value of formal reporting of model study and vulnerability of institutional archiving – the published report (Scott and Thorpe 1986) is the only effective remnant of this work, the government agency that undertook the project (Hydrology Centre, Ministry of Works and Development) having since been disestablished;
- the possibility and value of inferring reliability of supply for individual bores from a regional flow model;
- difficulties created by using inappropriate boundary conditions (i.e. specified gradient).

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<sup>4</sup> But note that this work was undertaken prior to the release of the first version of MODFLOW.



**Figure 3-1: Approximate extent of Ashburton-Rakaia groundwater flow model.**

#### *Christchurch - West Melton*

This groundwater model (Scott 1996) was undertaken primarily to evaluate the effects of increasing groundwater abstraction on groundwater-dependent flows in Christchurch urban streams. The extent of the model is shown in Figure 3-2. The USGS MODFLOW model was used together with the PEST parameter estimation technology to assist with model calibration and sensitivity analysis.

The model was developed without the use of a commercial graphical user interface. Fortran programs and batch-processing techniques were developed to allow convenient testing of parameter values and the use of automated calibration techniques. The aquifer was represented as a multi-layered system and MODFLOW's VCONT arrays used to implicitly include the effect of coastal aquitards.

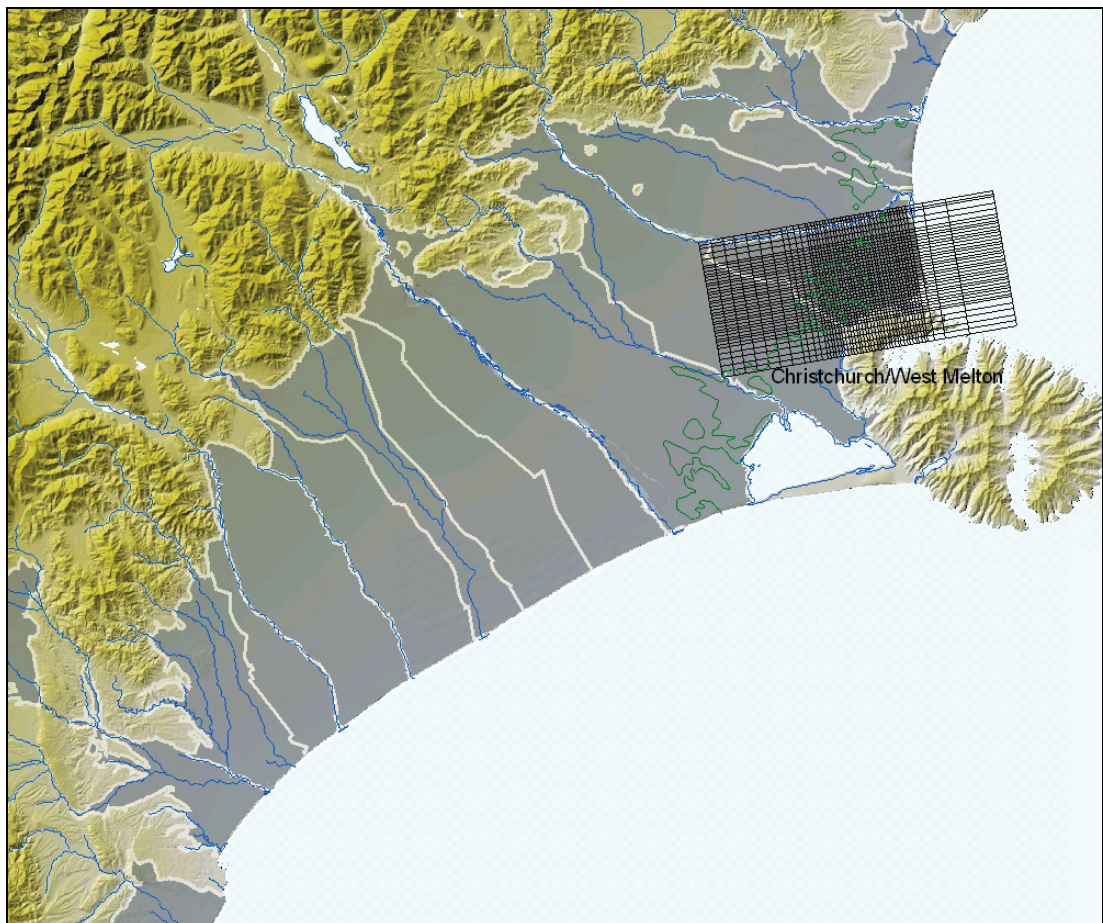
A detailed water use history was constructed from measured urban use, estimated industrial use and simulated irrigation water use. Future development scenarios considered the effects of scaling up the current spatial pattern of water use to consider the resulting change of reliability of groundwater-dependent urban stream flows (Scott 2001). Alternative future climate patterns were represented by considering three alternative re-sorted sequences of the historic climate record. The model was also used to consider the effects of further urbanisation through the loss of permeable area and the effectiveness of artificial recharge to augment groundwater supplies (Little and Scott 1999).

Application of the model revealed the different perspectives and expectations of resource analysts and planners which eventually led to the use of response function concepts to explore, evaluate and describe the potential effectiveness of real-time controls on groundwater abstraction (Scott 2003).

One of the particular values of the study has been the perspective provided by the water budget history. This is currently being updated with the intention of re-calibrating the model using more sophisticated methods. Initial re-calibration trials using a revised approach to regularisation appear to be promising but the limited spatial extent of the model domain prevents consideration of some water resource development options such as extensive river-supplied irrigation development in the Central Plains which is currently proposed in the area between the Rakaia and Waimakariri rivers.

Lessons learned from this study include:

- hydrologists, planners and decision makers can have very different perspectives and expectations about the use of models;
- the difficulty of conveying information about probability to decision makers;
- the limitations of relying on historical climate to simulate future scenarios;
- the need for procedures for data assimilation as opposed to ad hoc approaches;
- the value of data assimilation associated with model development in providing a broad overview of the water balance.



**Figure 3-2: Extent of Christchurch - West Melton groundwater flow model.**

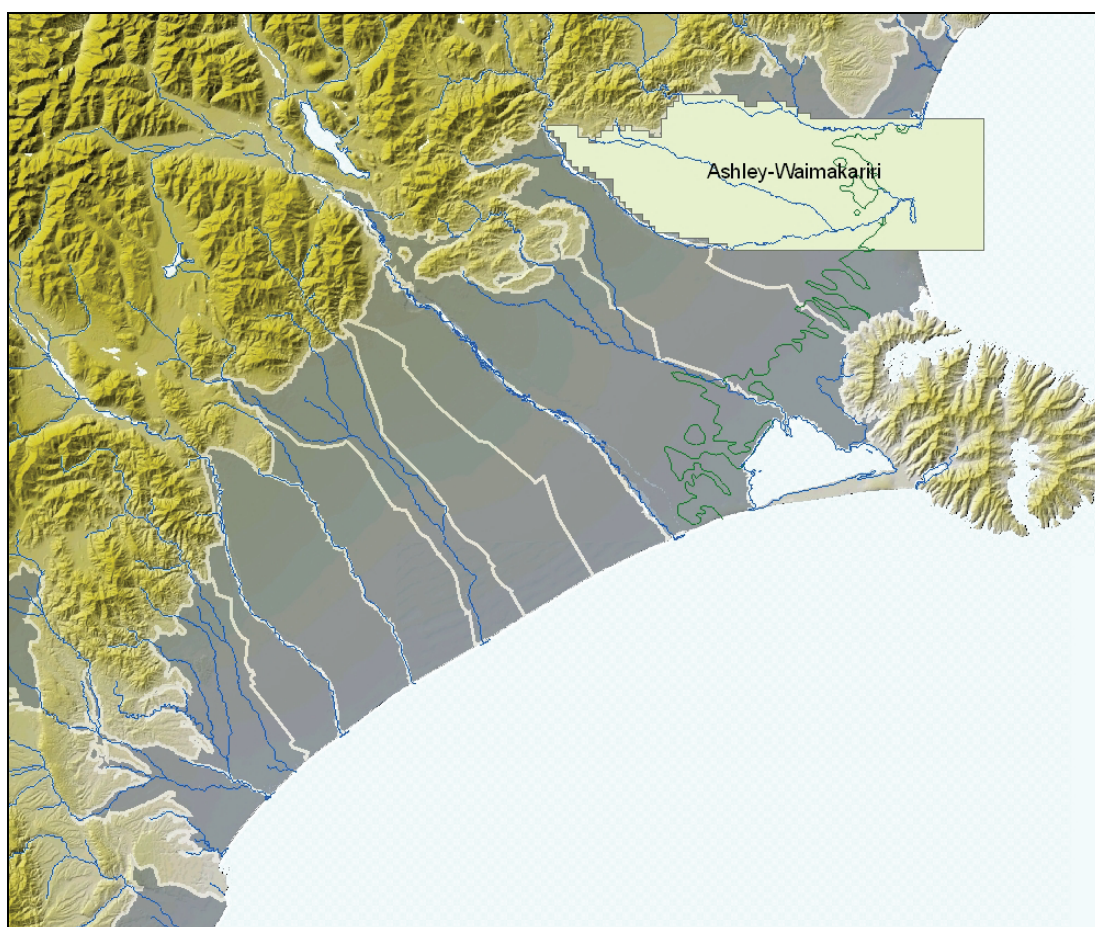
### *Ashley-Waimakariri*

Development of this groundwater model was commenced as part of a groundwater resource study intended to develop groundwater management policies (Sanders 2001). The extent of the model is shown in Figure 3-3. The Visual MODFLOW package was used to represent a multi-layered system with explicit representation of aquitards in the coastal margin of the model. A detailed analysis of the history of irrigation development in the area was undertaken to synthesise a record of irrigation water use.

Model calibration was undertaken manually and development was interrupted when the principal investigator ceased his employment with Environment Canterbury. Development of surface water-supplied irrigation in the area appears to have relieved some of the pressure on groundwater resources and shifted Environment Canterbury's priority to the consideration of groundwater issues in other areas within Canterbury.

Lessons learned from this study include:

- the value of using a graphical user interface (GUI) such as Visual MODFLOW (despite its limitations in handling extended time series model inputs);
- the vulnerability of a model project to staff changes;
- the value of data assimilation in providing a hydrological overview.



**Figure 3-3: Extent of Ashley-Waimakariri groundwater flow model.**

There have been other sub-regional groundwater modelling studies undertaken for parts of the Canterbury Plains (e.g. Anderson 1994, Thorley et al. 2005). However the three studies outlined above illustrate some of the key lessons learned from these spatially constrained approaches.

### **Regional studies**

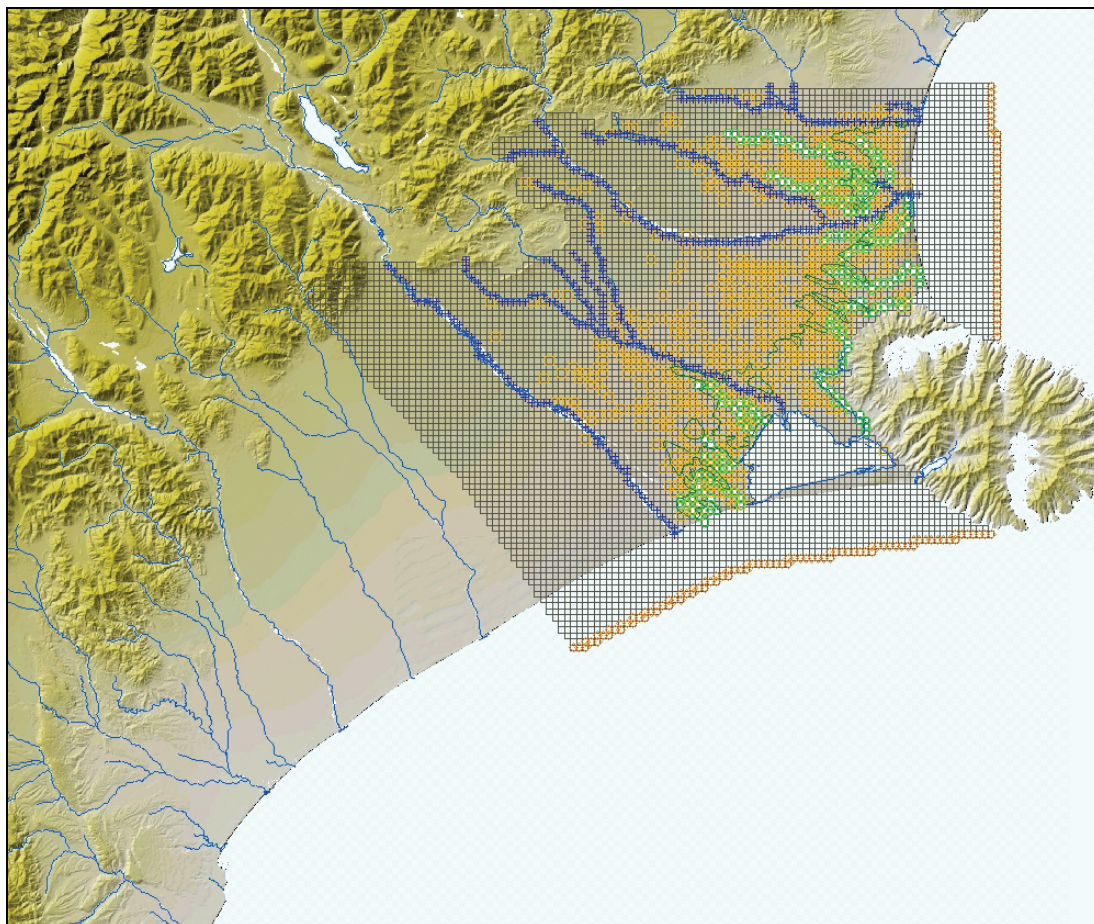
#### *Rakaia-Ashley*

This study was originally initiated as a research project with the objective of integrating related work on recharge processes (rainfall and river) and groundwater quality (chemical and isotope) and to demonstrate the potential for larger scale modelling. The project was initiated by the Institute of Geological and Nuclear Sciences (GNS) and undertaken in collaboration with the University of Otago and Environment Canterbury and funded, in part, by the Foundation for Research Science and Technology (FRST). The extent of the model is shown in Figure 3-4. The USGS MODFLOW model was employed with the GMS interface but with significant external data pre-processing and post-processing (Murray 2001a).

The project demonstrated the feasibility of a large-scale model and the potential to use the telescopic grid-refinement technique to consider localised issues (Murray 2001b). Groundwater age measurements were used to assist model calibration (White et al. 1999, White et al. 2001). Though the model was not fully calibrated it was used to undertake a preliminary evaluation of impacts on groundwater mounding that might occur as a result of a proposed large-scale river-supplied irrigation development (White et al. 2001). Work on further refinement of the model was cut short by the loss of funding from FRST and the untimely death of one of the principal collaborators (Dr Dave Murray, University of Otago).

#### Lessons learned:

- Regional scale modelling (and telescopic mesh refinement) is feasible;
- Potential utility of a model while it is still under development;
- Vulnerability of a project dependent on Central Government funding through external research provider;
- Critical role of key workers and the need for spreading of risk;
- Need for on-going documentation.



**Figure 3-4: Extent of Rakaia-Ashley groundwater flow model.**

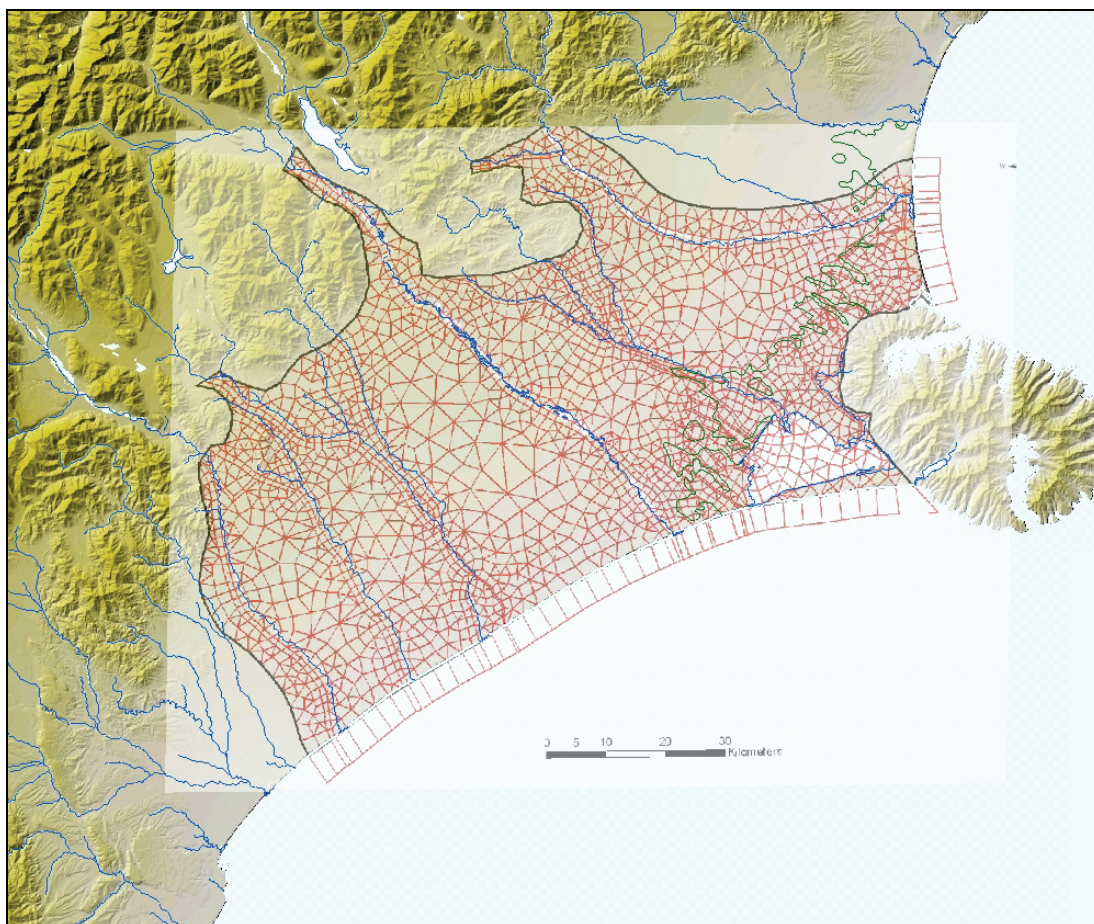
#### *Rangitata-Waimakariri*

This modelling study emerged from stakeholders' concerns about the sustainability of groundwater development either side of the Rakaia River and initially attracted funding support from local, regional and national government agencies. The decision to develop a regional model reflected an awareness of the need to consider surface water/groundwater interaction on a large scale – particularly in light of some of the water resource developments on the horizon. The extent of the model is shown in Figure 3-5 (Weir 2007).

The FEMWATER code was employed with the GMS interface. A new capability to describe river/groundwater interaction was developed with the support of public good science funding. This particular development eventually became the property of the privately owned consulting company which was formed during model development. The modelling approach included the simulation of flow within the vadose zone which resulted in very extended model run times (4 to 6 weeks to simulate a 40-year period). Though Environment Canterbury initially contributed to the project subsequent applications of the model to support resource consent applications has led to a more adversarial relationship. Apart from the extended run times the model has proven to have other technical deficiencies: for example the model has limited ability to calculate water budget components.

Lessons learned:

- Need for open access to models to be negotiated and agreed before work commences;
- Need for effective authority over technical directions;
- Need for in-house development for future use;
- Excessive model run time constrains model calibration and sensitivity analysis and limits scenario testing.



**Figure 3-5: Extent of Rangitata-Waimakariri groundwater flow model.**

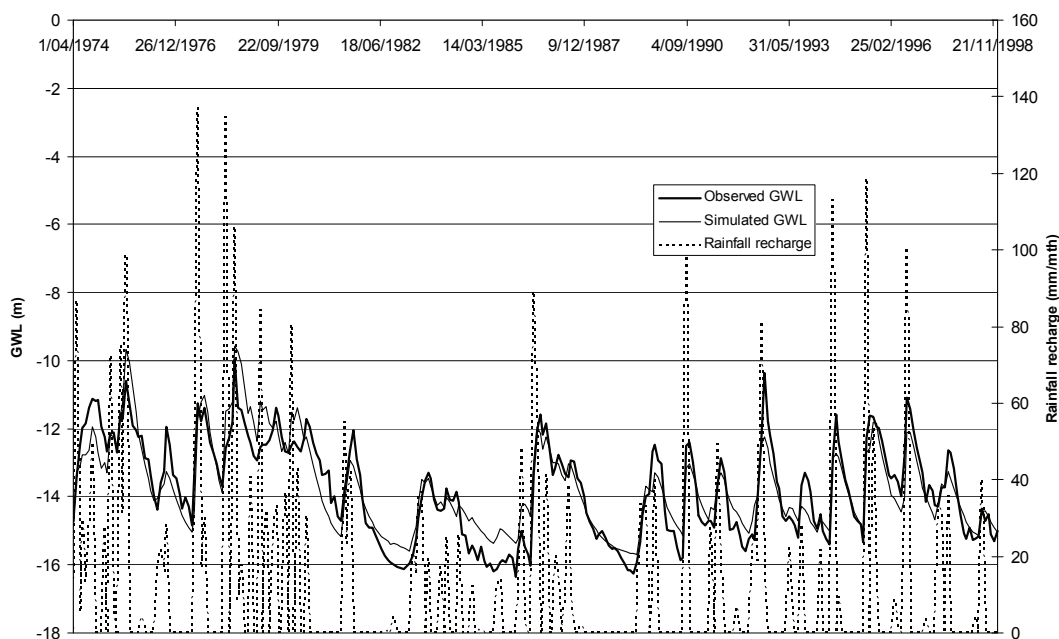
## **3.2 Related modelling work**

### **Soil moisture budget models**

All of the groundwater flow models referred to above have used independent soil-moisture budget methods to calculate land-surface recharge and, in several cases, to provide a basis for synthesizing groundwater abstraction. Simple moisture models have been evaluated using lysimeter drainage records (Thorpe and Scott 1999) and the potential for innovative approaches using neural networks and genetic algorithms has been explored (White et al. 2003, Hong et al. 2005).

### Time series analysis

Bidwell (2003) has demonstrated the use of the eigenmodel<sup>5</sup> for simulating groundwater behaviour. The model uses calculated land-surface recharge as an input - the very good agreement between observed and simulated groundwater levels achieved by the model (e.g. Figure 3-6) provides confirmation that the temporal pattern of the calculated recharge is reasonable.



**Figure 3-6: Simulation of groundwater level response to calculated rainfall recharge using the eigen model for a particular well (Bidwell pers. com.)**

### 3.3 Discussion

The aim of the Canterbury Plains regional groundwater model is to provide Environment Canterbury with a basis for the development of future groundwater management strategies. The methodology adopted for the modelling work will establish a framework for data assimilation and support the testing of alternative hydrogeological concepts while at the same time allowing simulation of alternative management options. In terms of the lessons learned from previous studies the planned approach is expected to:

- reduce the fragmentation and duplication of effort in assembling model inputs by developing systems for routine data assimilation;
- maintain in-house knowledge by establishing a modelling team and documenting procedures for all components of the project;
- explicitly deal with the inherent uncertainty of model predictions by adopting advanced model calibration and sensitivity and uncertainty analysis.

<sup>5</sup> Bidwell (2003) coined the name "eigenmodel" from the German term "eigen-" meaning "characteristic" in mathematical theory. The approach is derived from the partial differential equations of groundwater flow and involves the use of eigenvalues and eigenvectors to represent a complex linear system.

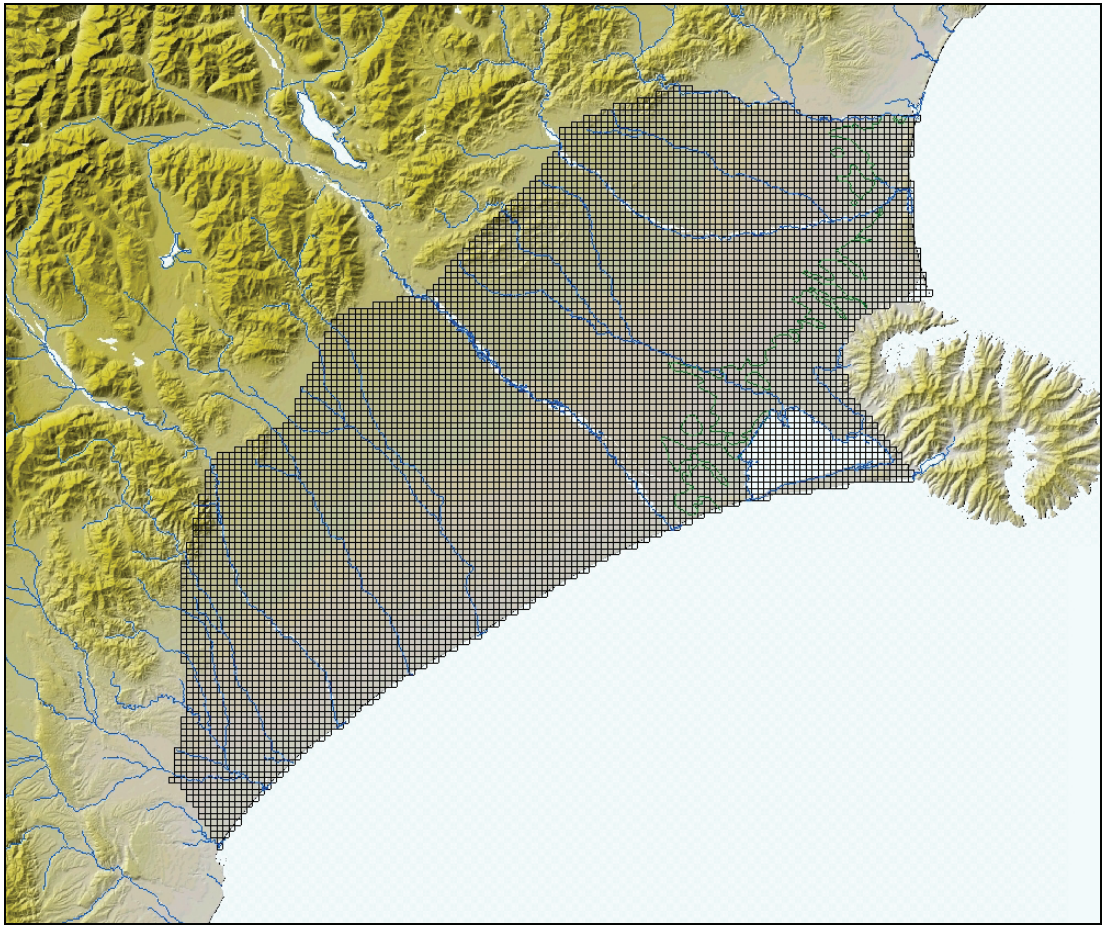
This project intends to produce more than a groundwater model. The broader goal is to develop groundwater management tools (plans, rules, strategies etc.) and the modelling project is seen as supporting that by providing:

- a framework for data assimilation;
- a basis for testing (and subsequently explaining) hydrogeological concepts;
- a means for simulating (and also subsequently explaining and demonstrating) alternative scenarios.

This approach to groundwater modelling is based on the following propositions:

- a major benefit of a groundwater modelling study is the improved understanding gained in the process. Hence it is desirable for that work to be done in-house to ensure that the organisation gains a lasting benefit;
- model predictions are inherently and unavoidably uncertain and it is necessary to make these uncertainties explicit and quantifiable. This involves a heavy computational burden which is made manageable by the use of advanced automatic calibration methods and is made feasible by the use of network computing;
- modelling work should be regarded as an on-going activity which is able to be adapted to new information and new priorities. Hence the need to codify and document procedures to allow the work to be continued by others;
- Model development should proceed in a way that reflects the relative confidence of all prior information. In the context of the Canterbury Plains groundwater systems the following hierarchy of prior information appears reasonable (from higher to lower certainty):
  - groundwater levels – temporal and spatial variability;
  - no flow boundaries – foothills and Banks Peninsula;
  - rainfall recharge inputs – temporal and spatial variability;
  - spatial limit of coastal aquitards;
  - groundwater abstraction history;
  - upper limits to river recharge;
  - groundwater discharge through the coastal boundary.

Progress to date on developing and applying this approach is described in the first technical progress report (Moore and Scott 2008) and uses the model domain illustrated in Figure 3-7 to provide a broad description of the groundwater flow regime in the interconnected Canterbury Plains alluvial groundwater system stretching from the Ashley River/Rakahuri to the Levels Plain in South Canterbury. A revised version of the model will extend beyond the coast using an equivalent freshwater head approach to allow more realistic simulation of groundwater levels close to the coast. At the same time the model's inland boundaries will be refined but it will remain essentially a model of the Canterbury Plains i.e. the South Canterbury, Waitaki and inland basin groundwater allocation zones will not be included.



**Figure 3-7: Extent of the regional groundwater model domain and grid.**

## 4. Modelling approach

To address the key problems faced in the use and management of Canterbury's groundwater resource (discussed in Section 2.5), and to avoid the problems associated with an ad hoc modelling approach to these issues (as discussed in Section 3), a region-wide groundwater modelling project has been embarked on. The project involves a large-scale regional groundwater model, with subsequent sub-model development occurring as further detail is required. It is intended that the regional groundwater modelling project will become part of Environment Canterbury's information database as well as being used to explain the groundwater system and its components and allow wider community participation in the examination and testing of model simulations.

This section discusses the general approach adopted for the regional groundwater model. This is based on the recognition of the following factors:

- prediction uncertainty is inherent in modelling;
- that uncertainty should be transparently addressed through the use of automated calibration and sensitivity analysis techniques;
- the improved understanding of the hydrogeological system that is gained from undertaking the modelling study is likely to be of greater value than the specific predictions;
- the data assimilation required for model development has an inherent value that supports resource monitoring and management.

The following discussion is structured using a series of typical and frequently asked questions regarding groundwater modelling methodology.

### 4.1 General

#### **Why should we construct such a model in this situation?**

Numerical models are built to better understand how complex groundwater systems behave and to better understand how those systems will respond to changes, i.e. to provide predictions. Such predictions could include how the groundwater system will respond to forecast drought conditions, or how the aquifer will respond to changes in its management. Even if a prediction is not explicitly stated, questions and hypotheses regarding the groundwater system are inherent in any modelling project, which implicitly involves some type of prediction.

Numerical modelling offers the necessary support required for consideration of alternative environmental management decisions.

#### **Why should we calibrate a model?**

The purpose of calibrating a model is to make more reliable predictions than if it had not been calibrated. Calibration involves iteratively adjusting the model parameters used to describe the real-world hydraulic properties until model outputs match field measurements. Typical measurements used in a groundwater flow model calibration include water levels, flows and sometimes groundwater age or concentration data. Given the importance of the region's groundwater resources, predictions should be as reliable as possible and hence calibration effort is warranted. Note however that the predictions made even with a calibrated model are still uncertain, as discussed in Section 4.2.

### **What calibration methodology should we use?**

Model calibration, or parameter estimation, can be undertaken manually with trial and error model runs. Alternatively software can be used to automate the calibration process to identify optimal parameters that allow model outputs which best fit field measurements. Figure 4-1 provides a schematic view of the model calibration process.

The use of automated calibration software has a number of benefits:

- it provides an objective basis for the choice of optimal parameters;
- the pain of undertaking a boring manual task is reduced;
- it is generally faster in reaching an optimal set of parameters;
- the information provided from the automatic parameter process, such as parameter correlation and/or resolution is highly informative of the reliability of the parameter estimates and any predictions made on the basis of those parameters.

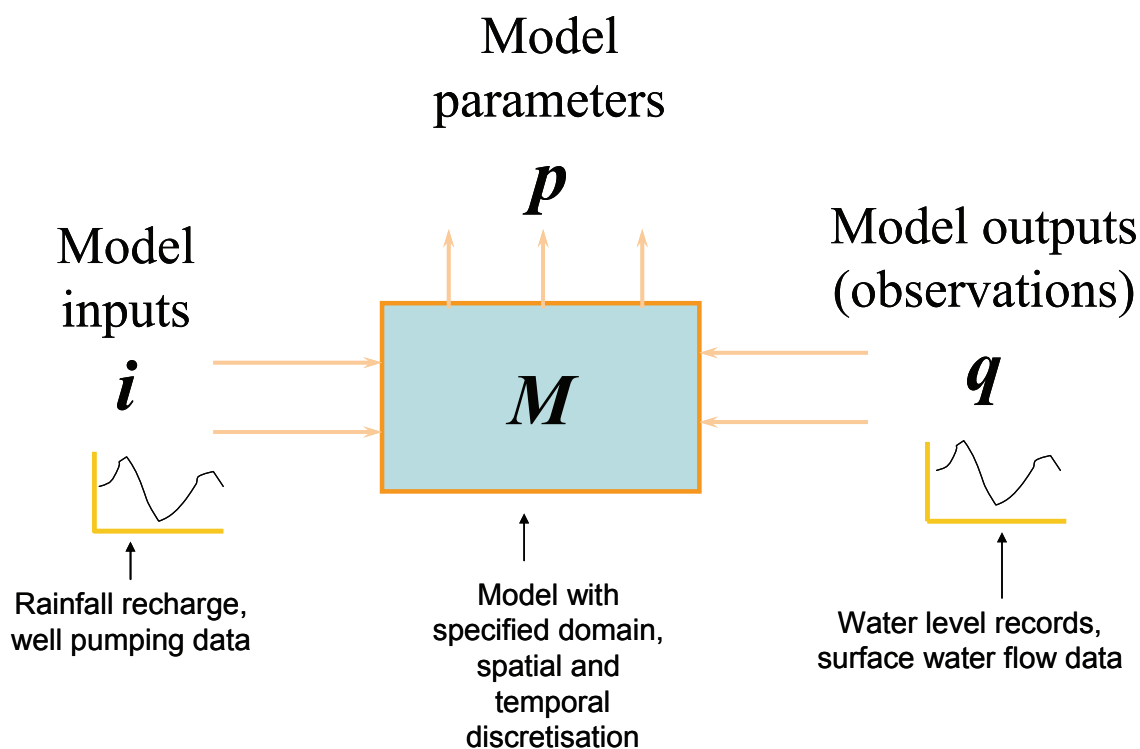
The fastest automatic calibration methods are built on a gradient-based parameter estimation algorithm (e.g. Gauss-Marquardt Levenberg). This method is generally robust for groundwater modelling problems. However where a modelling problem encounters local minima in objective function space, or the model derivatives cannot be continuously defined, global optimisation algorithms offer a generally robust alternative, but at the cost of far greater computational effort.

The parameter estimation software PEST has been adopted for this project (Doherty 2007a). PEST offers both gradient and global optimisation based parameter estimation, and a myriad of other capabilities, and is widely considered the best the industry has to offer. Of particular benefit to this study are the following three capabilities:

- PEST's implementation of mathematical regularisation - particularly SVD-Assist regularisation<sup>6</sup>;
- State of the art predictive uncertainty methodologies which are being implemented in PEST as they are developed, making this the best tool on the market for the solution and analysis of ill-posed problems, such as those encountered in groundwater modelling;
- PEST's parallel processing capability which allows the computational load to be shared amongst numerous processors.

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<sup>6</sup> SVD-Assist regularisation involves the use of Singular Value Decomposition which allows factorisation of the matrices that are solved when running the groundwater model.



**Figure 4-1: Schematic of the groundwater model calibration process used to infer model parameters.**

### What will the calibrated model represent?

The expected outcome of a model calibration exercise is a unique set of parameters which can be considered to represent the real-world system. In order to achieve a unique set of parameters to calibrate the model, real-world hydraulic property detail must be vastly simplified in the model representation. This simplification is required because there are almost always insufficient data to estimate parameters at a level of detail which is consistent with real-world hydraulic property complexity. Traditionally this simplification has been achieved by using zones of constant parameter value and adhering to the ‘principle of parsimony’ (Hill 1998), whereby modellers strive to parameterise their model with no greater parameter detail than is required to fit the measured data. However this practice causes a number of problems when the model is then used for predictive purposes (for further discussion see for example Hunt et al. 2007, Moore and Doherty 2006).

Recent advances in parameter estimation and model parameterisation methods<sup>7</sup> now provide a mathematical basis for the real-world simplification that must be applied to obtain unique parameter estimates. In addition (as is discussed later) these new methods assist in defining the effect that parameter simplification has on predictive uncertainty. Mathematical regularisation is the term for these mathematical simplification methods (Doherty 2003).

When used correctly mathematical regularisation allows maximal information content from the measurements to be extracted in the calibration process. Its use

<sup>7</sup> Parameterisation defines how parameters are represented in a model; parameter estimation refers to how parameters are calculated.

ensures that the model representation of the real world is simplified to the level at which parameters can be estimated uniquely, but no further. The benefits of mathematical regularisation are achieved by incorporating a multitude of parameters in the formulation of the calibration process (for example those defined as ‘pilot points’). Using a multitude of parameters allows the model to represent real-world detail, and the estimated parameter detail is then simplified via the regularised inversion process in a manner that is best indicated by the data<sup>8</sup>. The flexibility of this method allows not only the parameter values to be determined in the calibration process, but also the disposition of those parameters.

No matter what calibration strategy is used (traditional zone-based parameter parsimony, or regularised inversion) the outcome of a uniquely calibrated model will always be parameter fields which are vastly simplified versions of the real-world hydraulic properties. This leads to the next question which is concerned with the impact of this simplification on our ability to make accurate model predictions.

## 4.2 Model prediction uncertainty

### **If our model is calibrated why are our model predictions inaccurate?**

Simplification of the real-world hydraulic property detail in the calibrated model parameter fields is one of the most significant causes of prediction uncertainty for groundwater water models. This source of error is often very large, even if the outputs of our calibrated model perfectly reproduce the field measurements. This simplification based error occurs whenever the prediction is sensitive to the hydraulic property that is absent in the calibrated model parameter fields. For example, a pumping test drawdown prediction, or a stream depletion prediction made on the basis of data gathered in area A of a model, will almost certainly be in error when extrapolated to area B of the model (for which there are no data to support parameter detail).

Additional sources of model prediction error are measurement errors and model conceptualisation and structural errors. Measurement errors determine the accuracy of calibration targets, and are propagated through the model structure to form parameter and prediction errors. Model conceptualisation and structural errors include the definition of model boundaries, model input data, and model spatial and temporal discretisation.

### **Should we be concerned about predictive uncertainty analysis - why should we bother with it?**

As explained above, predictive uncertainty is an unavoidable part of groundwater modelling, even where a model output provides perfect fits to measured data. However the notion that modellers should attempt to analyse and report this uncertainty is relatively new. It is now considered best practise to undertake such analyses for the reasons listed in Pappenberger and Beven (2006), namely:

- it makes one think about the imprecision of the modelling process and how this imprecision may affect the performance of the decisions based on our modelling results;
- it makes the predictions of different experts more comparable and allows transparent assessment of the science behind the predictions;

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<sup>8</sup> The first technical progress report (Moore and Scott 2008) provides details on how regularised inversion has been implemented in this project.

- it allows for more fundamental retrospective analysis through model post-audit and allows new or revised decisions to be based on the full understanding of the problem rather than a partial snapshot;
- decision makers and the public have the right to know all limitations of such modelling work in order to make up their own minds and lobby for their own individual causes.

Pappenberger and Beven (2006) also address the common criticism that, because any application of an uncertainty estimation methodology requires that certain subjective assumptions be made, uncertainty analyses are themselves too subjective. They point out that the converse, which is to not undertake such an uncertainty analysis, implies that the modelling undertaken is objective; which is evidence of misplaced faith in physically-based modelling. To address this subjectivity modellers should aim to be transparent in their reporting of the assumptions used in an uncertainty assessment, so that they can be assessed and discussed. For this reason, every endeavour will be made by Environment Canterbury to accurately report the assumptions adopted in the regional groundwater model, including the predictive uncertainty analysis phase.

Predictive uncertainty analysis is important for political reasons alone but also because of the scrutiny that an Environment Canterbury model would need to withstand in the public consultation and legal hearing arenas. The explicit acknowledgement of model short-comings will assist in focussing any particular issues raised; for example, if specific model assumptions are challenged these can then be revisited. Equally important, predictive uncertainty analysis assists with:

- tailoring the model development (and data gathering) process to minimise the uncertainty of model predictions;
- assisting in the making of environmental management decisions.

Uncertainty analysis also allows managers to identify those model questions that can be answered reliably and those that cannot. If the formulation of management options is associated with an unacceptably high degree of predictive uncertainty, these management options may be reformulated to provide a greater degree of certainty. Examples of this are given in Section 5.2.

### **How can we describe the error of our model predictions?**

Classical regression-based predictive uncertainty analysis methods describe the uncertainty of predictions on the basis of model-to-measurement misfit alone. However, as is well documented (e.g. Cooley 2004, Moore and Doherty 2005, Tonkin et al. 2007), it is inappropriate to apply these methods to groundwater models. In contrast, Monte Carlo methods describe the full predictive error that occurs from model simplification and model-to-measurement misfit. Calibration constrained Monte Carlo analyses, as they are traditionally undertaken, require significant computer time.

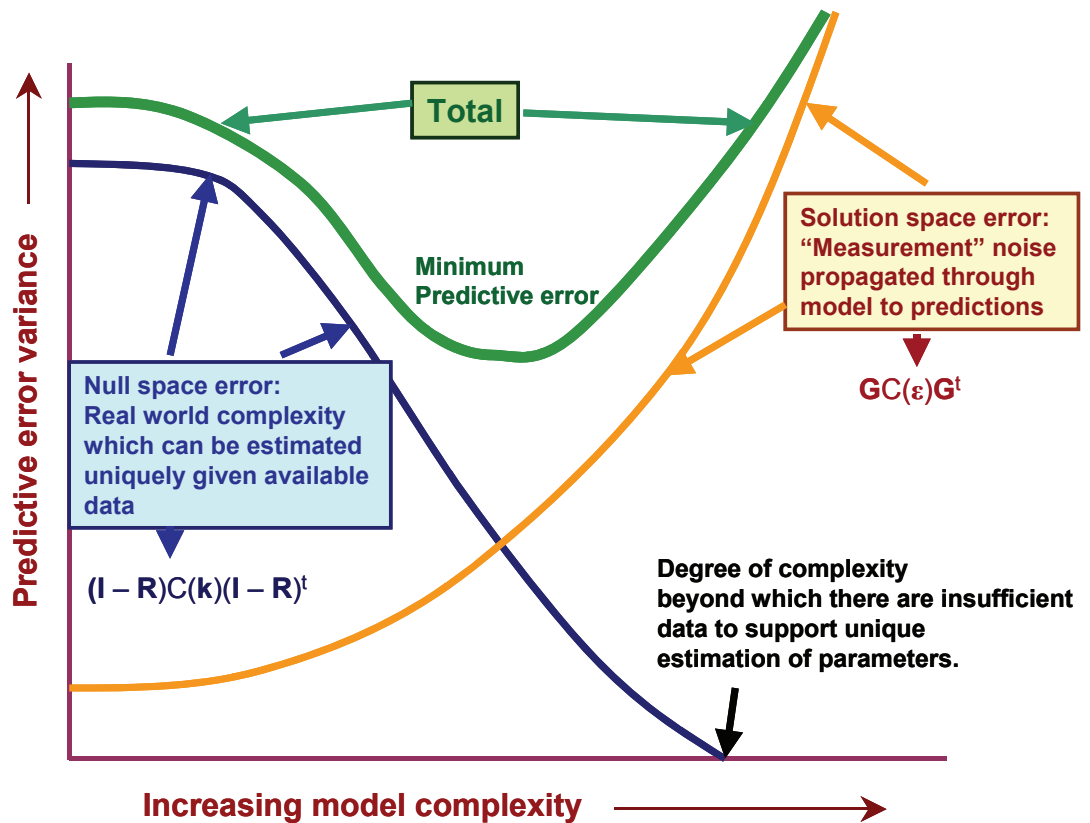
Reformulation of these uncertainty analyses via incorporation of mathematical regularisation techniques has recently been undertaken (Moore and Doherty 2005, Hunt et al. 2007, Tonkin et al. 2007, Doherty 2007b). The outcomes of these reformulations include quick, easy to use regression-based predictive uncertainty analyses which are robust for groundwater models, and Monte Carlo methods which can be undertaken for a fraction of the computational effort that was previously required. In addition, a significant benefit of these techniques is their flexibility, allowing the quantification of predictive uncertainty resulting from uncertain model

inputs that are usually considered known, e.g. boundary conditions or recharge inputs. This project aims to take advantage of these recently developed methods.

**How complex should the model be when considering uncertainty?**

The above discussion considered how data places a limit on the parameter detail or complexity that can be represented in a model and also how a model prediction can be sensitive to greater parameter detail than the data can support. Both of these considerations can be used in determining the level of model complexity.

Such considerations are a marked contrast to those used in the early days of computer-assisted mathematical modelling (e.g. 1970s and 1980s), where appropriate complexity was determined by the computing resources available. There was a naive expectation at that time that the only limit to the potential power of numerical groundwater models was inadequate computational resources. However, as the processing power of computers has vastly increased, it has become clear that the modern limit to the level of real-world process detail able to be simulated by a numerical groundwater model is imposed by the inadequacies of the data<sup>9</sup>. Optimal model parameter complexity can be defined via the trade-off between model prediction error resulting from real-world simplification, and the measurement errors propagated through the model structure as depicted in Figure 4-2 where optimal model complexity is defined by the complexity at which a prediction can be made with minimal error. Clearly, if they are to be made as accurately as possible, different model predictions are likely to require different model complexities.



**Figure 4-2: Relationship between model complexity and predictive accuracy.**

<sup>9</sup> Halford (2004) editorialises that “Relevant, additional data are more likely to dispel ignorance, rather than further simulation”.

Building a very complex model, where estimated parameters represent a real-world simplification that could be provided by a simple model, provides no benefits in terms of system representation. If regularised inversion is used, a model can be parameterised at a level of detail beyond that which can be represented in the calibrated parameter fields. This is in contrast to the situation where zones of constant parameter value are used to parameterise the model, as their use fixes both the parameterisation detail and the calibrated model parameter complexity at the same level, before calibration commences.

It is this ability of regularised inversion to define a different level of parameterisation detail (or complexity) than may be represented in the calibrated parameter field which has significant benefits for predictive uncertainty analyses. This is particularly so where the model prediction is very sensitive to a level of real-world detail, beyond which can be supported by the data. If the model is parameterised to a level of real-world detail on which the prediction depends, the model has then been constructed to be sensitive to this detail, even despite its simplified calibrated parameter field. Thus this important predictive detail, which cannot be uniquely represented in the calibrated parameter field, can still be accounted for in a predictive uncertainty analysis.

In this work, the choice of model parameterisation complexity is governed by these two considerations, viz. data availability and prediction uncertainty.

#### **Can data acquisition efforts be guided by consideration of increasing the accuracy of a model prediction?**

It is possible to compare the worth of disparate data types at a full range of locations in terms of how that data (if collected) would reduce the uncertainty of a model prediction - as described in Moore (2005). This ancillary use of the modelling work discussed herein, to guide data acquisition efforts, adds significant value to these modelling efforts. This type of pre-collection analysis is possible, as the actual data value (e.g. water levels or flow rates) does not need to be known to determine how the uncertainty of a prediction will be reduced, should the data be obtained.

#### **Using uncertainty to assist identification of best management options**

Typically the range of options available to manage a region's resources is theoretically unlimited, and considerations of both the physical and practical aspects of the resource systems are used to select the most viable of the many options. One such consideration that can be used is assessment of which model components contribute most to the uncertainty of a prediction. Another consideration is how reliably (or uncertain) can a management option prediction be made. As demonstrated by Doherty and Gallagher (2006) some management options can be simulated with a great deal more certainty than others. If more reliable management options are selected their effectiveness in the real world is also more likely. An example of this use of predictive uncertainty analysis is outlined in Section 5.2.

### **4.3 Optimisation methods**

Where appropriate, multi-objective optimisation methods can be used to clarify the best of a suite of management options as they allow consideration of the trade-off in alternative management options. Multi-objective optimisation methods such as the AMALGAM method described in Vrugt and Robinson (2007) and Wohling et al.

(2008) may have a role in future phases of the regional groundwater modelling project. Once optimisation procedures have been used, predictive uncertainty methods will be used to describe the uncertainty related to the optimal solution.

#### **4.4 Response functions<sup>10</sup>**

Response functions are defined by Johnson et al. (1998) as “analytical expressions, graphs or coefficients that describe the relative response of the groundwater system at a given location to a unit stress at a second location”. The use of response functions is based on the principle of superposition which is described by Reilly et al. (1987) as applying to linear systems where “the solution to a problem involving multiple inputs (or stresses) is equal to the sum of the solutions to a set of simpler individual problems that form a composite problem”. Superposition is routinely used in conjunction with analytical models of groundwater flow where the linearity requirement is often satisfied. Numerical models commonly include non-linear elements; however in appropriate circumstances it is possible to construct and use a model in a way that minimises the effect of those non-linearities (Hubbell, et al. 1997).

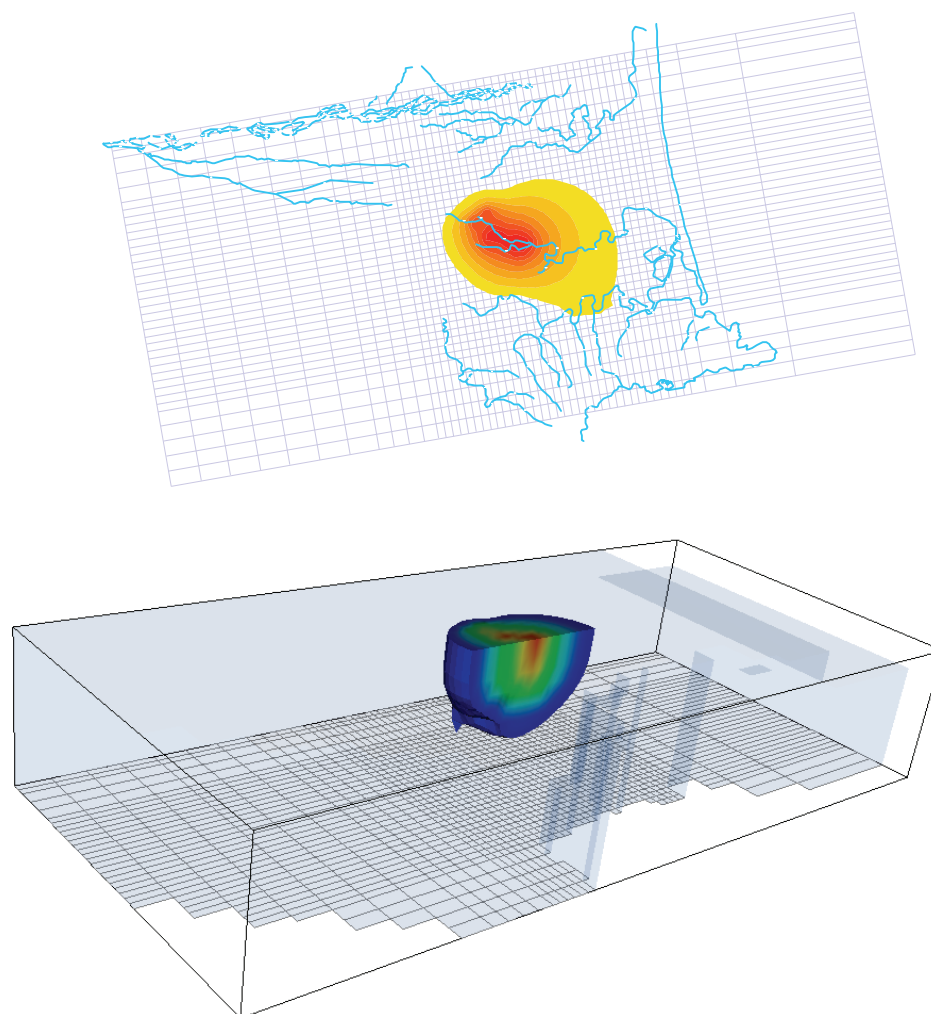
Where response functions are used to examine the transient response of a system it is often sufficient to develop a single function describing the system response to a specified change in stress e.g. the effect of a step change in river level on an adjacent groundwater level. Application to spatially non-homogeneous problems requires identification of many response functions to form a response function matrix. Johnson and Cosgrove (1999) use response ratios, defined as expressing cause and effect relationships at a single point in time, to describe the effect of spatial variation of pumping on surface water flow.

Response functions were applied to the Christchurch – West Melton groundwater model (Section 3.1) and proved to be effective tools for understanding and explaining model results.

Figure 4-3 provides an example of the use of response functions to describe the relative sensitivity of river flow to short-term pumping controls. It is expected that response functions will also be useful in interpreting and explaining the results of the regional groundwater model.

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<sup>10</sup> This description of response functions is taken from Scott (2003).



**Figure 4-3: Examples of the use of response function concepts. The upper plot shows the sensitivity of simulated low flows in the Avon River/Ōtakaro to the imposition of pumping constraints in the upper layer of the Christchurch – West Melton groundwater model. The lower plot presents a “sensitivity plume” developed from all five model layers (from Scott 2003).**

## 4.5 Model development

The regional modelling project will provide a broad description of the groundwater flow regime that occurs in the interconnected Canterbury Plains alluvial groundwater system. This regional scale view will allow broad-brush estimates of groundwater availability for allocation. However where issues are more localised, for example effects of abstraction on low-land stream flows, or risk of salt water entering the aquifer, the development of a sub-model will be required. The regional description of the flow regime requires the following:

- definition of the regional boundaries to this system e.g. foothill and coastal boundaries;
- definition of large river - aquifer interaction;
- definition of spring-fed stream flows;

- definition of large-scale variability of hydraulic conductivity and storativity parameters for each model layer.

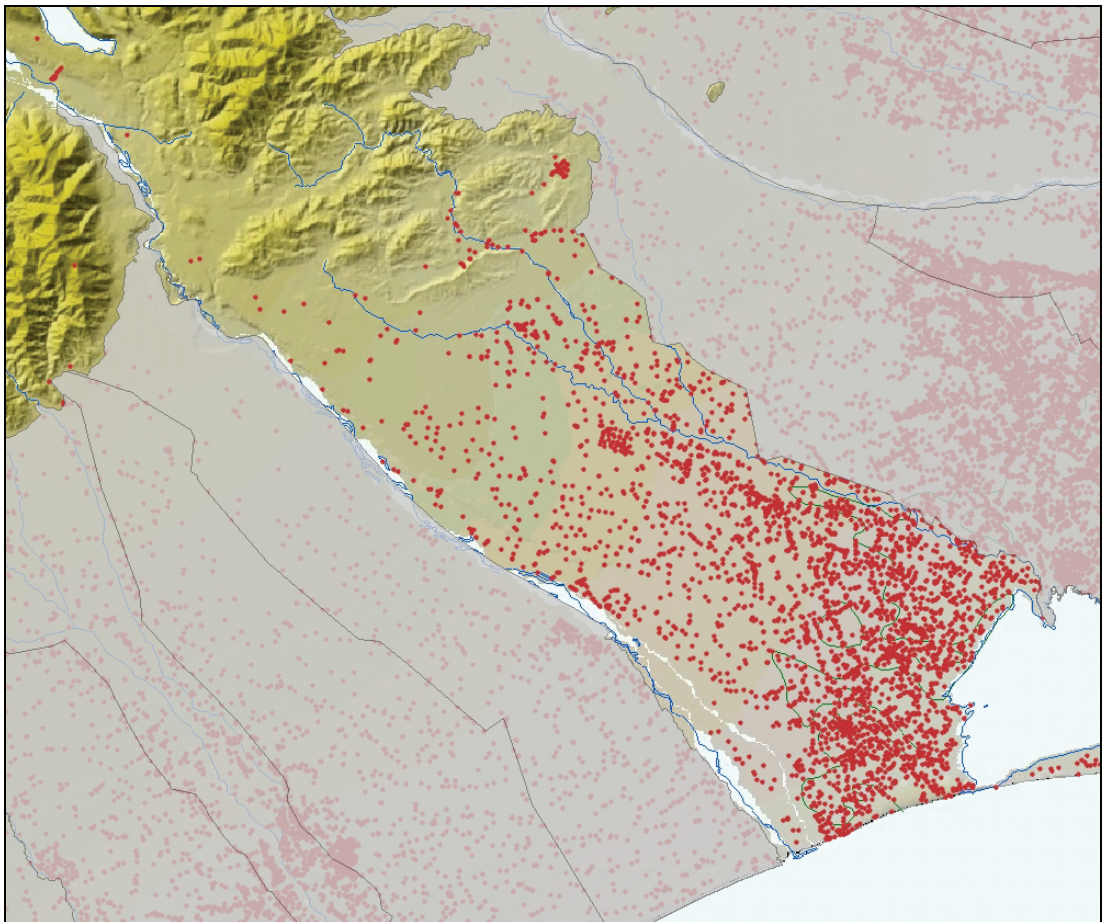
Sub-models are to be developed in areas where issues of concern are localised. Each local sub-model will be calibrated simultaneously with the regional model, so that consistency between models is maintained, while exploration of more localised aquifer management issues is undertaken. The following steps for sub-model development will be followed:

1. Definition of model purpose.
2. Definition of model prediction/predictions.
3. Construction of conceptual model of the sub-model region.
4. Construction of numerical sub-model.
5. Use linear pre-calibration uncertainty analysis to:
  - a. guide model complexity, such that the model is parameterised with sufficient detail to minimise predictive uncertainty, but not so much detail that predictive accuracy is compromised.
  - b. identify the components of the model that will contribute most to the predictive uncertainty.
6. Calibrate the model.
7. Guide data acquisition efforts where model predictive reliability can be enhanced.
8. Identify management option simulations (identify management options in consultation with Environment Canterbury staff)
9. Undertake optimisation and predictive uncertainty analyses.
10. Reporting.

## **5. Application of Canterbury Plains regional groundwater model to the development of groundwater management policies**

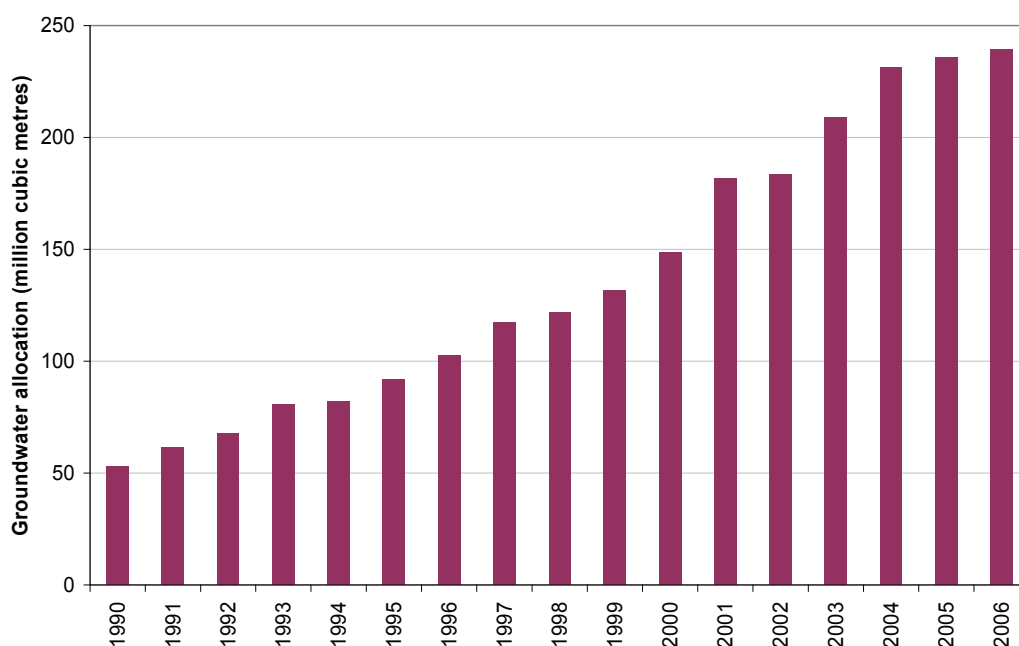
### **5.1 Issues and options for a selected groundwater management zone**

The Rakaia-Selwyn Groundwater Allocation Zone (Figure 5-1) provides a useful case example to consider how an analysis of model prediction uncertainty may be incorporated into the assessment of alternative groundwater management strategies. The Rakaia-Selwyn zone has been assessed as being highly allocated in that current allocation exceeds Environment Canterbury’s interim allocation limits. Recent applications for new permits to abstract water within the zone have been controversial and have been granted with complex conditions despite Environment Canterbury officers recommending that the applications should be declined. Elements of that decision were subsequently appealed by a number of parties and thought those appeals have been resolved the status of the zone remains a matter of considerable dispute. The fundamental question here is “to what extent has increased groundwater abstraction contributed to the observed decline in groundwater-dependent stream flow?”

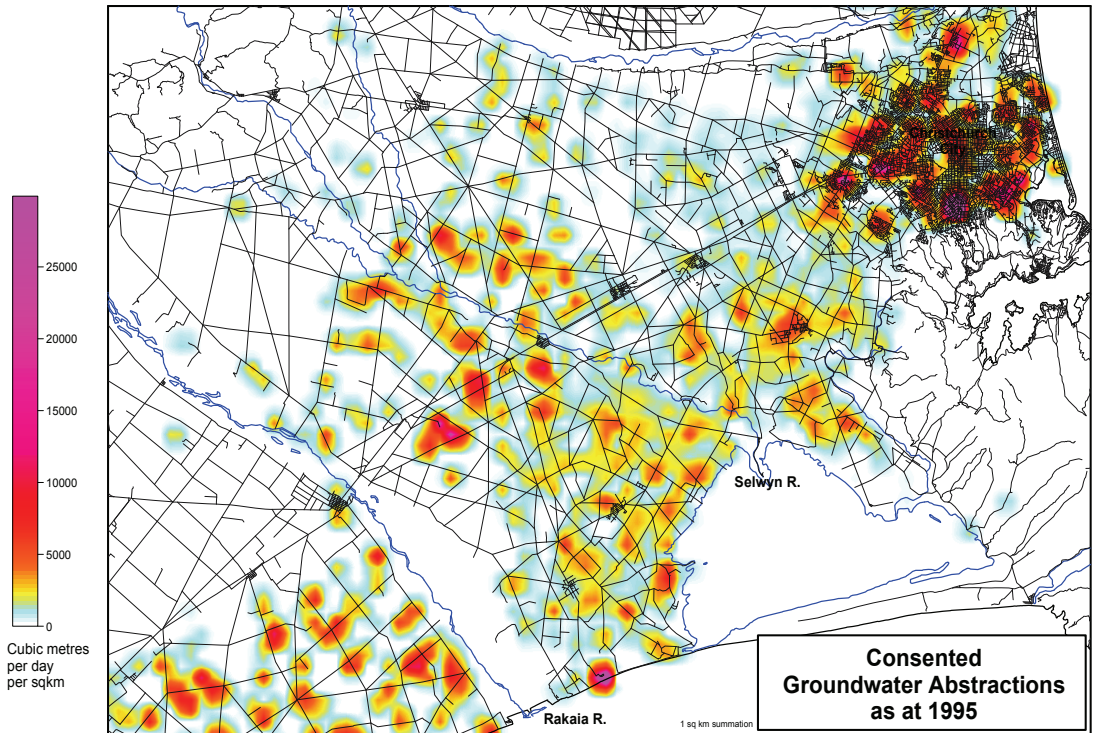


**Figure 5-1: The Rakaia-Selwyn Groundwater Allocation Zone and the distribution of wells within the zone.**

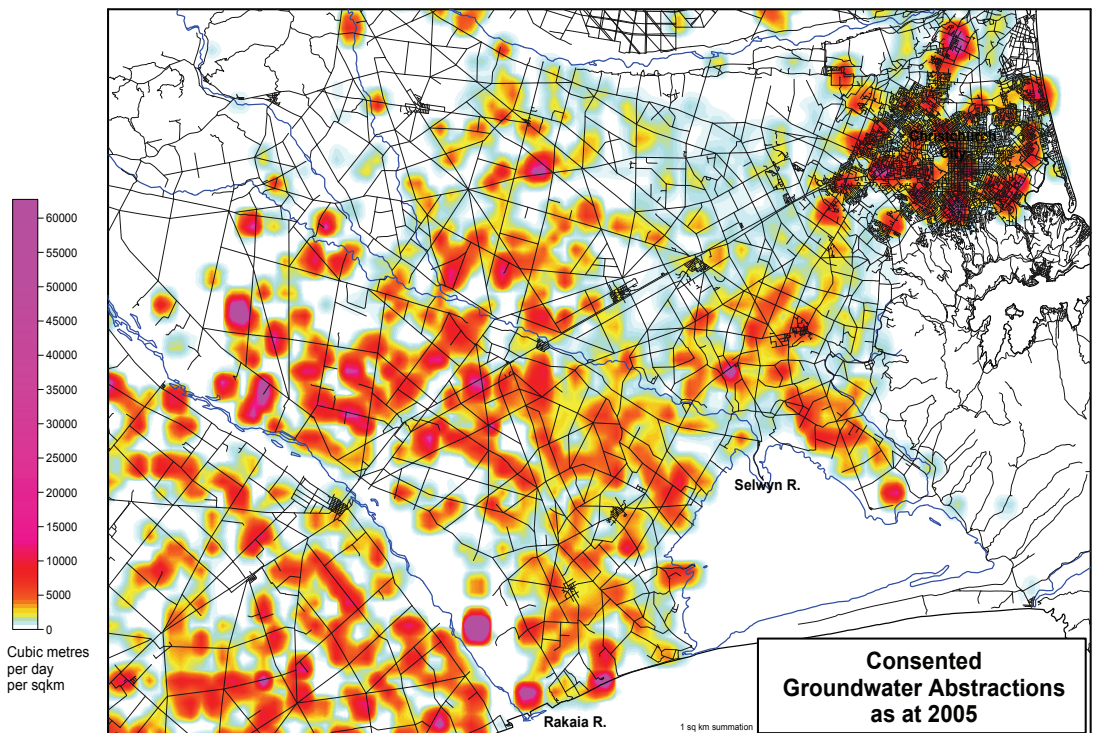
The rate and extent of groundwater development in the zone is indicated in Figure 5-2, Figure 5-3 and Figure 5-4. Figure 5-5 shows an estimate of the resulting groundwater abstraction (estimated actual use) in comparison to the calculated land-surface drainage. It appears that groundwater use has grown to the extent that, in recent years, it is comparable with the total land-surface recharge. An important issue in clarifying the significance of this development is the relative contribution from river recharge. The difficulty of directly measuring that component of the water balance means that to a large extent it must be inferred from model calibration and hence becomes a factor in any subsequent uncertainty analysis.



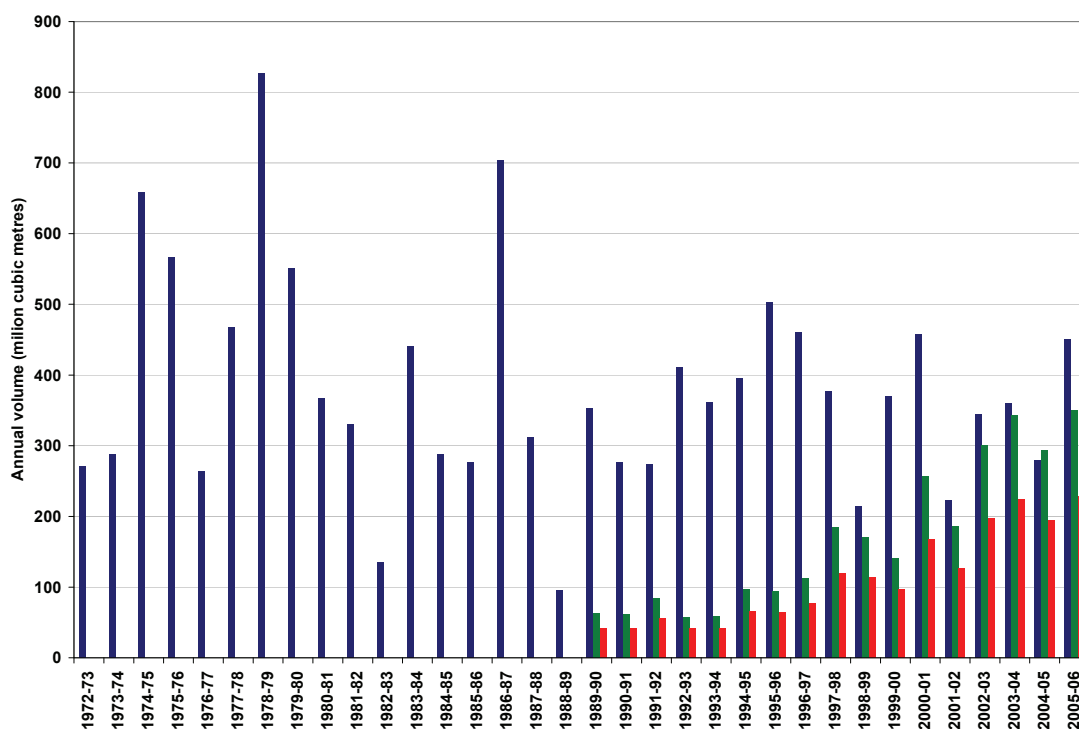
**Figure 5-2: Estimated annual groundwater allocation volume from the Rakaia Selwyn groundwater allocation zone from 1990 to 2006 (from Scott 2006).**



**Figure 5-3: Annual allocation volume from groundwater in the vicinity of the Rakaia Selwyn groundwater allocation zone in 1995 (m<sup>3</sup>/day per km<sup>2</sup>) (from Scott 2006).**



**Figure 5-4: Annual allocation volume from groundwater in the vicinity of the Rakaia Selwyn groundwater allocation zone in 2005 (m<sup>3</sup>/day per km<sup>2</sup>) (from Scott 2006).**



**Figure 5-5: Calculated land-surface recharge for the period 1972 – 2006 (blue) and estimated irrigation demand (green) and estimated actual use (red) since 1989-90 (from Scott 2006).**

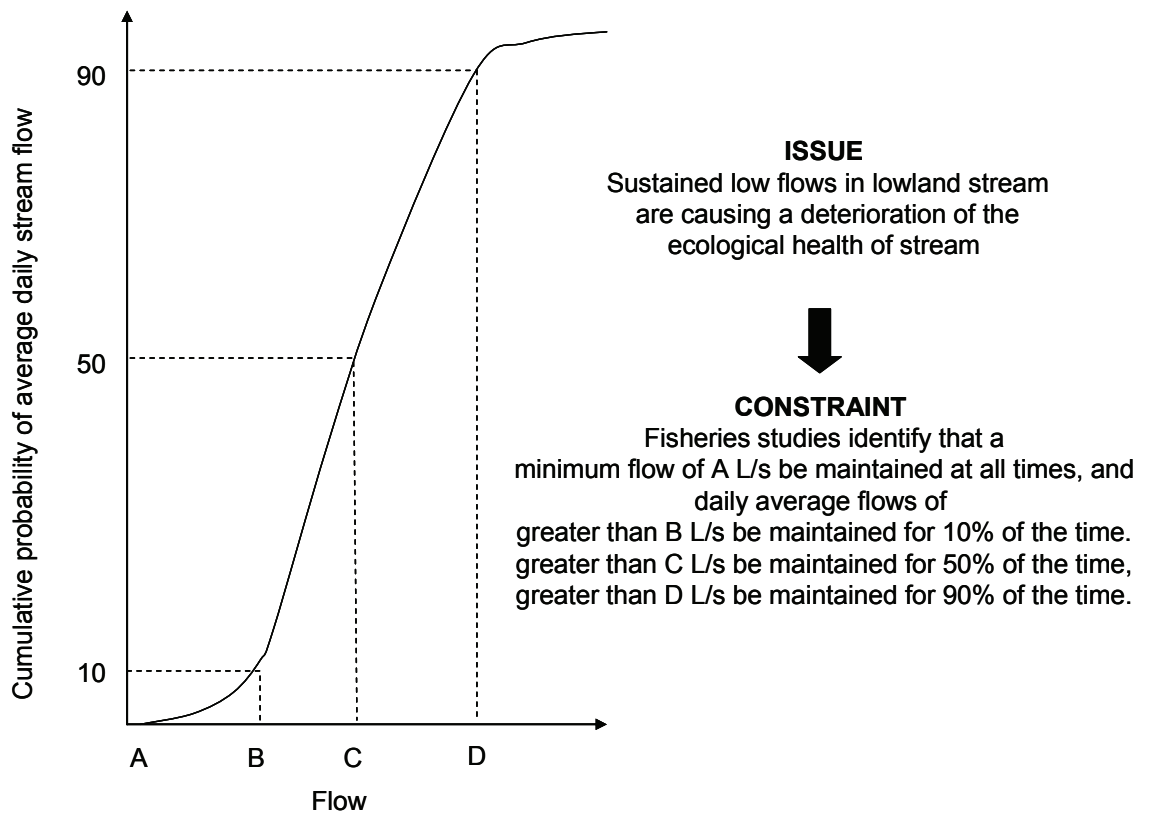
## 5.2 Identification of model questions and how the model assists identification of best management options

The regional groundwater model, as with most groundwater models, is being built with the intent of undertaking predictive simulations to assist in making decisions of how to best manage the groundwater resource, given the identified issues. The identification of the issues faced is the correct starting point for any modelling effort. Prior to using the model for predictive simulations, these issues need to be transformed into a quantifiable description, which can be used to form a constraint within which the resource system must be managed.

In the Rakaia Selwyn groundwater allocation zone the major issues raised in Section 5.1 relate to:

- flows in groundwater-dependent lowland streams;
- allocation limits such that farming businesses have some reliability of supply within predicted climate regimes.

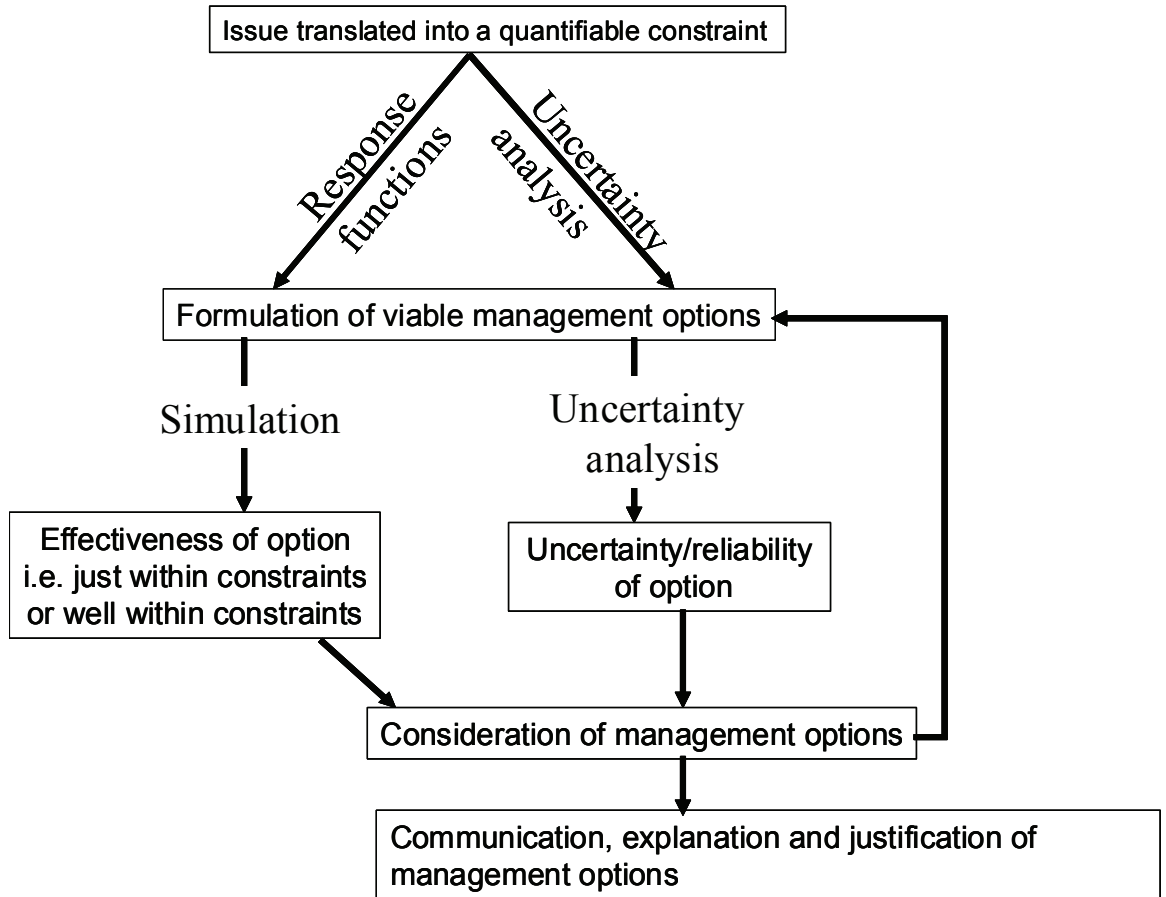
In Figure 5-6 the translation of the resource issue into a quantification of constraints is illustrated for the flow regime of a particular stream. A similar figure could be drafted for the issue of equity of allocation, to ensure that investments in irrigation dependent businesses are not unfairly compromised by over allocation of the resource.



**Figure 5-6: Quantification of constraints for a model issue.**

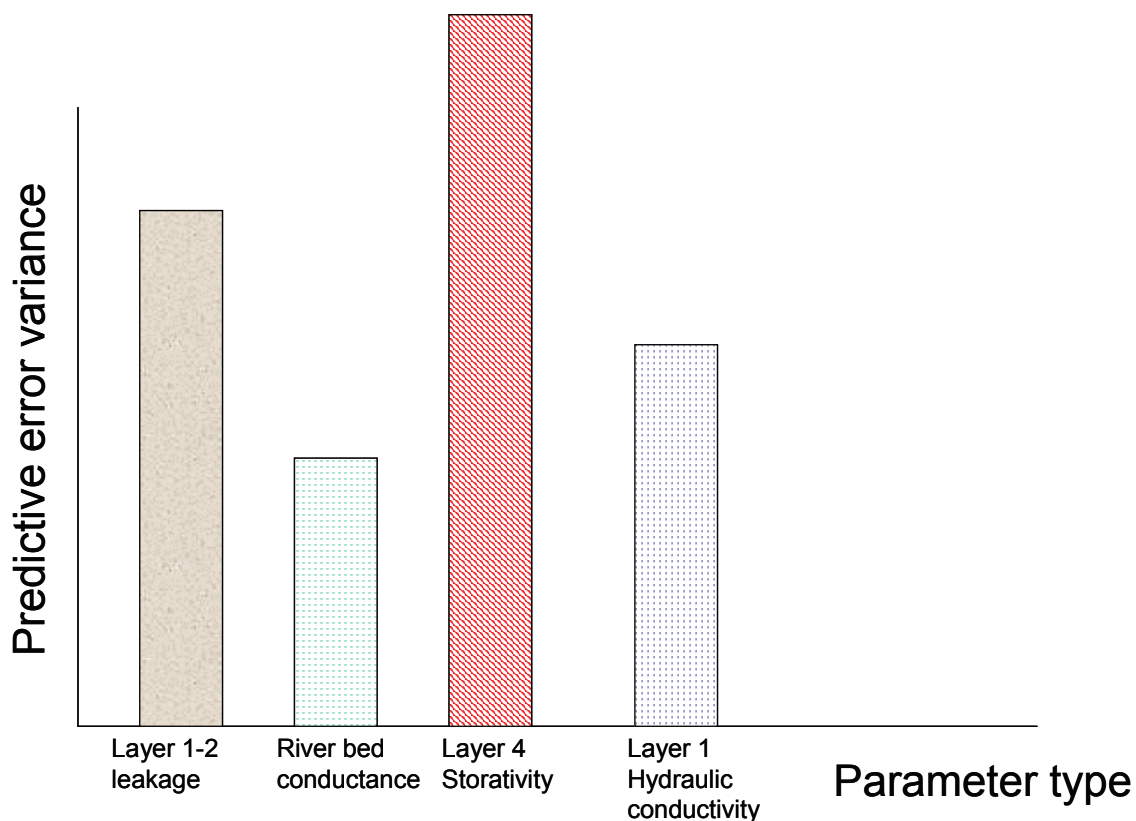
Typically an infinite range of management options exists to address a groundwater resource issue. The process of refining this range of options can be assisted by the use of response functions (discussed in Section 4.4) to formulate specific management regimes. Community consultation also assists in this refinement process as “what is practicable on the ground” is expressed, which can be assisted via use of the model as a communication tool. The interplay of these various modelling processes implemented in the making of management decisions is depicted in Figure 5-7.

The formulation of management regimes can also be guided by an assessment of which of the major system components contributes most to the uncertainty of the simulation of a flow regime (as shown in Figure 5-8). This is one part of the management option processing illustrated in Figure 5-7.



**Figure 5-7: Assessment of best management options.**

Once a list of viable preferred management options is compiled these must be quantified, transforming them into model questions in the same terms as the modelling constraints. The formulation of modelling questions therefore provides a means of objectively quantifying the effectiveness of the management option in terms of the issues of concern that have been identified.



**Figure 5-8: Contribution of model parameters to predictive error.**

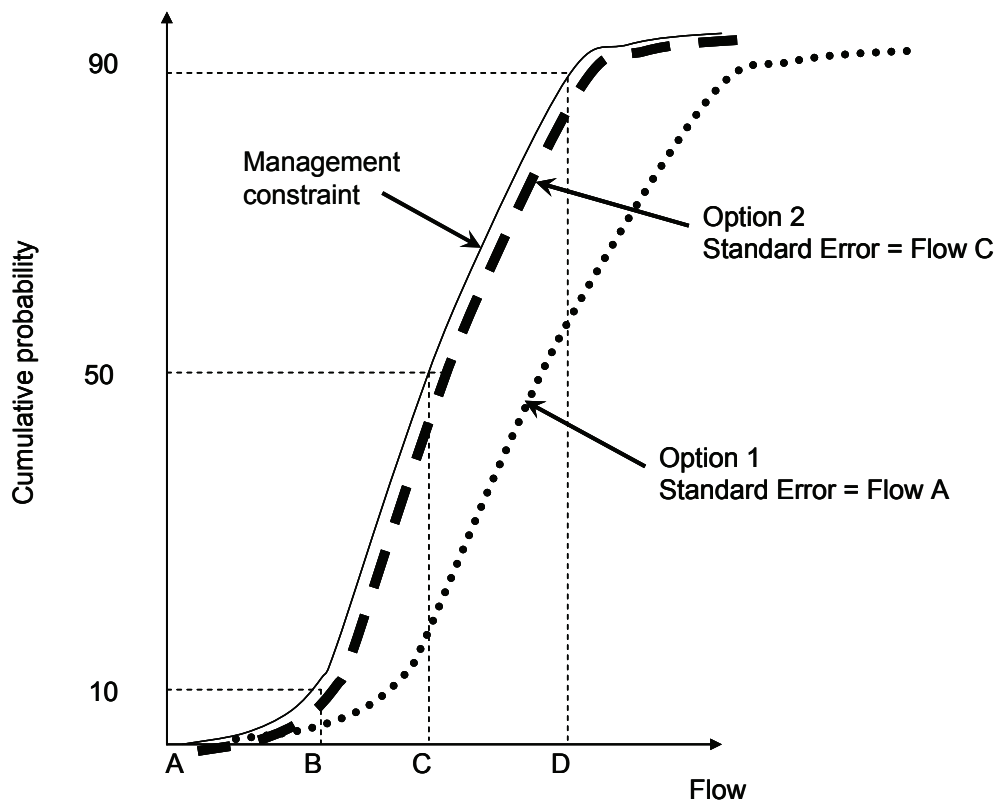
As mentioned in Section 4.2, in some circumstances a management regime may appear to be very effective, in terms of ensuring constraints (including conflicting constraints) are met almost exactly. However such a regime may only be able to be assessed with a very low degree of reliability. In contrast an alternative management option may be slightly less effective in terms of meeting constraints relatively exactly, but its outcome can be predicted very reliably. This idea is illustrated in Figure 5-9 where two possible management options (1 and 2) are assessed in terms of their ability to achieve compliance with the constraint outlined in Figure 5-6. Let us assume that Option 1 manages abstraction effects by imposing a 50% reduction in seasonal allocation over the entire region whenever trigger values of antecedent rainfall and/or stream flows are encountered. Option 2 will instead manage the abstraction effects on the stream via a spatially variable set of seasonal allocation restrictions; 60% for wells within 2 km of the stream, 30% for wells between 2 km and 10 km distant from the stream, and 10% for wells greater than 10 km distant.

The solid line cumulative flow curve in Figure 5-9 shows the flow regime that any management option will be evaluated against. That limiting curve represents the constraints the system is to be managed within (i.e. this is the same curve shown in Figure 5-6). Maximum allocation of the resource within that constraint would result from a management option that resulted in a cumulative flow distribution as close as possible to this curve. If the cumulative flow distribution resulting from any management option falls to the right hand side of the constraint flow regime curve, there is more flow in the stream than has been indicated as necessary, and so potentially more water available for allocation.

As can be seen, Option 1 falls well to the right of the limiting curve, indicating that it is effective in meeting the stream flow constraint, but that more water could be allocated. But also note, however, that the uncertainty of this predicted outcome of Option 1 is very small, with a standard error only a fraction of the very lowest recorded flow 'A' – i.e. the prediction is quite reliable.

In contrast, Option 2 maintains the desired flow regime close to the limiting curve. Unfortunately this apparently satisfactory management outcome is misleading, as the prediction is actually quite inaccurate, with a standard error equivalent to the median flow of the entire flow regime, flow C.

In this situation, a resource manager may prefer to adopt Option 1, although it appears at first glance to be overly conservative, given the certainty of the management outcome. In contrast Option 2, which initially appears to be superior, may be disregarded, when considering the reliability of the management outcome.



**Figure 5-9: Effectiveness and reliability of management Options 1 (dotted curve) and 2 (dashed curve) in terms of maintenance of a desired stream flow regime (solid line).**

## **6. Conclusions**

Groundwater use in the Canterbury region has increased significantly over the last ten years. This is particularly so for some parts of the Canterbury Plains where irrigation-dependent land use intensification has led to concerns about the sustainability of groundwater development. In those areas interim allocation limits for groundwater are being challenged by demands for additional groundwater-sourced irrigation. Development of a regional groundwater model is expected to deal with the scientific and policy gaps which are exposed in this situation.

A review of previous modelling studies within the Canterbury Plains highlights the need to take advantage of recent developments in model calibration techniques and to deal explicitly with the uncertainty of model prediction. A modelling approach based on these principles is outlined and its application to the development of management policies explored. Technical details of the methods under development and progress on applying the proposed approach in a prototype model are described in a companion technical progress report (Moore and Scott 2008). Ongoing work will be overseen by an in-house advisory group and reported for external peer review in subsequent progress reports.

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## 8. References

- Anderson B (2004): Groundwater between the Selwyn and Rakaia Rivers, Canterbury, New Zealand - A Hydrogeological Modelling Study. Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science with Honours in Geography at the University of Otago, Dunedin, New Zealand
- Bidwell VJ (2003): Groundwater Management Tools: Analytical Procedure and Case Studies. MAF Technical Paper No: 2003/6  
<http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/water-efficiency/groundwater-management-tools/tech-paper-0306-groundwater-management-tools.pdf>
- Cooley RL (2004): A theory for modeling ground-water flow in heterogeneous media. U.S. Geological Survey, Reston, Va.
- Dann RL, ME Close, L Pang, MJ Flintoft and RP Hector (2008): Complementary use of tracer and pumping tests to characterize a heterogeneous channelized aquifer system in New Zealand. Hydrogeology Journal, DOI 10.1007/s10040-008-0291-4.
- Davey G (2006): A contribution to the understanding of Canterbury Plains aquifers. Environment Canterbury Report No. U06/08.
- Doherty J (2003): Ground Water Model Calibration Using Pilot Points and Regularisation. Ground Water, 41(2), 170-177.
- Doherty J (2007a): PEST: Model-Independent Parameter Estimation. Version 11.3 of user manual. Watermark Numerical Computing, Brisbane, Australia, 2007. Downloadable from <http://www.sspa.com/pest>.
- Doherty J (2007b): PEST Addendum. Watermark Numerical Computing, Brisbane, Australia, 2007. Downloadable from <http://www.sspa.com/pest>.
- Doherty J and M Gallagher (2006): Analysis of Predictive Error of the Pioneer Valley Groundwater Model. Watermark Numerical Computing, December 2005.
- Halford KJ (2004): More data required. Editorial in Ground Water, 42(4), 477.
- Hill MC (1998): Methods and guidelines for effective model calibration. 98-4005, U.S. Geological Survey.
- Hong Y-S, PA White and DM Scott (2005): Automatic rainfall recharge model induction by evolutionary computational intelligence. Water Resources Research, 41, W08422, doi:10.1029/2004WR003577.
- Hubbell JM, CW Bishop, GS Johnson and JG Lucas (1997): Numerical ground-water flow modeling of the Snake River Plain aquifer using the superposition technique. Ground Water, 35(1), 59-66.
- Hunt BW (1976): Some computer models for ground water flow. Civil Engineering Research Report 76-11. University of Canterbury, New Zealand.
- Hunt RJ, J Doherty and MJ Tonkin (2007): Are models too simple? Arguments for increased parameterization. Ground Water 45(3): 254-262.
- Johnson GS, DM Cosgrove (1999): Application of steady state response ratios to the Snake River Plain aquifer. Idaho Water Resources Research Institute, 28pp, ([http://www.if.uidaho.edu/~johnson/ifiwrrri/pub\\_docs/rf-BOR11.PDF](http://www.if.uidaho.edu/~johnson/ifiwrrri/pub_docs/rf-BOR11.PDF)).
- Johnson GS, DM Cosgrove, J Spinazola (1998): Use of MODFLOW for development of response functions. MODFLOW'98 Conference, (<http://teton.if.uidaho.edu/~ifiwrrri/s3r/MODFLOW98.html>).

- Lincoln Environmental (2000): Information on Water Allocation in New Zealand. Prepared for Ministry for the Environment, Report No 4375/1, April 2000.
- Lincoln Environmental (2001): Water Allocation: A Strategic Overview. Prepared for Ministry for the Environment, Report No 4455/1, May 2001.
- Little RJ and DM Scott (1999): Christchurch-West Melton groundwater: Simulating groundwater augmentation. Canterbury Regional Council Report No. U98(33).
- MAF (2004): The Economic Value of Irrigation In New Zealand. MAF Technical Paper No: 04/01, ISBN No: 0-478-07798-X, April 2004.
- McDonald MG and AW Harbaugh (1988): A modular three-dimensional finite-difference ground-water flow model. USGS Techniques of Water-Resources Investigations, Book 6, Chapter A1, 576 pp.
- Moore C (2005): The use of regularized inversion in groundwater model calibration and prediction uncertainty analysis. A thesis submitted for the degree of Doctor of Philosophy at The University of Queensland in December 2005 by Catherine Moore.
- Moore C and D Scott (2008): Canterbury Plains regional groundwater model: Progress report to February 2008. Environment Canterbury Report No U08/5.
- Moore C and J Doherty (2005): Role of the calibration process in reducing model predictive error. Water Resources Research, Vol. 41(W05020, doi:10.1029/2004WR003501).
- Moore C and J Doherty (2006): The cost of uniqueness in groundwater model calibration. Advances in Water Resources, 29, 605-623 (doi:10.1016/j.advwatres.2005.07.003).
- Murray DL (1989): Postaudit analysis of the Ashburton-Rakaia groundwater model. Reprinted as Appendix 1 of Sanders R (1998): Groundwater flow models for the Ashburton – Rakaia Plains. Environment Canterbury Report U98/38.
- Murray DL (2001a): Groundwater model development for the Canterbury Plains from the Ashley River to Rakaia River. Report to Institute of Geological and Nuclear Sciences, University of Otago.
- Murray DL (2001b): Telescopic Mesh Refinement (TMR) using MODFLOW. Environment Canterbury Report U01/49.
- Pappenberger F and K Beven (2006): Ignorance is bliss: Or seven reasons not to use uncertainty analysis. Water Resources Research 42(5): Art. No. W05302.
- Reilly TE, OL Franke and GD Bennett (1987): The principle of superposition and its application in ground-water hydraulics. U.S. Geological Survey Techniques of Water Resources Investigations, Book 3, Chapter B6, 28pp.
- Sanders RA (2001): Ashley-Waimakariri groundwater investigation – 2000/01 report on development of a groundwater model. File IN6C-0040, 30 June 2001.
- Scott GL (1980): Hydrogeology of the Canterbury Plains between Ashburton and Rakaia Rivers, NZ. Journal of Hydrology (NZ), 19(1), pp 68-74.
- Scott DM (1992): An evaluation of flow net analysis for aquifer identification. Ground Water 30(5): 755-764.
- Scott DM (1996): Christchurch - West Melton groundwater investigation: Groundwater model status report. Report presented to the Canterbury Regional Council, 19pp.
- Scott DM (2001): Christchurch - West Melton groundwater investigation, Simulation of alternative groundwater abstraction scenarios and their effects on baseflows of the Avon and Heathcote Rivers. Environment Canterbury Report No. U00/33, 52pp.

- Scott DM (2003): Using response function concepts to model groundwater management scenarios. Proceedings of the MODFLOW2003 Conference, International Ground Water Modeling Center, Colorado School of Mines, Golden, CO.
- Scott DM (2006): Statement of evidence presented to the hearing of applications for water permits to take and use groundwater in the Rakaia Selwyn groundwater allocation zone. Environment Canterbury expert evidence.
- Scott DM (2007): Groundwater resources in New Zealand with particular emphasis on the Canterbury Region. Proceedings of the International Symposium on Groundwater Sustainability, Alicante, Spain, January 24-27, 2006.
- Scott DM and HR Thorpe (1986): Groundwater Resources Between the Rakaia and Ashburton Rivers. Hydrology Centre Publication No. 6. Ministry of Works and Development, Christchurch. 105pp.
- Thorley M, Peter Callander, H Williams, H Lough, M Kininmonth, B Henderson (2005): Christchurch City groundwater model. Proceedings of NZ Hydrological Society Annual Conference, Auckland, New Zealand.
- Thorpe HR and DM Scott (1999): An evaluation of four soil moisture models for estimating natural ground water recharge. *Journal of Hydrology (NZ)*, 38(2), 179-209.
- Tonkin M, J Doherty and C Moore (2007): Efficient nonlinear predictive error variance for highly parameterised models. *Water Resources Research* (in press).
- Vrugt JA and BA Robinson (2007): Improved evolutionary optimization from genetically adaptive multimethod search. Proceedings of the National Academy of Sciences of the United States of America. January 16, 2007, 104(3), 708–711.
- Weir JJ (2007): Canterbury Groundwater Model 2. Aqualinc Research Limited Report No L07079/1.
- White, P.A., Hong, T. and Murray, D.C., 1999. Validation of the Canterbury groundwater flow model using CFC-derived ages. Proceedings of NZ Hydrological Society Annual Conference, Napier, New Zealand.
- White, P.A., Murray, D.L., Hong, T., unpublished 2001. Central Plains irrigation scenario – predicted effects on groundwater. Report for URS consultants, October 2001.
- White, P.A., Stewart, M. K., Murray, D., Hong, Y-S. 2002. Regional model calibration using groundwater age measurements. Proceedings of NZ Hydrological Society Annual Conference, Blenheim, New Zealand.
- White PA, Y-S Hong, DL Murray, DM Scott and HR Thorpe (2003): Evaluation of regional models of rainfall recharge to groundwater by comparison with lysimeter measurements, Canterbury, New Zealand. *Journal of Hydrology (NZ)*, 42(1), 39-64.
- White PA, BMH Sharp and RR Reeves (2004): New Zealand water bodies of national importance for domestic use and industrial use. Prepared for Ministry of Economic Development. Institute of Geological & Nuclear Sciences, Client Report 2004/12, March 2004.
- Wohling, Th., GF Barkle and JA Vrugt (2008): Comparison of three multiobjective global optimization algorithms for inverse parameter estimation in unsaturated vadose zone modeling in the Lake Taupo catchment (New Zealand). *Soil Science Society of America Journal*, (in press).



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