

**Before the Commissioners appointed by Canterbury
Regional Council.**

***In the* The Resource Management Act 1991.
*matter of***

***And in the* 78 Applications to Take and Use Water in
matter of the Valetta (55) and Ashburton River (23)
Groundwater Allocation Zones.**

Section 42A Officer's Report

Date of Hearing: 21 July 2008

STATEMENT OF EVIDENCE OF JON WILLIAMSON

Dated: 2 July 2008

SKM

TABLE OF CONTENTS

1. Name and Qualifications.....	1
2. Code of Conduct.....	4
3. Introduction	4
4. Summary and Conclusions	6
5. Model Platform Selection	7
6. Model Conceptualisation.....	12
7. Boundary Conditions.....	15
8. Aquifer Hydraulic Properties	17
9. Model Run-times.....	23
10. Model Water Balance.....	23
11. Model Calibration	24
12. Model Results	24
13. Conclusion	25
14. Recommendation.....	25
15. References	27
Appendix A.	28

1. NAME AND QUALIFICATIONS

1.1 My name is **Jon Williamson**. I am an associate of the consulting firm Sinclair Knight Merz Limited (SKM) and have over 13 years professional environmental consulting experience. My qualifications include a Bachelor of Science (BSc) in Earth Science, and a Master of Science (Technology) first class honours (MSc(Tech)[I]) in Hydrology and Geology from the University of Waikato. I am a certified RMA Commissioner, an elected member of the Executive Committee of the NZ Hydrological Society, and a member of the International Association of Hydrogeologists (Australian Chapter).

1.2 My current position is Client Manager within the Water & Environment Business Unit of SKM. I have specialist technical expertise in Hydrology and Hydrogeology and as such my primary focus is Water Resource Management. My knowledge and experience covers a wide spectrum including data collection, manipulation and analysis; surface water and groundwater modelling; engineering design; report writing; community

and stakeholder engagement; expert technical evidence; and participating in and facilitating technical working panels.

1.3 Examples of groundwater modelling projects that I have been the Modeller or, in more recent times, the Modelling Director are provided in **Table 1**. The key observations to take from this table are the wide variety of project experiences (both scale and nature) and the variety of modelling platforms that I have used.

Table 1. Summary of Groundwater Modelling Experience.

Year	Project & Client	Indicative Model Scale	Model Code	Application of Model – assessment of:
2008	Wanganui Municipal Water Supply <i>Wanganui District Council</i>	200 hours	FEFLOW	<ul style="list-style-type: none"> ■ Groundwater flow regime ■ Hydrogeological conceptualisation ■ Interference effects
2007-2008	Waiheke Island Groundwater Model <i>Auckland Regional Council</i>	600 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Cumulative impacts ■ Saline intrusion ■ Interference effects ■ Resource management option testing (bore spacing, bore depth, costal setbacks, number of bores/pumping rates)
2008	Pike River Underground Coal Mine <i>Pike River Coal Limited</i>	200 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Seepage to ventilation shafts ■ Groundwater flow into tunnel across a fault
2008	Osborne Gold Mine Water Supply <i>Barrick Gold Pty Ltd</i>	300 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Regional impact of expended groundwater supply field
2008	Saraji Coal Mine <i>Newhope Corporation Ltd</i>	250 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Groundwater seepage to underground workings with time ■ Seepage pre- and post goaf collapse
2008	Suttor Creek and Eastern Creek Coal Mines <i>Xstrata Coal Pty Ltd</i>	500 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Groundwater seepage to underground workings with time ■ Seepage pre- and post goaf collapse
2008	Sweetwater Station Irrigation <i>Landcorp Farming Ltd</i>	300 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Assessment of regional cumulative impacts ■ Impact on surface water features
2007	King Orchard Avocado Irrigation <i>King Avocado Ltd</i>	300 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Assessment of regional cumulative impacts ■ Impact on surface water features
2007	Pauanui Sand Aquifer <i>Thames Coromandel District Council</i>	150 hours	FEMWATER (GMS)	<ul style="list-style-type: none"> ■ Saline intrusion assessment from municipal bore pumping
2006	Wairakei Estate Irrigation Planning <i>Wairakei Pastoral Limited</i>	200 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Aquifer sustainability to proposed 12,000 ha irrigation development. ■ Abstraction requirement of 4,000 L/s from approx. 45 bores.
2006	Torbay Sewer Tunnel Upgrade. <i>North Shore City Council</i>	100 hours	SEEP2D	<ul style="list-style-type: none"> ■ Tunnel seepages. ■ Pressure head on the pipe pre and post construction upgrade.
2006	Project Hobson Wastewater Tunnel. <i>Watercare Services Limited</i>	150 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Seepage rates to the 25x25 m vertical access shaft in Orakei Domain. ■ Different engineering options to mitigate seepage. ■ Likely extend and impact of depressurisation.
2006	Awanui Artesian Aquifer. <i>Northland Regional Council</i>	500 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ The likely effects of permanent closure of abandoned free flowing artesian bores on the surrounding environment.

Year	Project & Client	Indicative Model Scale	Model Code	Application of Model – assessment of:
2005	Otway Basin Drainage Scheme Hydrogeological Investigation. <i>Environment Waikato</i>	750 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Potential impacts on the Kopouatai peat dome from the proposed drainage scheme. ■ Model assists development of engineering design options to mitigate any potential impacts
2004	Northern Southland Groundwater Modelling Study. <i>Environment Southland</i>	500 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Implemented to defend water policy decisions that Environment Southland need to make with respect to pending groundwater abstraction consents and the impact on the Mataura River
2003	Ruawai Aquifer Regional Model <i>Northland Regional Council</i>	150 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Sustainable yield ■ Aquifer vulnerability ■ Groundwater impacts from pumping
2003	Riversdale Aquifer Management Zone Preliminary Sustainable Yield Assessment <i>Southland Regional Council</i>	150 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Sustainable yield ■ River recharge to aquifer ■ Effects of groundwater abstraction on spring flows and groundwater seepage to river
002	Russell Coastal Aquifer Sustainable Yield Study <i>Northland Regional Council</i>	250 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Sustainable yield ■ Saltwater intrusion ■ Resource management
2002	Proposed Southland Regional Landfill <i>AB Lime Ltd</i>	100 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Groundwater travel times ■ Impact from loss of recharge
2001	Kaiapoi Wastewater Treatment Plant <i>Waimakariri District Council.</i>	500 hours	MODFLOW/ MT3DMS (GMS)	<ul style="list-style-type: none"> ■ Options for enhancing infiltration ■ Treated effluent disposal ■ Contaminant transport
2001	Rangiora Wastewater Treatment Plant <i>Waimakariri District Council</i>	100 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Effluent remediation
2001	Three Kings Stormwater Soakage to Basalt Aquifer <i>Auckland City Council</i>	500 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Sustainability of disposal ■ Optimisation of stormwater disposal facilities configuration
2001	Phyllis Street Landfill <i>Auckland City Council</i>	150 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Maximum historical groundwater head elevations and seepage rates
2000	Chamberlain Park Golf Course Groundwater and Baseflow Impact <i>Auckland City Council</i>	300 hours	MODFLOW (GMS)	<ul style="list-style-type: none"> ■ Sustainable yield ■ Irrigation ■ Stream baseflow effects
2000	Aupouri Aquifer Sustainable Yield Study <i>Northland Regional Council</i>	200 hours	MODFLOW (Visual MF)	<ul style="list-style-type: none"> ■ Sustainable yield ■ Aquifer recharge ■ Resource management
1999	Cooks Beach Treated Effluent Irrigation <i>Tonkin & Taylor Ltd</i>	50 hours	MODFLOW (Visual MF)	<ul style="list-style-type: none"> ■ Sustainability of effluent disposal ■ Groundwater impacts
1999	Lake Conjola Sand Dune Exfiltration, NSW	100 hours	MODFLOW (Visual MF)	<ul style="list-style-type: none"> ■ Effluent remediation ■ Sustainability of disposal ■ Groundwater impacts ■ Site selection
1998	Whites Creek Waste Management Facility, NSW	100 hours	MODFLOW (Visual MF)	<ul style="list-style-type: none"> ■ Impact of mining
1998	Contaminant Transport Modelling of Varsol Spill at a Tannery Site, Melbourne	100 hours	MODFLOW MODPATH MT3D (Visual MF)	<ul style="list-style-type: none"> ■ Impact on river ■ Plume movement ■ Optimisation of remedial systems
1998	Residential Development Sewage Scheme, NSW	50 hours	MODFLOW MT3D (Visual MF)	<ul style="list-style-type: none"> ■ Contaminant plume in future
1998	Nebo Creek Alluvium Sustainable Yield Study, Qld	250 hours	MODFLOW (Visual MF)	<ul style="list-style-type: none"> ■ Sustainable yields ■ Town supply ■ Resource management

Year	Project & Client	Indicative Model Scale	Model Code	Application of Model – assessment of:
1988	Yandicoogina Channel Iron Deposit, WA	150 hours	MODFLOW (Visual MF)	<ul style="list-style-type: none"> ■ Mine advance dewatering
1997	Mt Pleasant Open Cut Coal Mine Water Management Study, Hunter Valley, NSW	500 hours	AQUIFEMNM ODFLOW	<ul style="list-style-type: none"> ■ Mine pit seepages ■ Regional groundwater impact
1997	Kayuga Open Cut Coal Mine Water Management Study, Hunter Valley, NSW	500 hours	AQUIFEMN	<ul style="list-style-type: none"> ■ Mine pit seepages ■ Regional groundwater impact
1996	Glendell Colliery Proposed Open Cut, NSW	500 hours	AQUIFEMN	<ul style="list-style-type: none"> ■ Mine pit seepages ■ Regional groundwater impact on both alluvial and hardrock aquifer ■ Advance dewatering strategy
1995	Anna Bay Sand Aquifer, NSW	1,000 hours	AQUIFEMN	<ul style="list-style-type: none"> ■ Sustainable yield ■ Salt water intrusion ■ Wetland dewatering

1.4 In addition to groundwater modelling experience, examples of other recent projects I have had a significant involvement in are provided in **Appendix A.**

2. CODE OF CONDUCT

2.1 I have read and agree to comply with the Code of Conduct for Expert Witnesses issued by the Environment Court on 31 July 2007.

3. QUALITY ASSURANCE

3.1 My evidence has been reviewed by SKM's Groundwater Modelling Practice Leader Mr Brian Barnett, who is based in Melbourne.

4. INTRODUCTION

4.1 I have been commissioned by Environment Canterbury to review the AquaLinc Groundwater Model of the Canterbury Plains as applied to the Valetta-Ashburton Groundwater Management Zones.

4.2 I am peripherally aware of the legacy or stigmas (depending on your viewpoint) attached to this model and its predecessors with respect to previous hearings. However, I do not consider myself to be fully versed in the details of the previous hearings and have deliberately focussed my evidence on the information before the panel for this hearing.

- 4.3 The objectives of my evidence are to provide an independent assessment of:
- (a) The appropriateness of the modelling procedures undertaken;
 - (b) The suitability of the constructed model to undertake the predictive role empowered upon it; and
 - (c) The confidence or certainty that can be applied to the results from the model and implications of any model uncertainty.
- 4.4 As part of my preparation for this hearing, I visited the Valetta and Ashburton River Zones on 29 May 2008. The key aspects of the management zones observed included:
- (a) The lowland drains and springs;
 - (b) The coastal sea terraces;
 - (c) The Hinds River outlet;
 - (d) The Rangitata Diversion race;
 - (e) The various branches of the Hinds and Ashburton Rivers in the upper part of the management zones; and
 - (f) The Highbank power scheme.
- 4.5 In preparing this evidence, I have:
- (a) Reviewed the relevant modelling documentation to satisfy my primary objectives; and
 - (b) Reviewed other evidence to provide me with the necessary background information on the nature of the application and hydrogeological setting.

These papers will be referenced where appropriate and are listed in **Section 14**.

5. SUMMARY AND CONCLUSIONS

Appropriateness of the Modelling Procedures

- 5.1 AquaLinc have developed a FEMWATER numerical groundwater model of the Canterbury Plains over an area of approximately 750,000 hectares. The model comprises fifteen layers representing five aquifers and four aquitards.
- 5.2 The development of the model was certainly a large undertaking given the scale of the model and the wide array of fundamental datasets (climate, soil, lithology, aquifer hydraulic property, groundwater level, stream flow, groundwater and surface water abstractions) that had to be collated and analysed.
- 5.3 Overall, I believe that the modelling procedures applied during the model construction, verification and predictive analysis have been undertaken in a largely appropriate manner. In general terms I concur with the view expressed in Merrick (2007) that the “model has been developed competently”.
- 5.4 While the procedures used in developing the model were largely appropriate, some of the interpretations and model options selected were in my opinion not soundly based or appropriately chosen. These include:
- (a) Selection of model platform (**Section 6**);
 - (b) Model layer conceptualisation (**Section 7**);
 - (c) Model hydraulic property assignment (**Section 9**);
 - (d) Selection of model time discretisation (**Section 10**);
 - (e) Model water balance (**Section 11**);

Suitability of the Model for the Predictive Purposes Employed

- 5.5 FEMWATER has serious deficiencies that would make it generally unsuitable for assessing regional scale problems where pumping induced stresses are likely to occur. In particular:

- (a) Its significant run times mean that calibration and sensitivity analysis cannot be undertaken in any meaningful way; and
- (b) The inability of the code to accurately report model water balance, particularly pumping rates and aquifer storage changes, make it totally unsatisfactory for the application before us.

5.6 Furthermore, it appears that the hydrogeological conceptualisation has been misrepresented in the model by the inclusion of impermeable barriers to vertical flow when competent aquitards (or aquicludes) are apparently not encountered in drill holes in this area. As a result it is highly likely that the model is underestimating the impacts of deep pumping on shallow aquifers and on surface waters.

Confidence or Certainty of the Model Results.

5.7 I have serious concerns about the reliability of the model and consequently would be very cautious about making resource management decisions based on the results from the current model. These concerns are elaborated in full in the following evidence.

6. MODEL PLATFORM SELECTION

6.1 The Canterbury Plains model is developed using the FEMWATER code. The rationale for selection of the FEMWATER code is not explained in AquaLinc (2007).

6.2 As will be discussed in paragraphs that follow, there are a number of concerns and flaws with FEMWATER, which are listed as follows:

- (a) It is not a mainstream model and hence has not been thoroughly tested nor accepted by industry.
- (b) It is inflexible in run-configuration selection (i.e. cannot deselect unsaturated zone simulation);
- (c) It is cumbersome in its run times;

- (d) It is difficult to parameterise compared to other models (i.e. many parameters are required by the FEMWATER to calculate specific storage and unsaturated zone conditions); and
- (e) It has inherent problems in calculating the model mass balance, and in particular the change in aquifer storage and changes in abstraction as it switches off “dry” pumping wells at each time step. These are critical flaws in the code as the model mass balance is a critical element of any groundwater modelling study.

The flaws may lead to erroneous resource management decisions, as will be explained below.

Common Use of FEMWATER

6.3 Merrick (2007) raises some uncertainty (see **Table 4, 4.13, 4.14, 4.15**) with regards to FEMWATER’s:

- (a) Appropriateness for the objectives of this study;
- (b) Reputability; and
- (c) Common use.

6.4 Point (a) is addressed in **paragraphs 5.6 to 5.19**.

6.5 Picking up on points (b) and (c) about reputability and common use of FEMWATER, there are few papers published in reputable scientific journals on the practical application of FEMWATER, particularly in comparison to more mainstream models such as MODFLOW and FEFLOW. This in itself suggests that the model has significant inherent problems, which are likely to be due to the difficulty in using the FEMWATER codes and in the uncertainty with results.

FEMWATER Inflexibility and Lengthy Runtimes

6.6 FEMWATER is a fully coupled unsaturated-saturated groundwater and contaminant transport simulation model and unlike other models that simulate unsaturated conditions (e.g. FEFLOW) the unsaturated component of the model cannot be turned off if it is not required. The

algorithms required for simulating unsaturated soil conditions are a significant contributor to model run times, which I understand are in the order of three weeks for the model calibration runs.

- 6.7 Such lengthy run times are quite inappropriate for a calibration model which must be run repeatedly either in a trial and error manner or with an inverse modelling routine. In either case, tens or even hundreds of model runs are usually required to reach an acceptable level of calibration.
- 6.8 For example, in a recent project where I was using FEMWATER for simulation of saline intrusion on a coastal sand spit (see **Table 1**), the model required three days to run a one-year simulation. At the end of this time the results showed significant instability and produced some unexpected results. The FEMWATER model was replaced with FEFLOW, which replicated the same scenario in less than 30 minutes with the expected result.

Unsaturated Zone Simulation in FEMWATER

- 6.9 I would seriously question why an unsaturated code was required for this study. There is no reporting of the soil saturation deficits under the baseline or proposed consenting scenarios, nor is there any need for these. What is of importance is the impact on the saturated groundwater conditions and stream/aquifer interaction.
- 6.10 The standard approach with a typical (saturated only) groundwater models of assigning rainfall recharge using an external recharge preconditioning model has been undertaken in this study (i.e., the unsaturated module in FEMWATER has not been used to drive this). Further, the river/stream package developed for FEMWATER and used in this studies appear analogous to that of MODFLOW. Hence, I do not understand why the model required the ability to simulate the unsaturated zone and the consequences of this (i.e. unacceptably long runtimes) have in my view made realistic calibration and sensitivity analysis impractical.
- 6.11 As a result of the long run times there is significant potential in the model for parameter non-uniqueness, which is essentially where different combinations of parameters (of which hydraulic conductivity, specific

storage, recharge rate are of most importance) can provide the same outcome. Non-uniqueness needs to be minimised by:

- (a) Considering multiple calibration targets (i.e. calibration against flux and head), which has been adequately carried out in AquaLinc (2007); and
- (b) Undertaking many runs during model calibration to confirm optimal parameter selection within the typical range expected for these materials and climate, which is unlikely to have been completed given the three week run times.

Parameterisation in FEMWATER

6.12 In FEMWATER the model calculates the actual specific storage (S_s) value during run-time based on the material properties assigned by the modeller, as shown in **Equation 1**.

Equation 1.
$$S_s = \rho g (\alpha + n\beta)$$

Where:

ρ = density of water	999.7 kg/m ³
g = gravitational acceleration	7.32E+10 m/day ²
α = compressibility of the aquifer material	Dependent on material type (see Table 6).
n = porosity	Dependent on material type.
β = compressibility of fluid	6.35E-20 m.d ² /kg at 10 deg C.

6.13 The calculation of S_s is governed primarily by the compressibility of the aquifer (α) and porosity (n), which are the only non-prescribed parameters.

6.14 The normal procedure in groundwater modelling is to assign S_s directly based on the storage coefficient (S) determined from test pumping results divided by the thickness of the aquifer (b) (i.e. $S_s = S/b$).

6.15 Change in S_s assignments to a model during the calibration procedure can easily be made within the range typically expected for the various material types. Experienced hydrogeologists are familiar with the range expected. While the procedure used in FEMWATER is one step removed

from this, competent modellers should be able to use the tools in FEMWATER to build a model that has an appropriate representation of aquifer storage. The important point is whether or not the modellers in this case have developed an appropriate representation of aquifer storage, as will be discussed further in **Section 8**.

FEMWATER Mass Balance Calculations

- 6.16 A thorough and accurate understanding of the mass balance of the aquifer system is a fundamental requirement for understanding the resource and ultimately making management decisions. **Equation 2** provides a basic expression of a hydrologic mass balance.

Equation 2.
$$\text{Inputs} + \text{Outputs} + \text{Change in Storage} = 0$$

Where:

Inputs are positive, and may include rainfall and irrigation recharge, leakage from surface water features, runoff infiltration and groundwater throughflow into the system.

Outputs are negative, and may include discharges to coast and surface water features, and groundwater abstraction at bores.

Change in storage can be either positive or negative depending on stresses on the system, and are exemplified by groundwater head increases or decreases, respectively.

- 6.17 The mass balance discrepancy of a groundwater model should ideally be less than 1% for numerical stability (MDBC, 2000).
- 6.18 As indicated in AquaLinc (2007) **Section 7.7.2**, FEMWATER does not have the ability to calculate:
- (a) Changes in aquifer storage; and
 - (b) Changes in abstraction volume caused by pumping wells going dry during simulation.
- 6.19 The implications of this are as follows:
- (a) There is no mechanism to check that the model accurately accounts for all water (i.e. that the law of conservation of mass holds – water can only be transferred not created or destroyed);

- (b) There is no mechanism to verify the volume of water that was actually abstracted from the model pumping wells during run-times (i.e. the modeller assigns a pumping rate, but the model will only deliver this rate while the bore is considered to have water available in the aquifer). Consequently, there can be no confidence in the results of the impact scenarios assessed with this model.

For example, if an additional cumulative abstraction of 1.6 m³/s was assigned to the model in 68 pumping bores and a number of these bores went dry during simulation, then the impact observed is that from the reduced amount of abstraction from the remaining active bores. However, because of FEMWATER's limitations in this area, the actual pumping rate is not known.

6.20 In this regard it is impossible to rely on this model for impact assessment.

7. MODEL CONCEPTUALISATION

Overview

7.1 My conceptual high-level understanding of the Canterbury Plains developed through assessment of evidence prepared for this hearing principally that of Davey (2007), Weir (2008), and Smith (2008) is as follows:

- (a) Groundwater recharge is driven by infiltration of rainfall, leakage from rivers, irrigation, stockwater races, and irrigation scheme distribution canals.
- (b) Groundwater flows from the alpine foot hills to the coast with localised variations in groundwater flow direction influenced by surface drainage features.
- (c) Depth to groundwater is greater in the upland areas of the plain, and shallow in the lowland areas of the plains.

- (d) In the north of the Canterbury Plains, layered sequences of alternating distinct aquifers and aquitards are prevalent. This is evidenced by distinct positive vertical pressure gradients (increasing hydraulic head with depth and upward flow potential) in many bores in this area; while
- (e) South of the Rakaia River and nearer the coast (mid to lower plains), the sequence is thought to be a more homogenous and isotropic¹ system (i.e. lacks alternate layering of aquifer and aquitards), as evidenced by the similar groundwater pressures in the deep and shallow aquifers (i.e., lack of vertical pressure gradient)².
- 7.2 The key aspect of the conceptual hydrogeology that is contentious in my mind is the nature (occurrence, extent, thickness and hydraulic characteristics) of the aquitards within the Hinds-Ashburton area. In particular, the magnitude of the difference in hydraulic property values between the aquifers and the aquitards.
- 7.3 As defined in Smith (2008), aquitards are low permeability geological materials that retard, but do not completely prevent groundwater flow. Davey (2007) states that the aquitards, being lacking in distinct paleosols, are likely to be of higher permeability than the current land surface, which is known to rapidly infiltrate rainfall.

Vertical Pressure Gradients

- 7.4 As a general rule, the presence of steep vertical pressure gradients³ indicates that an effective aquitard exists in the system. Hence, strong vertical pressure gradients can be used as evidence for the presence of aquitards⁴.

¹ For groundwater systems isotropy means aquifer properties (within a hydrogeologic unit) are the same in all directions.

² Localised downward vertical pressure gradients will be present in areas where leakage from surface water features such as rivers, streams, irrigation canals and border dyke schemes occur.

³ The direction of vertical leakage is governed by factors such as the elevation of the recharge area in relation to the point of interest, the impacts of groundwater extraction and the elevation of natural groundwater discharge features. In the Canterbury Plains one would expect maximum upward gradient potentials to exist near the coast because this is where there is the maximum elevation difference between the recharge sources across the plains and the local point of discharge (i.e. the ocean or local water table).

⁴ Note. Weak vertical pressure gradients (<1 m) can develop in systems without distinct aquitards where the aquifer sediments themselves provide progressive confinement with depth.

- 7.5 Competent aquitards would be expected to be dominated by silts and clays and be highly conspicuous from the typical gravel aquifers of the Canterbury Plains that comprise significantly higher proportions of clean gravels.
- 7.6 Smith (2008) in **paragraph 31** indicates that the Hinds-Ashburton areas lack lower permeability deposits [aquitards] bounding the aquifers, as occurs in the coastal Christchurch areas. Further, he summarises from the work of others that it is extremely difficult, if not impossible to correlate aquifer/aquitard sequences [in this area] because of the complex lithological information and predominantly gravel strata penetrated [paucity of distinctly lower permeability material]⁵.
- 7.7 This suggests that:
- (a) It would be unlikely that strong vertical pressure gradients could develop in the Valetta-Ashburton groundwater management zone; and that
 - (b) Any vertical pressure gradients that did develop are likely to be localised downward vertical gradients driven by leakage from surface features.
- 7.8 Merrick (2007) obviously had concerns about this and stated in **Table 2 q2.15** of his review that vertical pressure distribution maps should be generated to add support for the multi-layering in the model and inform on vertical flow directions.
- 7.9 **Figure 4-2** of AquaLinc (2007) appears to have been added to address Dr. Merrick's concerns. However, as shown, only negative (downward) vertical pressure gradients exist in the Hinds-Ashburton area – even near the coast, where you would expect the upward pressure gradients if significant aquitards prevailed.

This can only occur where vertical flow is impeded relative to the horizontal flows (i.e. vertical hydraulic conductivity is lower than horizontal hydraulic conductivity of the aquifer materials), which typically occurs in sedimentary systems.

⁵ Interpretation in square brackets added.

- 7.10 There would appear to be no evidence in this area for the distinct aquitards as built into the AquaLinc model (see **Figure 4-4**, AquaLinc (2007)).
- 7.11 The consequence of this interpretation will depend on the actual hydraulic property values employed for the aquitards, but in concept are likely to include:
- (a) Under estimated connectivity (water transfer) between the shallow and deep aquifers;
 - (b) Reduction in sensitivity in the shallow aquifer from pumping in the deep aquifer; and
 - (c) Significantly higher pressures in the deeper aquifer than occur in practice.
- 7.12 In summary, geological information suggests that there are no thick, competent aquitards in the Hinds-Ashburton area and impacts of deep pumping are therefore likely to propagate to the surface. The modellers have deviated from the conceptualisation by including thick aquitards in the model, which by their nature have unreasonably low vertical permeability for the actual material types that appear to exist in the field. AquaLinc (2007) therefore potentially understates the impacts on shallow aquifers and on surface water.

8. BOUNDARY CONDITIONS

Stream Package

- 8.1 There is some concern that the FEMWATER stream package developed for this project has not been verified. Given the serious issues surrounding the calculation of mass balance in FEMWATER as discussed in **paragraphs 5.16 to 5.19**, further critical analysis of the stream package is warranted.
- 8.2 Furthermore, in **Section 1.6** of AquaLinc (2007) a number of further software development issues are identified, which could be interpreted to suggest that the current version of the modelling code has deficiencies

that should be overcome before decision makers can have confidence in the reliability of the software.

Groundwater Abstraction Volumes

8.3 **Table 6-5** of AquaLinc (2007) presents the working to calculate historical abstraction, which was an input into the groundwater model for history matching (calibration) purposes. A relationship was developed between power use records and pumping volume, however the verification of the calculated abstraction versus metered abstraction for two farms (**Table 6-5**, AquaLinc (2007)) shows that the calculated abstractions are over predicted by 12% and 4%, respectively. On an annualised basis, this can lead to significant quantities of water being abstracted from the model and has implications for model calibration.

8.4 Using data from AquaLinc (2007) and Weir (2008) I have estimated that the over predicted groundwater abstractions applied in the model for the calibration period (i.e., historical simulation) could equate to an additional 13.7 Mm³/annum of groundwater being pumping from the Valetta-Ashburton zone during the calibration period than would likely have occurred (see **Table 2**).

Table 2. Calculation of over-estimated groundwater abstraction.

Bore Abstraction Volumes – data sourced from Table 6-5, AquaLinc (2007).					
Farm 1 (ha) - 306		m ³ /yr	Discrepancy		
			m ³ /yr	m ³ /ha/yr	% discr.
	measured	2,099,520			
	calculated	1,872,162	227,358	743.0	12%
Farm 2 (ha) - 247					
	measured	1,680,768			
	calculated	1,618,588	62,180	251.7	4%
Average			144,769	497.4	8%

Irrigation Volumes & Areas – data sourced from Figure 15 & Table 4, Weir (2008).

	Abstraction volume (m ³ /s)	Irrigation area (ha)	Irrigation discrepancy (m ³ /yr)
proposed	1.6	10,500	5,222,390
current	4.2	27,563*	13,708,773
cumulative	5.8	38,063	18,931,163

Notes: * Assumes an irrigation volume per unit areas of 0.000152 m³/s/ha, which is based on the ratio for the current application.

- 8.5 The implications of the apparent over-estimation in groundwater abstraction may include the following:
- (a) Lower hydraulic conductivity values than observed in practice would be required in the model to maintain groundwater levels. This appears to be the case and is discussed further in **Section 8**;
 - (b) Impacts in the shallow aquifer would be under-estimated given the proportional over prediction in irrigation return water that would occur.

Groundwater Abstraction Application

- 8.6 The AquaLinc (2007) model applies a uniform irrigation volume across 19 hydrological zones within the model domain, each averaging approximately 40,000 hectares. The alternative and more common approach is to apply the irrigation abstraction volume at the actual position of the consented bore or clusters of neighbouring bores.
- 8.7 The implication of using averaging over hydrological zones for assignment of groundwater abstraction is that the actual impacts of pumping observed in monitoring bores in close proximity to pumping bores would not be replicated adequately in the model without artificially low specific storage parameters. This also appears to be the case and is discussed further in **Section 8**.

9. AQUIFER HYDRAULIC PROPERTIES

Hydraulic Conductivity

- 9.1 AquaLinc (2007) (**Table 3-1**) categorise the lithological materials of the Canterbury Plains that are included in the simulation model into three units, as summarised in **Table 3**.

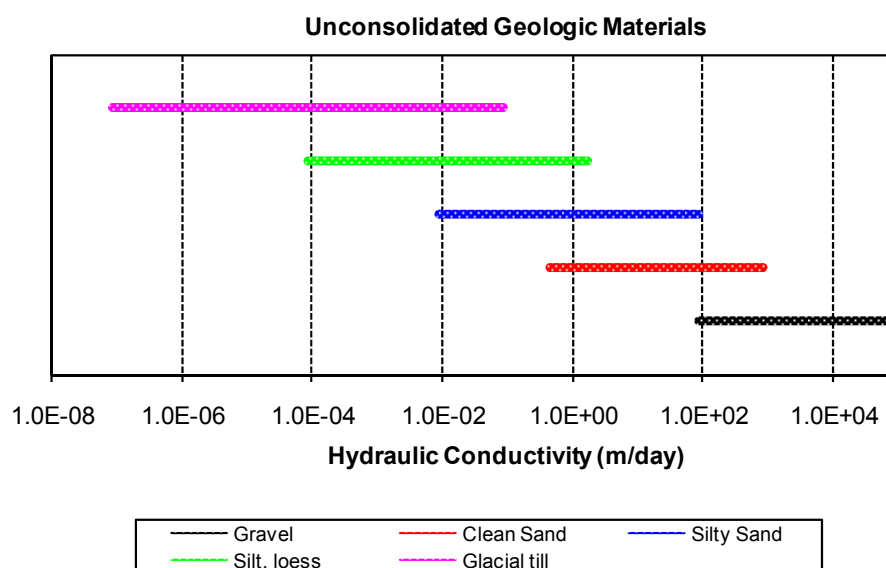
Table 3. Summary of lithological properties (from AquaLinc, 2007).

Simplified Code	Simplified Geological Description	Comment
1	Loose	Geological materials in this category are highly permeable (e.g. gravels and coarse sandy gravels).
2	Moderate	Geological materials in this category are moderately permeable (e.g. sands and gravels with silts).
3	Tight	Geological materials in this category have low permeability and are often aquitards (e.g. silts, clays and clay bound gravels).

9.2 Typical published hydraulic conductivity values for a range of unconsolidated geological materials including gravels and sands are provided in **Figure 1**.

Aquifer Hydraulic Conductivity

9.3 The AquaLinc (2007) model uses horizontal hydraulic conductivity (Kx and Ky) values for Aquifers 1 to 5 (see **Table 4**) that conform to the range normally expected for silty sand (at the lower end), to moderately clean gravels (at the upper end of the range). However, appraisal of the aquifer hydraulic conductivity zone figures provided in **Appendix J** of AquaLinc (2007) indicates that the distribution is more weighted towards the higher end of the range, which would seem appropriate based on the information available to me.



Source: Freeze & Cherry (1979).

Figure 1. Typical publicised hydraulic conductivity values (after Freeze and Cherry (1979)).

Table 4. Summary of hydraulic conductivity values used in AquaLinc (2007) model.

Aquifer	Kx & Ky	Kz
	(m/day)	(m/day)
Aquifer 1-5	5 to 2,400	0.05 to 24
Coastal Aquitards	0.5 to 240	2.5E ⁻⁵ to 0.012
Non-Coastal Aquitards	0.5 to 240	3.3E ⁻⁵ to 0.016

Aquitard Hydraulic Conductivity

- 9.4 From **Table 3**, conventional aquitards would fall into Category 3 – Tight. However, it appears from the evidence of Davey (2003), and Smith (2008) that this description would only apply to the aquitards of the Christchurch area, as over the majority of inland and southern areas of the plains there would appear to be no distinct aquitards.
- 9.5 For example, Davey (2007) describes the aquitards of the Canterbury Plains (excluding the aquitards in the Christchurch area) as consisting “of relatively thin (relative to the aquifers) sandy gravel layers” and indicates that the aquitards are “conspicuously lacking in any strata that would conventionally be described as aquitards”. Further, Davey (2007) states that these aquitards are not highly impermeable as there is “no evidence of laterally continuous layers of sand, silt, peat or clay”.
- 9.6 The AquaLinc (2007) model uses horizontal hydraulic conductivity (Kx and Ky) values for the Coastal Aquitards (see **Table 4**) that are within the range attributed to clean sands and at the lower end of the range for clean gravels, which conforms with the aquitard description of Davey (2007).
- 9.7 However, the vertical horizontal conductivity (Kz) assigned to the aquitards in AquaLinc (2007) are approximately 4 orders of magnitude or 10,000 times lower than the horizontal. In unconsolidated sedimentary deposits such as these alluvial and fluvial-glacial systems, it is typical for vertical anisotropy to occur because the sediments are deposited in layers and lenses that display alternating coarse and finer materials. However, the range of anisotropy expected is typically 10 to 300 times.
- 9.8 The Kz values for the aquitards range from 2.5x10⁻⁵ m/day to 1.6x10⁻² m/day (3x10⁻¹⁰ to 2x10⁻⁷ m/s), which are equivalent to that expected for

concrete and sedimentary hardrock⁶, respectively. AquaLinc (2007) appears to have used Kz values more representative of aquicludes rather than aquitards (which inherently have a degree of leakiness).

- 9.9 Furthermore, the hydraulic conductivity values for the coastal and inland aquitards are similar, yet as discussed in length, there is no evidence that the inland aquitards should have hydraulic conductivity as low as the coastal aquitards. The lack of strong vertical upward groundwater pressure gradients in the area of this application in particular suggests otherwise.
- 9.10 The implication of the inappropriately low Kz values will be a reduction in connectivity between the model layers and corresponding reduction in the effects on the shallow aquifer and surface water features from pumping within the deeper aquifers.

Specific Storage

- 9.11 **Equation 1** gives the equation used in FEMWATER for the calculation of specific storage (Ss) under fully saturated conditions. As stated in **Appendix D** of AquaLinc (2007), the compressibility of the aquifer material dominates the calculation of specific storage, because aquifer compressibility is generally greater than water compressibility.
- 9.12 Specific storage is related to the storage coefficient (S), the term usually defined in aquifer testing, by $S_s = S/b$, where b is the aquifer thickness.
- 9.13 **Appendix V** of AquaLinc (2007) provides values of aquifer compressibility (α), S and porosity (n) that were employed in the calibrated model, as summarised in **Table 5**.

Table 5. Summary of aquifer storage parameters used in AquaLinc (2007) model.

Aquifer	Aquifer compressibility (α)	Approx. storage coefficient (S)	Porosity (n) = θ_{sat}
	(m.day ² /kg)	(-)	(-)
Aquifer 1	2.0E ⁻¹⁷	1.0E ⁻²	0.01
Aquifer 2-5	1.0E ⁻²⁰	1.5E ⁻⁵	0.01
Coastal Aquitards	2.0E ⁻²⁰	3.0E ⁻⁵	0.01

⁶ For example, the typical hydraulic conductivity value for massive siltstone of the East Coast Bays Formation in the Auckland region is approximately 3×10^{-7} m/s.

Non-Coastal Aquitards	$2.0E^{-20}$	$3.0E^{-5}$	0.01
-----------------------	--------------	-------------	------

Notes: θ_{sat} is saturation soil moisture content = porosity of the soil.

9.14 **Table 6**, reproduced from Domenico and Mifflin (1965), summarises typical published values for aquifer compressibility. Aquifer compressibility increases with softer aquifer materials, which generally comprise higher clay contents. Conversely, consolidated massive rock materials have lower compressibility.

Table 6. Range of aquifer compressibility values (after Domenico and Mifflin, 1965).

Material	Aquifer compressibility (α) (m.d ² /kg)
Plastic clay	3.5E-17 to 2.7E-16
Stiff clay	1.7E-17 to 3.5E-17
Medium-hard clay	9.2E-18 to 1.7E-17
Loose sand	7.0E-18 to 1.3E-17
Dense sand	1.7E-18 to 2.7E-18
Dense, sandy gravel	7.0E-19 to 1.3E-18
Rock, fissured	4.4E-20 to 9.2E-20
Water at 10 deg C	6.35E-20
Rock, sound	4.4E-20

9.15 Comparing the AquaLinc (2007) aquifer compressibility values in **Table 5** with the typical published values in **Table 6**, the following is evident:

- (a) Aquifer 1 has an aquifer compressibility value (2.0×10^{-17} m.d²/kg) similar to stiff clay (1.7×10^{-17} to 3.5×10^{-17} m.d²/kg), which would not appear to be conceptually sound (i.e, the aquifers are predominantly gravels not clay);
- (b) Aquifer 2 to 5 have aquifer compressibility values (1.0×10^{-20} m.d²/kg) that are lower than competent rock (4.4×10^{-20} m.d²/kg), which would also not appear to be conceptually sound either; and
- (c) The coastal and non-coastal aquitards have the same aquifer compressibility, which is not consistent with the conceptual understanding that the inland aquifers have significantly lower clay content.

9.16 Furthermore, by using the aquifer and porosity values provided by AquaLinc (2007) and reproduced in **Table 5**, the calculated Ss and S values do not match those provided in AquaLinc (2007). For example, as shown in **Table 7**, the calculated Ss in Aquifer 1 is 1.46×10^{-3} and the resulting S assuming a 20 m aquifer thickness as reported in AquaLinc (2007) is 2.93×10^{-2} , whereas **Table 5** shows S for this aquifer to be 1.0×10^{-2} , which is nearly 300% lower. Similar findings occur for the other model layers.

Table 7. Summary of calculated Ss and S values.

Constant	ρ	g	α	β	n	Ss (calc)	S (calc)
Unit	kg/m ³	m/d ²	m.d ² /kg	m.d ² /kg		(-/m)	(-)
Aquifer 1	999.7	7.32E+10	2.00E-17	6.35E-20	0.01	1.46E-03	2.93E-02
Aquifer 2-5	999.7	7.32E+10	1.00E-20	6.35E-20	0.01	7.79E-07	1.56E-05
Coastal aquitards	999.7	7.32E+10	2.00E-20	6.35E-20	0.01	1.51E-06	3.02E-05
Non-coastal aquitards	999.7	7.32E+10	2.00E-20	6.35E-20	0.01	1.51E-06	3.02E-05

Notes:

- ρ = density of water
- g = gravitational acceleration
- α = compressibility of the aquifer material
- β = compressibility of fluid
- S = storage coefficient
- n = porosity
- Ss = specific storage

9.17 In addition, as is shown **Table 8**, the typical Ss values appropriate for gravel aquifers are in the order of 5×10^{-5} to 1×10^{-4} . The apparent wide range of values used by the modeller in this case from 10^{-3} to 10^{-7} (**Table 7**) and are not supported by the literature.

Table 8. Range of specific storage values (after Anderson and Woessner, 1992).

Material	Specific storage (m^{-1})
Plastic clay	2.6×10^{-3} to 2.0×10^{-2}
Stiff clay	1.3×10^{-3} to 2.6×10^{-3}
Medium-hard clay	9.2×10^{-4} to 1.3×10^{-3}
Loose sand	4.9×10^{-4} to 1.0×10^{-3}
Dense sand	1.3×10^{-4} to 2.0×10^{-4}
Dense, sandy gravel	4.9×10^{-5} to 1.0×10^{-4}
Rock, fissured	3.3×10^{-6} to 6.9×10^{-5}
Rock, sound	$< 3.3 \times 10^{-6}$

- 9.18 Porosity values in **Table 5** of 0.01 mean that the aquifer materials are only capable of holding 1% of their volume in water, which is incorrect for highly permeable gravel aquifers. Porosity values for clean gravels are more likely to be in the range of 30%. Furthermore, porosity is likely to vary with depth, yet AquaLinc (2007) implements a constant value with depth, which does not appear to be conceptually based.
- 9.19 In summary, the values of specific storage calculated in **Table 7** show far too much variation from that of water compressibility and hence they imply impossibly high or low values of aquifer compression and /or porosity. It indicates to me that the modeller is using the specific storage input parameters inappropriately and is artificially trying to raise and lower the effective specific storage to compensate for errors elsewhere in the model. These errors may include abstractions, vertical flow processes (i.e. leakage through the aquitards) or hydraulic conductivity.

10. MODEL RUN-TIMES

- 10.1 In addition to the unsaturated zone calculations in FEMWATER contributing to significant runtimes (**Section 5**), the model is setup with constant daily time steps that further contributes to this problem.
- 10.2 For a regional groundwater model considering impacts on groundwater levels and stream baseflows⁷, and not surface runoff or quickflow, daily timesteps are unnecessary.
- 10.3 For this application a variable timestep would be more appropriate whereby high river stage conditions that are likely to result in significant aquifer recharge are simulated with a fine timestep (in the order of days or weekly), while interim dry times and period of receding river levels are simulated with progressively coarser timesteps (up to a maximum of say two-monthly).

11. MODEL WATER BALANCE

- 11.1 **Figure 15** of Weir (2008) provides a water budget for Status Quo and Proposed Development scenarios simulated in the model.

⁷ Baseflow is the groundwater seepage component of streamflow.

- 11.2 There is a very significant problem with the water budgets in both scenarios in that neither is balanced. The differences I calculate from the data provided are 5.6 m³/s for the Status Quo and 5.1 m³/s for the Proposed Development scenarios, respectively⁸. These represent mass balance differences of 19% and 17% of the inputs for each scenario, which is far higher than the acceptable tolerance of 1% (MDBC, 2000).
- 11.3 This in my mind creates suspicion that something is lacking in the model and leads to further uncertainty in the robustness of the model. As discussed in **Section 5.16**, the missing element may be associated with the inability to report changes in aquifer storage or it may be associated with the models inability to report wells switching off and on.

12. MODEL CALIBRATION

- 12.1 On face value the calibration hydrographs and observed versus modelled error statistics look acceptable, but given the significant issues identified above with respect to:
- (a) The appropriateness of some of the model hydraulic parameters; and
 - (b) The inadequacies of the model to accurately report pumping rates and storage changes.

It is very likely that the model is strongly non-unique, and hence not an appropriate tool for predictive analysis (i.e. there can be no certainty over what it is predicting).

13. MODEL RESULTS

- 13.1 Because of the many uncertainties and deficiencies identified above, I can have no confidence in the model results. I do find it difficult to believe that an application of this scale can have negligible adverse effects on most surface water bodies in the area, as suggested in Weir (2008). Again, I believe this to be a function of the incorrect model

⁸ Note that Figure 15 actually reports differences of 7.4 and 7.3 m³/s, but this errors to be a typing error.

conceptualisation and deficiencies in FEMWATER's water balance accounting.

14. CONCLUSION

- 14.1 FEMWATER has serious deficiencies that would make it generally unsuitable for running a model of this type – in particular its inability to accurately report pumping rates and storage changes make it an unsatisfactory code for assessing aquifer response to pumping stresses.
- 14.2 The inclusion of an unsaturated zone model is mandatory in FEMWATER but is both unnecessary and problematic in that it has slowed model run times to the point where efficient modelling operations have been seriously impaired.
- 14.3 Such lengthy run times are quite inappropriate for a calibration model that must be run repeatedly, with typically tens or even hundreds of model runs usually required to reach an acceptable level of calibration and sensitivity analysis.
- 14.4 The hydrogeological conceptualisation has been misrepresented in the model by the inclusion of impermeable barriers to vertical flow when competent aquitards (or aquicludes) are apparently not encountered in drill holes in this area. As a result it is highly likely that the model is underestimating the impacts of deep pumping on shallow aquifers and on surface waters.

15. RECOMMENDATION

- 15.1 I strongly believe that there is too much uncertainty associated with FEMWATER and some of the conceptualisations and parameter selections built into this model to make a well informed decision on the matter before us.
- 15.2 The work undertaken in developing the fundamental datasets for the model appears to have been completed in an appropriate manner. In addition, because AquaLinc used the GMS interface to run FEMWATER, many of the datasets will be developed in a GIS (spatial) database.

Therefore, it would be a relatively straight task (compared to the work done to-date) to transpose the model into a more appropriate platform.

- 15.3 I recommend that the model be transposed into another finite element modelling code to enable a risk averse decision to be made. In this regard, I would recommend FEFLOW because i) it has the ability to select simulation of saturated groundwater flow only; ii) constraint conditions can be applied to pumping well so that the discharge rate reduces from the set rate depending on the water availability in the aquifer; and iii) it allows full water balance accounting.

JON WILLIAMSON

July 2008

16. REFERENCES

- Anderson, M. a. (1992). *Applied Groundwater Modelling - Simulation of Flow and Advective Transport*. Academic Press.
- AquaLinc Research Limited. (2007). *Canterbury Groundwater Model 2*.
- Davey, G. (2007). *Addendum to Environment Canterbury Reports U06/08 and U06/10*.
- Domenico, P., & Mifflin, M. (1965). Water From Low-Permeability Sediments and Land Subsidence. *Water Resources Research* , vol. 1 (4), 563-576.
- Fietje, L. (2008). *Evidence - Valetta and Ashburton Groundwater Management Zones Water Take Hearings*.
- Merrick, N. (2007). *Review of Canterbury Groundwater Model 2, New Zealand*.
- Murray-Darling Basin Commision. (2000). *Groundwater Flow Modelling Guideline*.
- Smith, M. (2008). *Evidence - Valetta and Ashburton Groundwater Management Zones Water Take Hearings*.
- Weir, J. (2008). *Evidence - Valetta and Ashburton Groundwater Management Zones Water Take Hearings*.

APPENDIX A.**EXAMPLES OF RECENT PROJECTS**

Upper Waikato River Landuse Change Flood Modelling Studies. Environment Waikato.

Hydrogeological Studies. Pike River Coal Limited.

Regional Evapotranspiration Study for the Waikato Region. Environment Waikato.

Member of the Waikato River Flood Hydrology Expert Technical Panel. Environment Waikato comprising technical representatives from key stakeholders (Mighty River Power, Carter Holt Harvey, Wairakei Pastoral Ltd, Environment Waikato).

Limestone Quarry Water Supply & Water Management Plan Assessment. McDonalds Lime Limited.

Esk River Hydropower Development. Trustpower Ltd.

Takou Bay Station Irrigation Dam Feasibility Analysis. Landcorp Farming Limited.

Traveston Crossing Dam Environmental Impact Statement. Queensland Water Infrastructure. Internal reviewer.

Hinz Dam Raising Project. SunWater Queensland. Internal reviewer.

Options to Improve Water Allocation Outcomes (2006). Report Prepared for the Ministry for the Environment, Ministry for Agriculture and Forestry, and Ministry of Economic Development.

Tairua-Pauanui Water Supply Scheme Options Assessment & Development of Water Management Strategy. Thames Coromandel District Council.

Waiheke Island – Groundwater Model Development for Sustainable Yield Assessment. Auckland Regional Council.

Victoria Park Tunnel. Hydrogeological Drilling, Test Pumping and Dewatering Analysis for Specimen Design. Transit NZ.

Kawakawa Water Supply – Riverbank Filtration Borefield. Scheme Development Review. Far North District Council.

Concept Design & Resource Consenting of a 400 ML Avocado Irrigation Dam. Clearwater Orchard Limited.

National Cost Benefit Analysis of Water Allocation in the Waitaki Catchment. Environmental Analysis. Ministry of Economic Development.

Aratiatia Station Irrigation Concept Planning. Landcorp Farming Ltd.

National Irrigation Concept Planning & Scoping Study. Landcorp Farming Ltd.

Expert Witness for Wairakei Pastoral Limited on Ecologic Hearing (Waikato). June 2005.

National Farm Water Supply Study. Landcorp Farming Limited.

Rangiputa Station Groundwater Supply & Farm Drainage Study. Landcorp Farming Limited.

Sweetwaters Station Dairy Farm Supply Consents. Landcorp Farming Limited.

Westcoast Farms Land Development Project Resource Consents. Landcorp Farming Limited.

Otway Basin (Paeroa-Tahuna Rd) Proposed Drainage Scheme Hydrogeological Investigation and Assessment of Engineering Design Options. Environment Waikato.

Southland Regional Landfill Statement of Evidence on Hydrogeological, Surface Water and Ecological Matters.

Tasman Solid Waste Landfill Hydrogeological Security Review. Norske Skog Limited.