Freshwater resources management: Starting SMART characterization of New Zealand's aquifers

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Abstract

The overall aim of the proposed research is to develop a suite of highly innovative methods for characterizing New Zealand's groundwater systems. Information needs will be determined by stakeholder consultation, but are likely to include the measurement of groundwater volume and changes over time, aquifer hydraulic properties, and fluxes of groundwater interchange with surface waters. Traditional methods for determining these properties exist — drilling, aquifer pump testing, river gauging — but are too time consuming and costly for wide scale application. We will focus on novel methods that provide the most accurate data "passively," meaning they rely on existing data sources wherever possible, or on new measurements that can be made over large areas with little effort and minimal cost. The methods to be used will be prioritized through stakeholder consultation but may include ambient noise seismic tomography, airborne geophysical surveying, satellite remote sensing, and real-time fiber optic temperature sensing. Validation will be achieved through use of multiple methods in case study areas yet to be selected, and by "ground-truthing" the existing data obtained from traditional methods. Foreseen are Sensor Web Solutions where timely in situ field measurements will be available online and serve as a validation source for the satellite monitoring results. Overarching research will be undertaken in order to develop a consistent and objective framework for quantification of uncertainty, and a web portal which is used for amalgamating harmonised 3D groundwater datasets will be available and help to meet stakeholder needs for open access, ease of use, and interoperability with existing systems.

Introduction

Groundwater resources account for about half of New Zealand's abstractive water needs (White 2001). Groundwater supplies about 80 percent of all water used in the agricultural sector (White 2001,Rajanayaka et al. 2010) which is valued at about NZ$17 billion, or 10 percent of the GDP (Statistics New Zealand 2010a). Groundwater also supplies the base flow to streams and springs, which are vital to the nation's NZ$7 billion tourism industry (Statistics New Zealand 2010b) and to the cultural, environmental and recreational values of New Zealanders. The reliance on groundwater will increase in the future since the surface water is fully allocated in many catchments (White 2001, Rajanayaka et al. 2010).

Despite the importance of New Zealand's groundwater resources, we still lack essential information related to their basic properties which are required to avoid overexploitation of resources and water scarcity situations where humans and the economy will be stressed due to insufficient water supply. The issues which will be addressed in this research program will be determined by stakeholder consultation, but are likely to include the following:

> • *The total volume of groundwater, nationally and in individual aquifers, and changes in it over time, has only been estimated crudely (White and Reeves 2002, White 2007). Groundwater volume storage is a key term in the water balance equation. Without this information it is impossible to determine whether current allocation limits are sustainable, or to what extent we are "mining"*

> *groundwater in some aquifers.*
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> *• Aquifer hydraulic properties have been measured for very few wells. Hydraulic conductivity is a key variable in Darcy's Law, the main equation describing groundwater flow, but a recent national compilation indicates that it has been robustly measured at only 200 wells (Meilhac et al. 2010). Transmissivity and storativity have been robustly measured at only 2.300 wells. Without knowing an aquifer's hydraulic properties, it is impossible to apply groundwater models of any type or at any scale. It is also impossible to evaluate local or cumulative effects of pumping at the estimated 13,000 wells across New Zealand that have consents to abstract groundwater but at which hydraulic properties are unknown.*
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> *• Fluxes across the groundwater surface water interface are not known. This includes the locations and volumes of groundwater recharge from rainfall, and groundwater interchange with streams, rivers and lakes. Without this information it is very difficult to manage the water resource holistically.*
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> *• Groundwater age still needs to be determined and refined at the aquifer scale. Without understanding groundwater age, the development of effective management strategies is severely hampered by an inability to establish cause-and-effect in terms of aquifer response to human influence.*

Traditional methods for aquifer mapping and characterization exist but they are prohibitively time consuming and too costly for wide scale application. Such methods also generally provide data at very limited spatial and temporal resolution. The traditional method for estimating aquifer volume is to drill boreholes at several locations in order to determine the depth to the basement, ideally in conjunction with some type of geophysical survey to interpolate the basement surface between boreholes. Hydraulic properties are typically determined by aquifer testing, in which water is pumped from the well of interest while groundwater levels are monitored at nearby boreholes. Fluxes of water into or out of a stream are typically quantified by concurrent gauging surveys, in which discharge is compared between two stream reaches. Rainfall recharge to aquifers is traditionally measured using paired lysimeters; however, fewer than ten lysimeter stations are currently operating in New Zealand, providing extremely poor coverage of the spatial variation of rainfall recharge. The determination of groundwater age at the aquifer scale requires a time-series analysis of tracers, such as tritium, in multiple wells. Overall, it is reasonable to estimate that national mapping of aquifers using traditional techniques would cost between NZ$20-$30 million, and require a decade or more to complete.

The overall aim of the SMART Aquifer Characterization research program is to assemble and validate a suite of highly innovative techniques that can be applied in order to map and characterize New Zealand's aquifers. The methods to be used will be prioritized through stakeholder consultation but may include ambient noise seismic tomography, airborne geophysical surveying, satellite remote sensing, fiber optic temperature sensing, and novel age tracers (Table 1). The emphasis will be on techniques that provide accurate data "passively," meaning that they rely on existing data sources wherever possible, or on new measurements that can be made over large areas with little effort and minimal cost. Validation will be achieved by the use of multiple methods in case study areas yet to be selected, and by "ground-truthing" of existing data, obtained from traditional methods. Overarching research will be undertaken to develop both a:

> *1. Consistent objective framework for quantification of uncertainty, and*
>
> *2. A web portal and harmonised 3D groundwater database that will meet stakeholder needs for open access, ease of use, and interoperability with existing systems.*

The structure of the research program is shown in Figure 1.

Table 1: Aquifer properties to be measured and proposed methods to be applied in the Smart Aquifer Characterization research program.

Figure 1: Research program structure. Four of the Research Aims are for over-arching activities; the remaining four are based on methods listed in Table 1. Most Research Aims will be co-led by NZ and EU researchers. The program will support four PhD students and one post-doctoral fellow, to be co-supervised by NZ and EU researchers.

Methods to be used

The characterization of New Zealand’s aquifers will be facilitated through techniques and methodologies from geophysics, satellite remote sensing, and novel age tracers. Harmonisation of datasets and seamless visualisation in three-dimensional WebGIS are key for communication and decision making.

Geophysics

About 15,000 earthquakes, most of them minor, are recorded in New Zealand each year. Seismic signals from the earthquakes, recorded by the GeoNet Network, are a rich source of data that is in many ways the same as signals obtained from active seismic surveying. Method 1 will involve the use of seismic response to earthquakes to develop a map depicting aquifer thickness (Yordkayhun et al. 2009), from which groundwater volume will be estimated. Method 2 is based on ambient monitoring between periods of earthquake activity (Lin et al. 2007, Behr et al. 2010). Autocorrelation of ambient noise signals from any single seismic monitoring station can be used to determine the depth to the basement at that location, whereas cross-correlation of ambient noise between pairs of stations can be used to determine the depth to the basement along a section. Method 3 will infer local aquifer hydraulic properties based on observed groundwater level changes recorded across much of New Zealand after the Christchurch earthquakes (Cox et al. 2010a, Cox et al. 2010b, Ezzy et al. 2010). This is analogous to a traditional aquifer test, where the earthquake response is used instead of a pump to perturb the groundwater level (Wang and Manga 2010). Method 4 will aim at determining aquifer hydraulic properties by establishing the relationships between traditional aquifer test data and seismic velocities inferred from Methods 1 and 2 (Telesca 2010, Hyndman et al. 2000). This research will also employ airborne electromagnetic (EM) techniques that will be complementary to the seismic methods described above. EM surveys have been recently carried out by GlassEarth Ltd. and Otago Regional Council over 13.000 kilometers2 of Otago and 8,000 kilometers2 of the Taupo Volcanic Zone. This EM data is now publicly available through Crown Minerals and has proved to be valuable in the groundwater context (Houlbrooke and Rekker 2010). Method 5 will use the EM data to determine and spatially resolve aquifer thickness and degree of saturation with groundwater (Siemon et al. 2009). Method 6 will use the EM data to infer the clay and silt content of the aquifer, which in turn relates to aquifer hydraulic properties (Siemon et al. 2009, Robinson et al. 2008).

Satellite Remote Sensing

Many recent advances in satellite remote sensing are applicable to groundwater characterization (Brunner et al. 2007). Most techniques have not been used in New Zealand, even though much of the satellite data is free or low cost. Method 7 will test GRACE satellite gravimetry as an indicator of seasonal change in groundwater volume over large spatial scales (Andersen et al. 2005, Ramillien et al. 2005). Method 8 will apply satellite differential synthetic aperture radar (InSAR) to evaluate seasonal changes in groundwater volume at a finer spatial scale, inferred from sub-centimeter changes in ground elevation caused by groundwater abstraction (Galloway and Hoffmann 2007). Method 9 will evaluate spatial distribution of rainfall recharge to groundwater, based on the difference between precipitation and evapotranspiration, both of which can be estimated from satellite data collected by ASAR, MODIS, LANDSAT, ASTER, GRACE and the Sentinel-1 which is set to be launched in 2013 (Swenson and Wahr 2006). Method 10 will test satellite thermal imagery from MODIS and ASTER to evaluate river temperatures, from which zones of groundwater inflow to the river may be identified (Kay et al. 2001). This research will link with FP7 projects on global water scarcity including GLOWASIS, and land subsidence in coastal lowlands as seen in SUBCOAST.

Temperature Sensing

This research will evaluate recently developed methods for mapping the locations, time scales and volumes of water fluxes between groundwater and surface water in the river-aquifer continuum. In areas where groundwater-river interaction is identified from satellite imagery or traditional concurrent gauging surveys, method 11 will develop finer spatial and temporal scale maps of groundwater-river interchange using distributed temperature sensing (DTS). DTS makes use of a fiber optic cable up to 3 kilometers long that is immersed in a river. Based on back-scattering of light though the cable, river water temperature can be determined (Selker 2008). From this, locations of groundwater inflow to the river can be identified in real time at a resolution of about 1 m (Westhoff et al. 2007). Method 12 will use vertical profiling of water temperature beneath the river bed to quantify fluxes between groundwater and the river, as we recently demonstrated in the Ruataniwha Plains (Meilhac et al. 2009).

Novel Age Tracers

Tritium is the ideal tracer for water age. While existing methods for analysis are highly accurate, they have a turnaround time of about one month. Method 13 will investigate the use of accelerator mass spectrometry for tritium analysis in a matter of minutes (Povinec 2010, Chiarappa-Zucca et al. 2002). Method 14 will develop new gas tracers to replace the chlorofluorocarbons, which are becoming less useful for water dating due to declension the atmospheric concentration following the Montreal Protocol (Archie 1999, Mcculloch et al. 2003, Culbertson et al. 2004). Method 15 will establish methods for estimating age based on chemical proxies, including commonly monitored chemical parameters. For example, concentrations of major ions and silica can be related to water age by statistics or partial equilibrium thermodynamics (Daughney et al. 2010, Glynn and Plummer 2005).

Uncertainty Quantification

Uncertainty quantification (UQ) overarches all lines of investigation in this proposal, because none of the aquifer properties listed in Table 1 can be directly measured very inexpensively or very accurately. Thus, the observational data must be used to infer the aquifer properties of interest, based on computer simulations of the groundwater system. This research aims to develop a consistent and objective framework for UQ. UQ will be applied to the forward problem, which refers to the computational simulation of the groundwater system, and to the inverse problem, which relates to calibration or “ground-truthing” of the computational model to the observational dataset. UQ will be formulated in the context of Bayesian inference, in which all uncertainties are modelled as probability distributions that are propagated through the computational models (Fox 2008).

Data Synthesis and Visualization

Aquifers are inherently three-dimensional in their geometry and some properties, such as groundwater volume, may vary with time (White 2009, White and Reeves 1999). Three-dimensional and four-dimensional databases and visualization systems are therefore required for all aspects of this project. This research aim will develop a harmonized data portal for 3D and 4D groundwater information that will build upon existing NZ and EU systems, and meet the needs of stakeholders in terms of open access, interoperability and ease of use. Web enablement of real-time in-situ sensors (Bröring et al. 2011) will be used to obtain data for ground-truthing the methods to be developed in other research aims.

Authors

Hermann Klug's research expertise focuses on the development of holistic landscape planning approaches using GIS and Remote Sensing for integrated water resources and landscape management. Involved in several transdisciplinary projects, Klug is working at the interface of the climatology, pedology and hydrology with a special focus on harmonization processes of environmental datasets and setting up of Spatial Data Infrastructures and WebPortal services.

Christopher Daughney is an aqueous environmental geochemist with research interests in experimental and modelling approaches for characterizing chemical equilibria in water rock systems. His special areas of interest include: 1) chemical evolution of groundwater at the catchment scale and the use of tracer methods for evaluating in-situ chemical processes such as groundwater-surface water interaction and rates of water-rock interaction, and 2) surface complexation modelling of adsorption of metals and organics by mineral surfaces and bacterial cells. His scientific reputation is indicated by more than 400 citations to his research articles in the last 10 years, and by his appointment as an Associate Editor of the prestigious journal Geochimica et CosmochimicaActa (2007 to present).

Floris Verhagen is a geo hydrologist with interest in all aspects of groundwater management. Specifically, he is dealing with quantity/quality, monitoring/modeling, and technical/policy aspects. He has special interest in integrating different results in an overall analysis of system behavior of the water system. He has special interest in the behavior of interaction of ground water and surface water. This interaction is evident all over the Netherlands, but it lacks sufficient knowledge about this behavior.

Rogier Westerhoff is dealing with the incorporation of Earth observation and geo-hydrological sensor network technology in flood and drought warning systems. His personal focus is on global research on Earth observation techniques in water management.

Nicholas Dudley Ward is an Applied Mathematician and Engineer specializing in simulation modeling of natural processes. He has considerable expertise in the mathematics underlying the numerical computation and hence accurate simulation of physical processes, as well as probability theory which underlies the rigorous quantification of uncertainty.

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References

Andersen, O.B., Seneviratne, S.I., Hinderer, J., Viterbo, P. 2005. GRACE-derived terrestrial water storage depletion associated with the 2003 European heat wave. Geophys. Res. Lett., 32 (18): L18405.

Archie, M. 1999. CFC and Halon replacements in the environment. Journal of Fluorine Chemistry, 100 (1-2): 163-173.

Behr, Y., Townend, J., Bannister, S., Savage, M.K. 2010. Shear velocity structure of the Northland Peninsula, New Zealand, inferred from ambient noise correlations. J. Geophys. Res., 115 (B5): B05309.

Bröring, A., Echterhoff, J., Jirka, S., Simonis, I., Everding, T., Stasch, C., Liang, S., Lemmens, R. 2011. New Generation Sensor Web Enablement. Sensors, 11 (3): 2652-2699.

Brunner, P., Hendricks Franssen, H.J., Kgotlhang, L., Bauer-Gottwein, P., Kinzelbach, W. 2007. How can remote sensing contribute in groundwater modeling? Hydrogeology Journal, 15 (1): 5-18.

Chiarappa-Zucca, M.L., Dingley, K.H., Roberts, M.L., Velsko, C.A., Love, A.H. 2002. Sample Preparation for Quantitation of Tritium by Accelerator Mass Spectrometry. Analytical Chemistry, 74 (24): 6285-6290.

Cox, S.C., Quigley, M., Villamor, P., Beavan, R., Ristau, J. Teams from University of Canterbury and GeoNet-GNS Science (2010). The Canterbury earthquake: Overview summary. New Zealand Hydrological Society Conference, 2010a.

Cox, S.C., Song, S.H., White, P., Davie, T., Davidson, P., Strong, D. The Canterbury and other earthquakes: Far field effects on groundwater. New Zealand Hydrological Society Conference, 2010b.

Culbertson, J.A., Prins, J.M., Grimsrud, E.P., Rasmussen, R.A., Khalil, M.a.K., Shearer, M.J. 2004. Observed trends for CF3-containing compounds in background air at Cape Meares, Oregon, Point Barrow, Alaska, and Palmer Station, Antarctica. Chemosphere, 55 (8): 1109-1119.

Daughney, C., Morgenstern, U., Van Der Raaij, R., Reeves, R. 2010. Discriminant analysis for estimation of groundwater age from hydrochemistry and well construction: application to New Zealand aquifers. Hydrogeology Journal, 18 (2): 417-428.

Directive. 2007/2/EC. Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE). http://tinyurl.com/65pzem5

Ezzy, T.R., Scott, D., Cox, S.C., Collins, D., Weeber, D., Durney, P. The Darfield earthquake: Groundwater response in Canterbury. New Zealand Hydrological Society Conference, 2010.

Fox, C. 2008. Recent advances in inferential solutions to inverse problems. Inverse Problems in Science and Engineering, 16 (6): 797-810.

Galloway, D., Hoffmann, J. 2007. The application of satellite differential SAR interferometry-derived ground displacements in hydrogeology. Hydrogeology Journal, 15 (1): 133-154.

Glynn, P.D., Plummer, L.N. 2005. Geochemistry and the understanding of ground-water systems. Hydrogeology Journal, 13 (1): 263-287.

Houlbrooke, C., Rekker, J. Application of airborne geophysical data for groundwater resource management in the Tarras-Bendigo Basin, Otago. New Zealand Hydrological Society Conference, 2010.

Hyndman, D.W., Harris, J.M., Gorelick, S.M. 2000. Inferring the relation between seismic slowness and hydraulic conductivity in heterogeneous aquifers. Water Resour. Res., 36 (8): 2121-2132.

Kay, J., Handcock, R.N., Gillespie, A., Konrad, C., Burges, S., Naveh, N., Booth, D. Stream-temperature estimation from thermal infrared images. International Symposium on Geoscience and Remote Sensing, 2001. 112-114.

Lin, F.-C., Ritzwoller, M.H., Townend, J., Bannister, S., Savage, M.K. 2007. Ambient noise Rayleigh wave tomography of New Zealand. Geophysical Journal International, 170 (2): 649-666.

Mcculloch, A., Midgley, P.M., Ashford, P. 2003. Releases of refrigerant gases (CFC-12, HCFC-22 and HFC-134a) to the atmosphere. Atmospheric Environment, 37 (7): 889-902.

Meilhac, C., Cameron, S., Minni, G. 2010. Compilation of aquifer test data for sites in the National Groundwater Monitoring Programme. GNS Science Report 2009/19. xx p.

Meilhac, C., Reeves, R.R., Zemansky, G., White, P.A., Jebbour, N. 2009. Field investigation of groundwater-surface water interactions, Ruataniwha Plains. xx p.

Povinec, P. 2010. Trends in radiometrics and mass spectrometry technologies: synergy in environmental analyses. Journal of Radioanalytical and Nuclear Chemistry, 286 (2): 401-407.

Rajanayaka, C., Donaggio, J., Mcewan, H. 2010. Update of water allocation and estimates of actual water use of consented takes – 2009-2010. Aqualinc Research Report H10002/3. xx p.

Ramillien, G., Frappart, F., Cazenave, A., Güntner, A. 2005. Time variations of land water storage from an inversion of 2 years of GRACE geoids. Earth and Planetary Science Letters, 235 (1-2): 283-301.

Robinson, D.A., Binley, A., Crook, N., Day-Lewis, F.D., Ferré, T.P.A., Grauch, V.J.S., Knight, R., Knoll, M., Lakshmi, V., Miller, R., Nyquist, J., Pellerin, L., Singha, K., Slater, L. 2008. Advancing process-based watershed hydrological research using near-surface geophysics: a vision for, and review of, electrical and magnetic geophysical methods. Hydrological Processes, 22 (18): 3604-3635.

Selker, J. 2008. Fiber optics for environmental sensing. Sensors 25: 5.

Siemon, B., Christiansen, A.V., Auken, E. 2009. A review of helicopter-borne electromagnetic methods for groundwater exploration. Near Surface Geophys., 7: 629- 646.

Statistics New Zealand 2010a. National accounts: Year ended 2010. Statistics New Zealand 2010a. National accounts: Year ended 2010. Statistics New Zealand 2010a. National accounts: Year ended 2010.

Statistics New Zealand 2010b. Tourism satellite account. Statistics New Zealand 2010b. Tourism satellite account. Statistics New Zealand 2010b. Tourism satellite account.

Swenson, S., Wahr, J. 2006. Estimating Large-Scale Precipitation Minus Evapotranspiration from GRACE Satellite Gravity Measurements. Journal of Hydrometeorology, 7 (2): 252-270.

Telesca, L. 2010. Analysis of the Cross-Correlation between Seismicity and Water Level in the Koyna Area of India. Bulletin of the Seismological Society of America, 100 (5A): 2317-2321.

Wang, C.-Y., Manga, M. 2010. Earthquakes and Water. Berlin: Springer-Verlag. 225 p.

Westhoff, M.C., Savenije, H.H.G., Luxemburg, W.M.J., Stelling, G.S., Van De Giesen, N.C., Selker, J.S., Pfister, L., Uhlenbrook, S. 2007. A distributed stream temperature model using high resolution temperature observations. Hydrol. Earth Syst. Sci., 11 (4): 1469-1480.

White, P.A. 2001. Groundwater resources in New Zealand. In: Rosen, M.R.,White, P.A. (eds.) Groundwaters of New Zealand. Wellington: New Zealand Hydrological Society, 47-75.

White, P.A. 2007. New Zealand groundwater volumes – Update for June 2005. Unpublished letter report to Statistics New Zealand. xx p.

White, P.A. 2009. Avon River springs catchment, Christchurch City, New Zealand. Australian Journal of Earth Sciences, 56 (1): 61-70.

White, P.A., Reeves, R.R. 1999. Waimea Plains aquifer structure as determined by three-dimensional computer modelling. J. Hydrol. NZ, 40: 49-75.

White, P.A., Reeves, R.R. 2002. The volume of groundwater in New Zealand 1994 to 2001. GNS Science Client Report 2002/79. xx p.

Yordkayhun, S., Tryggvason, A., Norden, B., Juhlin, C., Bergman, B. 2009. 3D seismic traveltime tomography imaging of the shallow subsurface at the CO2SINK project site, Ketzin, Germany. Geophysics, 74: G1-G15.