

# Evaluation of selected satellite remote sensing methods for characterising New Zealand aquifers

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## Abstract

Satellite remote sensing methods related to terrestrial hydrology hold promise for the future, but their current utility for aquifer characterisation is highly questionable. One objective of the GNS SMART aquifer characterisation (SAC) project called for assessing the potential application of satellite remote sensing methods to characterise New Zealand aquifers. Four methods were specified in the project proposal: (1) using GRACE satellite gravimetry to indicate seasonal change in groundwater volume over large areas; (2) using interferometric synthetic aperture RADAR (InSAR) to evaluate seasonal changes in groundwater volume caused by groundwater abstraction at a finer spatial scale than GRACE; (3) using satellite estimates of precipitation (P) and evapotranspiration (ET) to estimate rainfall recharge by their difference (i.e.,  $P - ET$ ); and (4) satellite thermal infrared (TIR) imagery to identify zones of groundwater inflow to rivers. Two additional methods came up during the assessment: (1) estimation of soil moisture from satellite remote sensing data, both with regard to its role in groundwater recharge and as a surrogate for identifying variation in depth of the shallow groundwater table; and (2) modelling of an equilibrium water table to estimate water table depth using satellite remote sensing input data.

The first step of the project for this objective was a review of the world-wide scientific literature in order to decide which methods had potential for improved characterisation of New Zealand aquifers and should proceed to testing in New Zealand catchments. This review indicated that five of these six methods are not currently useful for this purpose in New Zealand. However, it was concluded that the use of InSAR technology for both estimating seasonal changes in groundwater volume and for quantification of confined aquifer specific storage and confining layer vertical hydraulic conductivity has potential utility for New Zealand and merits further assessment. It was recommended that this method be applied to test catchments in New Zealand during the next phase of the project.

## Keywords

satellite remote sensing, GRACE gravimetry, InSAR, subsidence, uplift, electromagnetic, microwave, soil moisture, evapotranspiration, precipitation, thermal infrared, aquifer characterisation, rainfall recharge, shallow groundwater table, equilibrium water table

## Introduction

The SMART aquifer characterisation project came out of a joint meeting co-hosted by the European-New Zealand bilateral project FRENZ (Facilitating Research co-operation

between Europe and New Zealand) and the New Zealand Foundation for Research, Science and Technology (FRST) (which later became the Ministry of Science and Innovation (MSI), now part of the Ministry of Business, Innovation and Employment (MBIE)). This meeting took place in Rotorua in March 2011 and was attended by selected scientists from Europe and New Zealand, including one from GNS. GNS focussed on the research question posed for the meeting: “How might groundwater resources be consistently characterised and mapped at the national and regional scales” (FRENZ and FRST, 2011).

As a result of the meeting, MSI later provided GNS and its European co-operators with a research grant to ‘identify, develop, apply, validate, and optimise a suite of novel methods for accurate, rapid cost-effective characterisation and mapping of New Zealand’s aquifer systems’ (Daughney, 2011; GNS and MSI, 2011). This research project became known as the SMART Aquifer Characterisation (SAC) project, with the acronym SMART standing for ‘save money and reduce time’. The focus of this research was novel methods that provide accurate data ‘passively,’ i.e., relying on existing data sources wherever possible, or on new measurements that can be made over large areas with little effort and minimal cost (Daughney, 2011; GNS and MSI, 2011). These novel methods would be used to supplement traditional aquifer characterisation methods. The SAC project paired a New Zealand scientist working with a European scientist in each research aim.

One aim was to assess the potential for existing satellite remote sensing methods ‘to advance the understanding of aquifer systems in New Zealand’ (GNS and MSI, 2011). Four satellite remote sensing methods were to be considered: (1) using GRACE satellite gravimetry to indicate seasonal change in groundwater volume over large areas;

(2) using interferometric synthetic aperture radar (InSAR) to evaluate seasonal changes in groundwater volume caused by groundwater abstraction, at a finer spatial scale than GRACE; (3) estimating the distribution of rainfall recharge to groundwater, based on the difference between (satellite) precipitation (P) and evapotranspiration (ET); and (4) using satellite thermal infrared (TIR) imagery to identify ‘zones of groundwater inflow to ... river(s)’ (Daughney, 2011; GNS and MSI, 2011).

The first step of the project was to review the four methods and select those potentially useful in New Zealand. Test applications of potentially useful methods would take place in the next step of the project. At the outset, it was recognized that GRACE satellite gravimetry and TIR were unlikely to be useful due to scale limitations and that there were conceptual problems with  $P - ET$  as an indicator of rainfall recharge to groundwater.

This paper reports primarily on the initial review of the four satellite remote sensing methods. In addition, this review discusses the potential utility of an additional satellite remote sensing method that came up during the project (i.e., use of satellite data to estimate soil moisture) and the concept of a long-term or ‘equilibrium’ groundwater table advocated by one of the European co-operators as being related to satellite remote sensing.

### **Characteristics of New Zealand aquifers relevant to satellite remote sensing**

The nature of New Zealand aquifer systems is an important factor in determining the potential applicability of satellite remote sensing methods. The initial step of the SAC project called for evaluating the existing state of knowledge regarding New Zealand aquifers, including both a literature review and a compilation of national, regional, and aquifer-scale datasets (GNS and MSI, 2011). However, GNS concluded that this step

could not be achieved within the allocated time frame and budget and, therefore, it was not carried out. It thus became necessary to rely on limited historic information, such as that found in Rosen and White (2001) and White and Reeves (2002). Those references constitute the best available compilations, but provided only sparse coverage at the time they were written and are further outdated today. Better information is available, but has generally not been compiled.

There are important limitations to the use of satellite remote sensing. Satellite imagery, being obtained from high altitudes, covers large areas and may have limited spatial resolution. Signal noise is also greater than for ground or even aerially-based sensing methods. This results in three important shortcomings:

1. Resolution – While some satellite methods can achieve better resolution (on the order of metres), others have relatively coarse spatial resolution (on the order of tens to hundreds of kilometres);
2. Vegetation – Some satellite methods may be less effective over densely vegetated areas such as forests, because the signal from the Earth’s surface either cannot reach the satellite or is otherwise affected

by the presence of vegetation (Wagner *et al.*, 1999);

3. Topography – Satellite methods can be affected by topography in areas of steep terrain (van Zyl *et al.*, 1993). Correction factors for the RADAR backscatter coefficient are therefore sometimes applied to improve accuracy of soil moisture estimates in mountainous areas (Goyal *et al.*, 1999), while other scientists simply flag the data as erroneous in areas where surface topography angles exceed 20° to 25° (W. Dorigo as cited by Zemansky and Westerhoff, 2015).

Resolution is a particularly important factor, as New Zealand aquifers are typically small in areal extent (Table 1). Based on professional judgement, 60% can be classified as small (i.e., less than 100 km<sup>2</sup>) and the largest single New Zealand aquifer is only 5,330 km<sup>2</sup>, while the largest combination of adjacent aquifers (i.e., in the Canterbury region) totals less than 8,000 km<sup>2</sup>. The estimated combined area of all New Zealand aquifers is only 79,800 km<sup>2</sup>, or about 30% of the 269,000 km<sup>2</sup> total area of the country (MfE, 2009). In comparison, a single large aquifer in the United States, the Ogallala aquifer, covers 451,000 km<sup>2</sup> (Hornbeck and

**Table 1** – Areal extent of aquifers in New Zealand.

Size of New Zealand Aquifers (km <sup>2</sup> )*					
Minimum	Median	Mean	Maximum	Std Dev	Count
2	50	385	5,330	832	207
*Total area of all New Zealand aquifers: 79,800 km <sup>2</sup>					
Small			Size Classification of New Zealand Aquifers		
Small			Medium		
Small			Large		
<100 km <sup>2</sup>			100 – 1,000 km <sup>2</sup>		
124 aquifers			58 aquifers		
60%			28%		
>1,000 km <sup>2</sup>			25 aquifers		
			12%		

Source: Unpublished data, compiled during preparation of White and Reeves (2002)

Keskin, 2012). Based on this factor alone, the resolution of GRACE satellite gravimetry is too coarse for application to any single New Zealand aquifer.

Land cover and topography are particularly important factors in New Zealand. Most of New Zealand's land area lies under substantial vegetation and consists of relatively high and steeply-sloping terrain. Approximately 50% of New Zealand land cover is classified as native forest, while another 11% is classified as exotic forest and shrubland or horticulture (MfE, 2009). Only about one-third of the area of New Zealand is classified as 'flat to rolling country' with slopes of 16° or less, while the remaining two thirds is relatively steep hill or mountainous terrain (Moot *et al.*, 2013). More than half of the land in New Zealand has slopes of greater than 30° (Fischer, 2012). Much of the mountainous terrain is relatively high, with 20% of the land area of the North Island and 60% of the South Island at elevations of 1,500 m or higher, roughly 43% of the total land area of New Zealand (Dennis, 2012a; Dennis, 2012b). Although the correlation between vegetation cover, topography, and aquifer location has not been rigorously analysed, visual comparison of relevant maps indicates that the bulk of the land area of New Zealand underlain by known aquifers is covered by grasslands and crops instead of forests (e.g., aquifers underlying the Aupouri Peninsula, Haurakei Plain, Heretaunga Plain, and Ruataniwha Plain of the North Island and aquifers underlying the Waimea Plain, Wairau Valley, Central Plain and other Canterbury locations, and Southland of the South Island).

## Research Methods

This paper primarily involves a literature review over a period of 18 months commencing in January 2012, with assistance from the GNS library system. During the

review, the American Geophysical Union's (AGU) Chapman Conference on Remote Sensing of the Terrestrial Water Cycle was held in Kona, Hawaii in February 2012. Informal interviews and discussions with a number of scientists with expertise in satellite remote sensing occurred there and during the remainder of the review. The Chapman conference was sponsored by the United States National Science Foundation and the National Aeronautics and Space Administration (NASA), and its programme provided an opportunity to review the state-of-the-art of satellite remote sensing science for hydrologic purposes, specifically including applications to groundwater (AGU, 2012). Additional review of the literature continued after August 2013, primarily with regard to the P – ET and soil moisture methods and the concept of the equilibrium water table (EWT). This included focussed discussions with National Institute of Water and Atmospheric Research (NIWA) scientists having relevant expertise.

## Review of satellite-based methods

Results of the review of the original four satellite remote sensing methods in the SAC project and the additional soil moisture method are detailed in Zemansky and Westerhoff (2015) and summarised below. The review of the EWT concept is also summarised below.

### GRACE satellite gravimetry *General GRACE background*

The gravity recovery and climate experiment (GRACE) is a joint mission with the German Aerospace Center and the German Research Center for Geosciences, in partnership with the Center for Space Research at the University of Texas at Austin. It is managed by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology (CalTech) for NASA (JPL, 2012). The GRACE mission

uses two satellites orbiting in tandem about 220 km apart at an altitude of less than 500 km to measure the Earth's gravity field. That gravity field is constantly changing, with most of the variable signal coming from the Earth's fluid envelope, including the storage of groundwater (Wahr, 2007).

### ***Principles of satellite gravimetry***

GRACE satellites determine the Earth's gravity using precise measurements of the relative and absolute positions of the satellites and how they change in response to variations in gravity. As the GRACE satellites orbit the Earth, areas with slightly stronger gravity (i.e., with a greater concentration of mass) affect the lead satellite first, pulling it away from the trailing satellite. As the satellites continue, the trailing satellite is then pulled toward the lead satellite. The changes in distance between the satellites are detected by a microwave ranging system that can measure the changes to an accuracy of better than 1  $\mu\text{m}$  (Wahr, 2007). At the same time, non-gravitational accelerations are measured by an accelerometer at each satellite centre of mass, so only accelerations caused by gravity are considered. The exact positions of the satellites over the Earth are determined by GPS receivers to within a centimetre or less (NASA, 2003; 2013).

Raw data from the GRACE satellites are processed by the German Aerospace Center and delivered to the German Research Center for Geosciences and JPL for preparation of a Level-2 data product that is publically available on a monthly basis (UTCSR, 2013). Release 05 (RL05), in current use, reportedly brought several improvements for GRACE data compared to its immediate predecessor (RL04), including a significant reduction in noise (Bettadpur and the UTCSR Level-2 Team, 2012).

GRACE Level-2 data represent continental water storage, model errors, and noise over land from which atmospheric mass variations,

ocean tides, and global ocean circulation variations have been removed (Frederic and Guillame, 2012). What is left is known as 'total' or 'terrestrial' water storage. This is the difference in mass for the month, in units of cm of 'equivalent water thickness', from the long-term average over the period of record (JPL, 2013; Frederic and Guillame, 2012).

### ***Application of GRACE data to groundwater elsewhere***

GRACE data have been used to evaluate changes in terrestrial water storage over time for a number of aquifers around the world, for example, southern Mali within the Niger River basin in Africa (Henry *et al.*, 2012), parts of China (Moiwo *et al.*, 2009) and India (Science Daily, 2009 and Editor, 2012), the Murray River basin in Australia (Leblanc *et al.*, 2012), central Europe (Andersen *et al.*, 2005), in Canada (Yirdaw and Snelgrove, 2011), and at a variety of locations in the United States, including central California (Famiglietti *et al.*, 2011; Scanlon *et al.*, 2012) and the Ogallala aquifer (Longuevergne *et al.*, 2010; Scanlon *et al.*, 2012). In many of these cases, GRACE data have indicated that groundwater depletion is occurring in areas of high groundwater use. Also, in the United States, GRACE data form the basis of weekly estimates of groundwater storage across the country (NDMC, 2013). Although most of these report successful use of GRACE data, a study in Australia had contrary findings. In that case, 'clear trends' of terrestrial water storage for a number of GRACE grid cells in Australia were compared with water level data from wells in the grid cells. The correlation between the two was categorized as 'generally poor' (Tregoning *et al.*, 2012).

### ***Application of GRACE data in New Zealand***

GRACE data do not appear to have been applied to New Zealand aquifers; no published studies were found during the initial literature search for this project. One reason is that GRACE data are relatively coarse,



provided on a 1° latitude by 1° longitude grid, so New Zealand is covered by only 32 GRACE grid cells. The distance between parallels of latitude on the surface of the Earth is about 111 km, while the distance between meridians of longitude varies with latitude, from about 111 km at the equator to zero at the poles. At 40° south latitude, close to the north-south centre of New Zealand, it is about 85 km. Therefore, each grid cell would have an area of approximately 9,400 km<sup>2</sup>, which is larger than the largest single aquifer in New Zealand. A number of studies have indicated that the minimum aquifer size necessary for utilizing GRACE data is 200,000 km<sup>2</sup> (e.g., Ramillien *et al.*, 2004; Tregoning *et al.*, 2012).

More recently, S. Swenson (2012, *pers. comm.*; 2013, *pers. comm.*) suggested using GRACE data to determine a basin-wide average water storage for New Zealand as a whole, using all 32 GRACE grid cells. He calculated the basin-wide average water storage first using RL04 output, but later updated his calculation using RL05 output (Fig. 1). The amplitude of the RL04 signal (red line) for composite GRACE data covering New Zealand generally exceeds that of the RL05 signal (black line) for the same time frame, presumably due to a greater amount of noise.

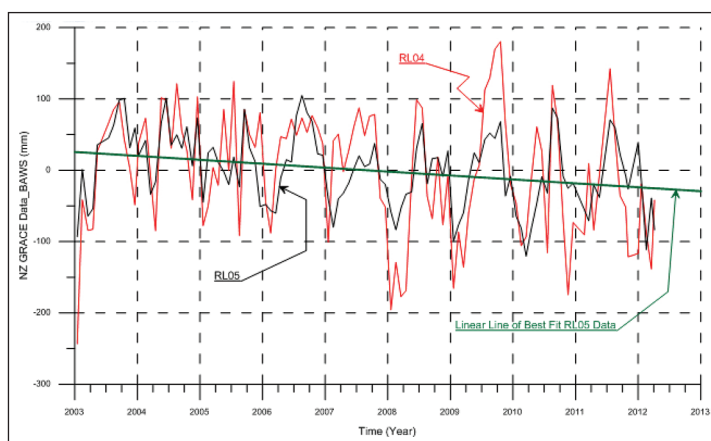
Variation in the time series data appears to be consistent with expected seasonal changes during the annual hydrologic cycle (i.e., more groundwater storage in the winter and less in the summer). This apparent seasonality is statistically significant at the 5% level. Analysis of the RL05 data, after adjusting for seasonality, indicates with a confidence level of 95% that storage has declined at a mean rate of 5.6 mm/year.

## Interferometric synthetic aperture RADAR (InSAR)

### General InSAR background

Ground elevation may subside or be uplifted due to various causes, including tectonic forces and the abstraction or recharge, respectively, of subsurface fluids such as groundwater. Satellites equipped with InSAR can measure these ground elevation changes and, when groundwater is involved, they can be related to both change in aquifer storage and important hydraulic properties (i.e., confined aquifer specific storage and confining layer vertical hydraulic conductivity).

In an unconsolidated aquifer, the abstraction of groundwater results in a certain amount of dewatering, accompanied by settlement of the aquifer matrix, while in a confined aquifer abstraction reduces



**Figure 1** – GRACE basin-wide average water storage (BAWS) time series for New Zealand (data from Swenson, 2012 and 2013).

effective stress. The reduction in effective stress ( $d\sigma_e$ ) is equivalent to the change in aquifer pressure ( $dP$ ), which can be related to aquifer compressibility ( $\alpha$ ) by Equation 1, if the original aquifer thickness ( $b$ ) and change in aquifer thickness ( $db$ ) are known (Fetter, 2001):

$$\alpha = -\frac{db/b}{d\sigma_e} \quad (1)$$

If it is assumed that subsidence caused by reduction in aquifer pressure is equivalent to aquifer compaction and acts only in the vertical direction (i.e., change in aquifer thickness), confined aquifer specific storage ( $S_s$ ) can be calculated from Equation 2 using the  $\alpha$  value determined from Equation 1 as follows (Fetter, 2001):

$$S_s = \rho_w g (\alpha + n \beta) \quad (2)$$

where:  $\rho_w$  = the density of water (999 kg/m<sup>3</sup> at 15° C);  
 $g$  = the acceleration due to gravity (9.8 m/sec<sup>2</sup>);  
 $n$  = aquifer porosity (measureable from samples);  
 $\beta$  = compressibility of water (4.67 × 10<sup>-10</sup> m<sup>2</sup>/N at 15° C).

Data on subsidence over time during pumping tests can also be used to characterise both specific storage of the confined aquifer and the vertical hydraulic conductivity of the confining unit above it, using a semi-logarithmic ‘compaction plot’ method (Burbey, 2003). In this method, it is assumed that (1) horizontal strain is negligible; (2) the hydraulic conductivity of the confining unit is at least two orders of magnitude less than that of the aquifer; and (3) the compressibility of the confining unit is more than one order of magnitude greater than that of the aquifer (Burbey, 2003).

Although the second and third assumptions are likely, research has shown that the first,

having to do with horizontal strain, is not. Burbey (2013) noted that horizontal strain may actually lead to a greater quantity of water released from storage than vertical compaction. This leads to overestimates of storage when horizontal strain is assumed to be negligible but is actually substantial.

### ***Principles of InSAR***

A full discussion of the principles of InSAR is beyond the scope of this paper, but a brief sketch is useful. RADAR imaging is an active method of remote sensing that uses electromagnetic waves, usually of microwave frequency (1-10 GHz), to illuminate a target. The distance to the target is determined by the round-trip travel time from the RADAR antenna to the target, and the characteristics of the returning wave or backscatter (power, phase, and polarization) depend largely on the properties of the Earth’s surface (Curlander and McDonough, 1991).

InSAR is widely used to measure deformation of the Earth’s surface (i.e., land subsidence or uplift). By differencing the phase from two RADAR images acquired at separate times, maps of range change between the antenna and ground can be obtained with millimetre precision (Massonnet and Feigl, 1998).

InSAR offers high precision, is non-invasive, can be used to collect data over large areas, and can collect data during night or day or under cloudy conditions. It is constrained, though, by ground surface characteristics (including vegetation cover), atmospheric signal delay, and the need to have archived data from two different times (Hanssen, 2001). Because of the potential effect of vegetation cover, the use of longer wavelength RADAR is recommended when available (Furuta *et al.*, 2005; Aobpaet *et al.*, 2008). This would favour PALSAR with L-band RADAR equipment on the ALOS satellite, for example, over ERS SAR C-band RADAR.

### Application of InSAR to groundwater elsewhere

InSAR has been applied to analyze potential impacts of abstraction and recharge of groundwater around the world. For example:

1. In Las Vegas, Nevada, both subsidence and uplift related to operation of a water supply well field were detected. Subsidence was at a maximum rate of 3.7 cm/year (Amelung *et al.*, 1999).
2. In Mexico City, Mexico, subsidence at a maximum rate of 30 cm/year due to deep groundwater abstraction was detected (Osmanoglu *et al.*, 2011).
3. In the Gioai Tauro Plain of Italy, subsidence was detected at a mean rate of 11 mm/year between 1992 and 2007 due to groundwater abstraction (Kruiver *et al.*, 2011).

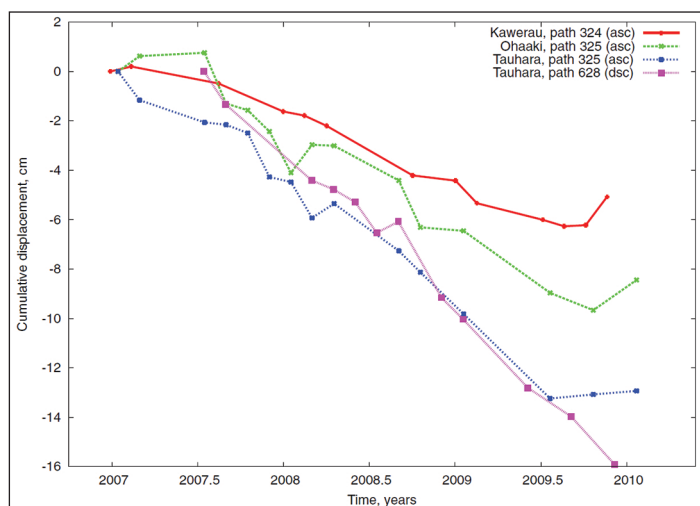
### Application of InSAR in New Zealand

InSAR has not previously been applied to New Zealand aquifers, but has been used to estimate ground displacement caused by the 2010-2011 Christchurch earthquakes (Amos, 2011; Elliot *et al.*, 2013) and subsidence within the Taupo volcanic zone related to extraction of fluids for geothermal power generation (Samsonov *et al.*, 2011).

The latter case is analogous to groundwater abstraction for water supply. Samsonov *et al.* (2011) used ALOS-Palsar observations over a three-year period at three geothermal fields in the Taupo volcanic zone. Ascending path InSAR results correlated well with GPS data. Mean subsidence rates ranged from about 2 to 5 cm/year. Figure 2 shows the plot of subsidence over time from this study using InSAR data. Samsonov *et al.* (2011) were unable to compare their results with actual operational data because the power companies considered such data 'commercially sensitive' and would not make it available.

GNS currently holds 10 years of Envisat InSAR data for the North Island of New Zealand (Hamling, 2013), which are available for future research. Preliminary large-scale processing of these data over a portion of the central North Island from the Hauraki Gulf to Hawke's Bay is shown in Figure 3, which shows both horizontal spatial distribution and a cross-section indicating displacement. It was generated from 33 interferograms covering the period 16 November 2003 through 23 May 2010. Warm colours (i.e., yellows, oranges, and reds) indicate motion away from the satellite line-of-sight (i.e., subsidence) while cold colours (i.e., greens and blues) indicate motion toward the satellite (i.e., uplift).

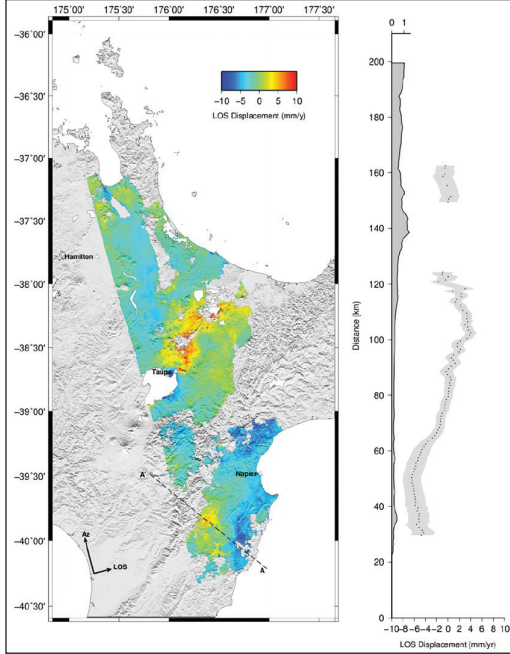
Several areas of subsidence are evident in the Taupo volcanic zone north-northeast of Taupo and the Ruataniwha Plains south-southwest of Napier. The rate of subsidence indicated for the orange-coloured



**Figure 2** – TVZ geothermal field time-series displacement (from Samsonov *et al.*, 2011)



areas is 5 mm/year (Hamling, 2013). This is a geologically active area and further study would be necessary to isolate the cause of this subsidence and the potential role, if any, of groundwater abstraction.



**Figure 3** – Preliminary processing of Envisat InSAR data for central North Island, New Zealand (Hamling, 2013). The north up convention has been followed.

### Estimating rainfall recharge using satellite precipitation (P) minus evapotranspiration (ET)

#### *General P – ET background*

Rain (P) and evapotranspiration (ET) are major components of the hydrologic cycle for quantifying catchment water budgets. However, although P – ET ‘is the net flux of water from the atmosphere to the earth’s surface’ (Swenson and Wahr, 2006), it is more a maximum upper bound than an indication of actual rainfall recharge to groundwater. A water budget is a relatively simple but powerful tool to account for water moving into, out of, or being stored within

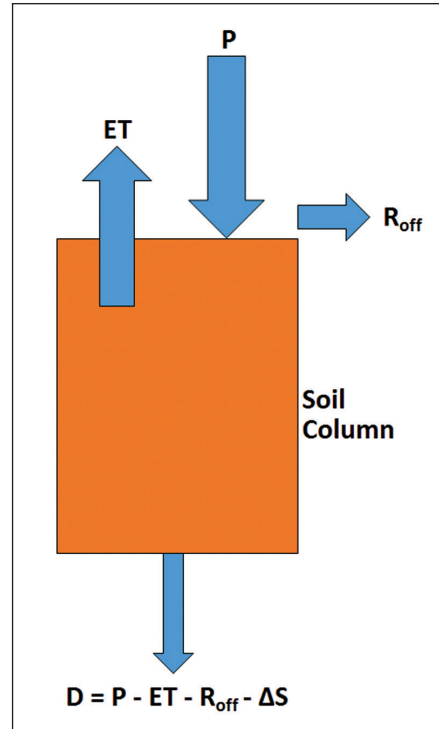
some control volume. The general form of the water budget for a control volume (CV) is:

$$\text{Inputs to CV} = \text{Outputs from CV} + \text{Change of Storage } (\Delta S) \text{ within CV} \quad (3)$$

Broken down by specific components, rain is the major input and evapotranspiration the major output. Surface runoff ( $R_{\text{off}}$ ) and soil drainage to groundwater (D, aka rainfall recharge) are other outputs. Rearranging terms, the water budget for the soil column CV (see Fig. 4) is given by Healy (2010) as Equation 4:

$$D = P - ET - R_{\text{off}} - \Delta S \quad (4)$$

As this equation indicates, P – ET will not equal rainfall recharge to groundwater except when a long period of equilibrium is assumed (i.e., there is no change in storage) and in the unusual case where there is no surface runoff.



**Figure 4** – Water budget for a specified soil column volume (from Healy, 2010).

## **Rain measurement**

### **Rainfall measurements in New Zealand**

In New Zealand, a large network of conventional land-based rain gauges is operated by various organizations, including NIWA, 15 regional councils or unitary authorities, MetService, energy companies with hydropower facilities, and KiwiRail. A partial survey in 2010 identified 735 land-based rain gauges operated by regional councils (Zemansky *et al.*, 2010), and there are hundreds of rain gauges monitored by NIWA or other authorities. If New Zealand's rain gauge network were evenly distributed, there would probably be about 50 land-based rain gauges per 10,000 km<sup>2</sup> land area.

Land-based gauges are the accepted standard for rainfall monitoring throughout the world. NIWA uses long-term data from such a network to compile national data sets for a spatial interpolation model that provides coverage of the entire country on a regular grid with a spacing of 0.05 degrees (approximately 5 km) (Henderson *et al.*, 2011).

### **Satellite remote sensing of rain**

Satellite-based rain data are widely available from a multitude of United States and European sources at no charge to the user. The instruments on the satellites involved fall within three broad categories: (1) visible infrared sensors; (2) passive microwave sensors; and (3) active microwave using precipitation RADAR. The joint US and Japan tropical rainfall measuring mission launched in 1997 has become the gold standard for satellite precipitation monitoring.

### **Potential utility of satellite remote sensing for New Zealand**

Research has shown that satellite remote sensing of rain is unlikely to be useful except where land-based rain gauge networks provide very sparse coverage (i.e., fewer than four rain gauges within an area of

approximately 10,000 km<sup>2</sup>) (Renzullo *et al.*, 2011). This would be approximately on a 1° latitude by 1° longitude grid cell basis. Given the number of rain gauges in New Zealand, satellite remote sensing of rain is unlikely to offer useful additional information to that obtained via data from the rain gauge network (this view was confirmed by NIWA scientists).

## **Estimation of evapotranspiration (ET)**

### **ET background**

'Evapotranspiration (ET) is the process by which water is transported from the Earth's surface to the atmosphere by evaporation from surfaces (soils and wet vegetation) and by transpiration from plants through stomata in the plant leaves' (SCKCEN, 2013). It is a function of weather variables (e.g., air temperature and wind velocity), surface variables influencing evaporation from soil and wet vegetation and transpiration from plants, and subsurface variables such as soil texture and moisture. Unfortunately, for all practical purposes, ET cannot be directly measured but must be inferred from quantification of other parameters that are measureable. The inference process involves modelling, and a large variety of models have been developed. Some models produce an estimate of 'potential' ET (PET), but Equation 4 requires 'actual' ET (AET or ET<sub>a</sub>). PET is ET that would theoretically occur under specified weather conditions if the available water were unlimited, while AET is ET that actually occurs under prevailing conditions. Authors are not always clear about precisely what type of ET they are discussing. Herein, because AET is needed for Equation 4, I default to AET unless PET is specifically noted. AET is 'one of the most uncertain terms in the world's water balance' (Miralles *et al.*, 2011a) and 'arguably the most difficult ... to determine' accurately (Jovanovic and Israel, 2012). Our ability to observe AET is poor and we are left

with imprecise and uncertain estimates of its magnitude that are difficult to validate. For example, AET from the Earth's global land mass is generally estimated at somewhere between 58,000 and 85,000 km<sup>3</sup>/year, a range that is nearly 50% of its lower value (Miralles *et al.*, 2011b).

### Satellite remote sensing of AET

A number of methods have been developed for using satellite data to attempt to estimate AET. These are generally classified as (1) 'thermal-based'; or (2) vegetative index methods (Glenn *et al.*, 2011). Three examples are the two energy balance algorithms SEBAL (surface energy balance algorithm for land) and MOD16 (surface energy balance algorithm for land using MODIS data), and the water balance algorithm GLEAM (global land-surface evaporation Amsterdam methodology). These methods have limitations that affect their possible use in the varied environmental conditions found in New Zealand. For example, SEBAL is only suitable for use in flat terrain and cannot be used in forested catchments (Glenn *et al.*, 2011).

Eddy-covariance (EC) flux tower estimates are often used as the standard of comparison when attempting to validate satellite remote sensing AET estimates. Results from these attempts often produce poor correlations. Land surface models, including water balance models, are also used for this purpose, sometimes incorporating flux tower data (Williams *et al.*, 2009). Flux towers typically measure a large suite of parameters, including mass and energy flux densities (e.g., latent heat, sensible heat, soil heat conduction, and canopy heat storage), meteorologic variables (e.g., net radiation, air temperature, and wind speed and direction), soil characteristics (e.g., soil moisture), and vegetation characteristics (e.g., albedo and leaf area index). The major international network of flux towers, known as FLUXNET, includes about 545 such towers worldwide (Baldocchi *et al.*, 2001).

Because of a recent decade-long drought, substantial flux tower work has been done in Australia (Glenn *et al.*, 2011). Much less has been done in New Zealand. Ag Research, NIWA, and the University of Waikato have a few flux towers, but full information about their locations, design, and capabilities was not available for this review.

Comparisons of AET estimates from satellite remote sensing products with those from flux towers often indicate discrepancies, showing either substantial over- or underestimation (Ramoelo *et al.*, 2014). However, most of the papers assessed appeared to show underestimates (e.g., Bastiaanssen *et al.*, 1998; Ramoelo *et al.*, 2014). Flux tower estimates are known to have 'accuracy errors on the order of 15% to 30%' (Glenn *et al.*, 2011) and are 'are more prone to underestimation than to overestimation' (King *et al.*, 2011). During a major Australian study, it was found that correlation coefficients ( $r$ ) between tower ET<sub>a</sub> and remote sensing estimates were all less than 0.5 at daily time steps, and that flux tower and remote sensing model AET estimates could differ by 10% to 30%. By aggregating data to monthly time steps, this was improved (i.e., to the 10% to 20% range) (Glenn *et al.*, 2011).

Bastiaanssen *et al.* (1998) provide an example of the use of flux towers to try to validate satellite remote sensing AET estimates. They reported what appeared to be a good fit for their 25 pixel data. However, their published plot was inconsistent with their data points and was inappropriately biased by one high outlier. Removing that outlier results in a much smaller slope of 0.50 and coefficient of determination ( $r^2$ ) of 0.34. Slopes and  $r^2$  values were substantially smaller for 91 pixel data. This indicates a marginal relationship between satellite-determined AET and flux tower data and does not successfully validate the satellite remote sensing estimates.

The accuracy of the SEBAL algorithm has been reported to vary from as low as 67% to as high as 95% for instantaneous estimates, and a few percent higher for longer term estimates (Matinfar, 2012; Brutsaert and Sugita, 1992). Similarly low slopes and  $r$  or  $r^2$  values were reported in attempts to validate data for GLEAM and MOD16. For example, the linear best fit for a plot of data reported by Miralles *et al.* (2011b) for annual AET estimated by GLEAM when compared to AET data from 43 flux towers had a slope of 0.68 and an  $r^2$  of 0.63 (Zemansky and Westerhoff, 2015). In another recently published study attempting to validate MOD16 estimates for a savannah ecosystem in Africa, MOD16 achieved 'reasonable accuracy' with low bias early on in two of the nine years studied, but overestimated AET compared to flux tower estimates (22.4 to 33.3%) in three of the years and underestimated AET in the remaining four years of the period (-55.7 to -16.44%).  $r^2$  values for the nine years ranged from 0.26 to 0.85 and most were less than 0.60 (Ramoelo *et al.*, 2014).

Westerhoff and White (2014) recommend the use of satellite remote sensing-derived AET and specifically referred to the improved MOD16 MODIS method of Mu *et al.* (2011). However, these improvements were apparently only marginal. Mu *et al.* (2011) report that they increased  $r$  values from 0.83 to 0.86 when MOD16 AET estimates were compared with flux tower data using tower-specific meteorology. The improved MOD16 method was one of the eight models assessed by Chen *et al.* (2014). They found that model performance 'differed substantially,' with the highest AET estimate from another model 59% greater than that produced by the improved MOD16 method. They also reported that 'energy partitioning' was 'substantially' different between the 'three process models' (including the improved MOD16 model) and there were 'significant differences in the interannual variation of

ET' produced by different models as well as spatial trends that were 'substantially different' over time. This was unexpected, as the three process models had all been 'evaluated and validated globally'. Chen *et al.* (2014) concluded that it is necessary to examine model structure to improve the ET component estimations and critical model parameters.

Researchers in Australia compared AET results from non-satellite and other satellite remote sensing methods with land surface models, i.e., hydrologic models relying on water balances. This comparison included eight methods (three soil water balance methods and five satellite algorithms), yielding 16 AET products. They concluded that 'for large areas of Australia, where  $ET_a$  is dependent mostly upon rain, the estimates based on hydrologic model approaches performed best,' but for areas receiving lateral inflow, methods using remotely sensed inputs were needed. They recommended that the best solution for Australia's operational AET requirements was 'An interim daily gridded AET product ... based on the AWRA (water balance) model... substituted by estimates from the CMRS (using satellite remote sensing inputs) method for inflow areas' (King *et al.*, 2011).

Long *et al.* (2014) recently looked at a large region in the south-central United States and compared results from four land surface models with those from two remote sensing approaches (MODIS and AVHRR). They concluded that satellite remote sensing estimates were generally lower (up to 27%) than those from land surface models and had greater uncertainties (by factors of two to three).

The costs for satellite-based ET estimates and their inaccuracy are also major concerns. As noted by Nouri *et al.* (2013), 'most of them need extensive time investment, medium to high levels of skills and are quite expensive.' Evidence from different parts of

the world shows substantial problems when validation of satellite remote sensing AET estimates is attempted, including low  $r$  and  $r^2$  values, high root mean square error and high relative error, both low and high bias, and large variation in performance. In addition to studies already noted, Pollaco *et al.* (2012), Gibson *et al.* (2013), Nazdri and Hashim (2014), and Yao *et al.* (2014) are pertinent.

A final concern regarding the use of satellite remote sensing ET products, beyond the question of accuracy and cost, is their potential availability. The two MODIS sensors often used for satellite remote sensing AET products are aboard satellites launched in 1999 (Terra) and 2002 (Aqua). These sensors had initial design lives of only 5 years and there were no plans for follow-on sensors with the same characteristics (King *et al.*, 2011). As NASA pointed out in a recent status update, 'MODIS is aging and will end soon' (Killough, 2014) and there are uncertainties about the availability and quality of data from other existing satellite sources of 'similar information' (Killough, 2014). Potentially equivalent future products from European sensors, if they become available, may be relatively expensive (King *et al.*, 2011). The history of earth-observing satellites is one in which there are often gaps in instrument coverage and delays in the launching of new satellites, even when they've been planned and authorized.

### **Using satellite thermal infrared (TIR) to identify groundwater influent to rivers**

#### **General TIR background**

When there are temperature differences between shallow groundwater influent to a stream and the water flowing in the stream, the differences can be used to identify zones of groundwater inflow. This may be accomplished in several ways: (1) manual stream temperature measurement; (2) distributed temperature sensing by placing fibre optic cable on the stream bottom (which

detects the temperature near the groundwater-streamflow interface); or (3) using thermal infrared remote sensing. Summer, when the ratio of stream flow to influent groundwater is relatively low and groundwater temperature is low compared to stream temperature (which also means it 'tends to stay at the bottom' for some distance downstream before mixing), is best for distributed temperature sensing work (Meijerink *et al.*, 2007). In contrast, the best chance of success for satellite TIR imagery may be during winter conditions, when relatively warmer groundwater rises through cooler stream flow (Meijerink *et al.*, 2007). However, in the New Zealand winter stream flow is likely to be highest, relative to influent groundwater fluxes, which would dilute the temperature signal. Ideally, satellite TIR imagery would be used to localize potential groundwater inflow areas for more detailed assessment using manual measurements or distributed temperature sensing technology.

#### **Satellite TIR imagery**

IR radiation is electromagnetic radiation with a wavelength in the 0.75 to 1,000  $\mu\text{m}$  range, just above the wavelength of visible light. The TIR portion of the spectrum suitable for detecting longwave thermal energy emissions is in the 8 to 15  $\mu\text{m}$  range (Science Mission Directorate, 2010). Various types of photo-detectors or radiometers can measure TIR radiation and use it to estimate the temperature of the objects involved (Aggarwal, 2003; Prakash, 2000; Paschotta, 2008). For remote sensing applications, these instruments measure emitted TIR radiation in the top 100  $\mu\text{m}$  layer of water (Handcock *et al.*, 2012).

A number of satellites have TIR measuring capability; however, only two have sufficiently high resolution for preliminary consideration: (1) Landsat; and (2) Terra (with an ASTER instrument). Typically, thermal and spatial resolution available for these is less than 1°C and in the 60 to 120 m range, respectively (Zemansky and Westerhoff, 2015).



### ***Application of satellite TIR imagery for groundwater-stream interactions***

Although airborne TIR imagery has been used to study stream temperatures, there is no indication in the literature that satellite TIR imagery has been successfully used to identify groundwater-stream interactions anywhere in the world. This is apparently due to spatial resolution limitations. As Cherkauer *et al.* (2005) concluded, when considering application of ASTER data to streams in Washington state, the available resolution of 90 m ‘makes it difficult to obtain pixels that contain only water on all but the widest river reaches (e.g., the Columbia River with widths between 300 and 500 m).’

With the possible exception of a few reaches in the largest New Zealand rivers at flood stage, spatial resolution for satellite TIR imagery in the 60 to 120 m range is insufficient for the water-filled widths of streams in New Zealand. For example, during annual floods for the period 1973 to 2003 the mean channel widths of the Waikato River, New Zealand’s longest river, between Horotiu Landfill and the Narrows Bridge near Hamilton were in the 89 to 95 m range. Maximum flood widths were in the 136 to 159 m range (Smart, 2005).

### **Soil Moisture and an Equilibrium Water Table (EWT)**

#### ***Soil moisture***

#### **General soil moisture background**

The use of satellite data to estimate soil moisture is relevant to determining terrestrial water storage by GRACE, to evapotranspiration, and to rainfall recharge. Soil moisture is the component of the hydrologic cycle that controls the partitioning of precipitation into infiltration and runoff (Sabel, 2013).

How much rain infiltrates into the soil depends on how permeable the soil is and the antecedent soil moisture. Unsaturated

zone permeability is strongly related to both soil texture and soil moisture (Fetter, 2001). Rain that infiltrates into subsurface soil may ultimately evaporate directly to the atmosphere, be taken up by plant roots and transpired to the atmosphere, be held in place within the unsaturated zone by capillary forces, or move vertically downward under gravity to contribute to groundwater recharge, while rain that doesn’t infiltrate becomes surface runoff (Fetter, 2001; Hendriks, 2010).

There is a voluminous global literature on the spatial and temporal variability of soil moisture and how best to measure it (e.g., Pandey and Pandey, 2010; Zhu *et al.*, 2013; Lin, 2012). Soil scientists have developed in-situ measuring equipment that is widely installed in agricultural areas where irrigation is used, including in New Zealand (particularly in the Canterbury Region), and they utilize geostatistical procedures for interpolating between soil moisture data points (e.g., Lakhankar *et al.*, 2010). There is also information indicating some degree of relationship between soil moisture and underlying shallow water tables.

#### **Soil moisture monitoring in New Zealand**

NIWA has a network of 40 sites around the country where soil moisture is measured and recorded by in-situ probes. Soil moisture is also monitored at other sites using in-situ probes for research and by farmers in Canterbury and other locations for efficient application of irrigation water (Aqualinc, 2009). Estimation at unmonitored sites is challenging because soil moisture is a function of climate, and site soil and vegetation types. NIWA’s hydrologic model calculates daily soil moisture within the root zone (typically a depth of 1 m below ground level [BGL]) for all catchments in New Zealand. It also calculates depth to the shallow groundwater table (Henderson *et al.*, 2011).

### ***Satellite estimation of soil moisture***

Both passive and active microwave methods of estimating soil moisture are available. The passive method involves measurement of brightness temperatures (e.g., by the AMSR-E microwave radiometer instrument on the Aqua satellite that was operational until October 2011). These may then be converted to soil moisture values using the Land Parameter Retrieval Model (LPRM) on a 0.25° grid (de Jeu *et al.*, 2008; Owe *et al.*, 2008). In contrast, active microwave soil moisture estimation is based on the principle that RADAR backscatter is lowest when there is no water present in surface soil and highest when surface soil is saturated (Wagner *et al.*, 2007; Zhao *et al.*, 2006). Active microwave methods of soil moisture estimation are more accurate and have better spatial resolution than passive, but have the disadvantage of increased noise due to vegetation (Wagner, 1999; Wagner *et al.*, 2007). Soil moisture may also be estimated from satellite land surface temperature data (Wen *et al.*, 2003).

A major limitation of satellite-derived soil moisture estimates is that satellites sense moisture conditions at the ground surface and for only a very thin layer of soil immediately underneath the surface. Numerous studies have shown that both passive and active satellite-derived soil moisture estimates are strongly influenced by 0 to 5 cm depth soil (Draper *et al.*, 2009; Gruhier *et al.*, 2010).

Efforts to validate satellite-derived soil moisture estimates with in-situ data of various kinds tend to have correlation coefficients ( $r$ ) that vary considerably, but are often in the range of 0.6 to 0.8; for example, Wagner *et al.* (1999), de Jeu and Owe (2003), Wagner *et al.* (2007), Brocca *et al.* (2011) and Su *et al.* (2013). This is not a very high indication of correlation. Technical problems inherent in validation include differing measurement depths and spatial resolutions, as well as the general variability of in-situ soil moisture values.

### **Relationship between soil moisture and shallow groundwater tables**

Changes in soil moisture have been shown to correlate with changes in the depth to shallow groundwater tables. Sutanadjaja (2012), for example, found good correlation between a Soil Water Index, 'a measure of the profile or average root zone soil moisture content' over the first metre of the soil column (Wagner *et al.*, 1999, as cited by Sutanadjaja, 2012) and the depth to the groundwater table. The correlation appeared strongest at shallower depths but was noticeable for their site conditions to as deep as 8.7 metres BGL. The Soil Water Index is a product of the C-band scatterometers aboard the ERS-1 and ERS-2 satellites, produced by applying an algorithm to the raw surface soil moisture that penetrates only to the 0.5 to 2 cm depth range (Wagner *et al.*, 1999; de Jeu *et al.*, 2008; Sutanadjaja, 2012).

The literature in general supports the potential for a relationship between soil moisture and shallow groundwater tables when there is a direct hydraulic connection to the water table. To what depths this relationship might hold apparently varies with site-specific conditions (e.g., soil texture). Whereas Sutanadjaja (2012) found a relationship at his site to a depth of c. 8 m, others have found it only at much shallower depths. For example, Alkhaier *et al.* (2009) reported a correlation between volumetric soil moisture and water table depth between about 1 and 4 metres BGL. However, other studies have found substantial variation and low  $r$  and  $r^2$  values (Pan *et al.*, 2008; Alkhaier, 2011; Alkhaier *et al.*, 2012). For example, Alkhaier *et al.* (2012) show that for a soil moisture value of 0.21 m<sup>3</sup>/m<sup>3</sup> the groundwater table depth could be anywhere in the 2 to 4 m range.

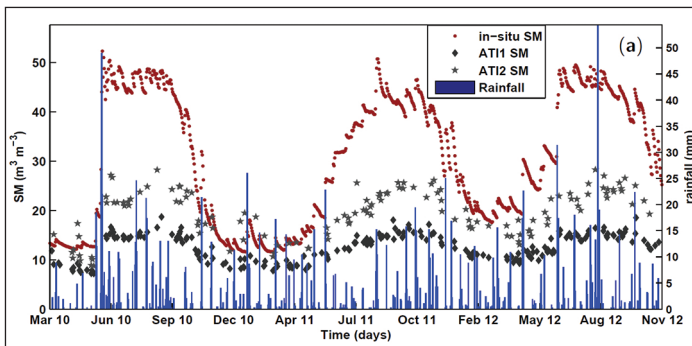
### Application of satellite remote sensing of soil moisture in New Zealand

Satellite remote sensing of soil moisture has been trialled in the Canterbury area as an input variable for the 'ET Tool' algorithm, but does not appear to have been used in New Zealand for aquifer characterisation. The trial was aimed at producing estimates of PET and AET, crop water deficit, and rain surplus. In-situ soil moisture measurements from 276 sites were used for validation, at intervals of 10 to 15 cm over the soil profile (Simons and Voogt, 2012). In-situ soil measurement data at 15 cm depth were compared with two types of soil moisture estimates from satellite remote sensing. Both satellite estimation methods ran substantially below in-situ measurements, but ASCAT data were closer than MODIS. MODIS estimates typically ran 25% to 50% below in-situ measurements. Simons and Voogt (2012) attributed this to problems of spatial scale (point measurements vs. 12.5 km pixels).

More recently, satellite remote sensing estimates of soil moisture were compared with in situ observations at sites in the Canterbury Region (Sohrabinia, 2013). Part of the research involved using two methods to calculate soil moisture by the difference between near surface air temperature and land surface temperature (LST) using MODIS data for six sites. Results from three years of comparison data for the Rangiora site, graphically shown in Figure 5, are

typical. The black stars and diamonds from satellite remote sensing methods are generally substantially lower than in situ data with the largest discrepancy occurring during the relatively wet winter months. During those months, in situ soil moisture was often more than twice as high as satellite remote sensing estimates. Results varied between sites with interference reportedly caused by local effects such as bodies of open water and mountainous topography. The range of correlation coefficients for both methods at all six sites was from 0.42 to 0.78 with a mean of 0.64. Although it was concluded that 'satellite observed LST is useful for the estimation of some land surface properties over a long-term period (10 years) and at large spatial domain,' it was also found that 'environmental phenomena, such as cloud cover, dense vegetation and rugged topography limit the use of remotely sensed data'.

With regard to the relationship between soil moisture and the depth to the shallow groundwater table, one study in New Zealand found that these two variables had different variability characteristics, making it unlikely that a consistent relationship could be modelled very well (McMillan and Svrinivasan, 2014) and that the soil moisture-derived estimate of depth for the shallow water table has limited possible application and is questionable for aquifers in New Zealand. Site-specific soils data



**Figure 5** – Satellite-based soil moisture (ATI1 black diamonds and ATI2 black stars) vs. in-situ soil moisture (red squares) (from Sohrabinia, 2013).

would probably be necessary for reasonable certainty and there seems little useful purpose for this approach when there are an estimated 1,740 well sites in New Zealand being used by regional councils to monitor actual groundwater levels (Zemansky *et al.*, 2010), and a much greater number of additional wells available. For example, Westerhoff and White (2014) used groundwater level data for nearly 4,500 wells in the Canterbury region alone in their project. In areas with so many water supply wells, the depth to the groundwater table is well-known, making estimation of it by satellite remote sensing of soil moisture superfluous.

### ***Simulated equilibrium water table (EWT)***

During the course of the SAC project, the concept of an equilibrium water table (EWT) using satellite remote sensing data was promoted as being potentially useful for aquifer characterisation in New Zealand (R. Westerhoff, 2012, *pers. comm.*; C. Daughney, 2012, *pers. comm.*). Due to time constraints, this subject was not included in Zemansky and Westerhoff (2015) when it was being prepared in July 2013, but information about this concept is presented here.

### **General EWT background**

There is a limited published literature outlining the EWT concept (Fan *et al.*, 2007; Miguez-Macho *et al.*, 2007; Miguez-Macho *et al.*, 2008; Fan and Miguez-Macho, 2010; Fan *et al.*, 2013). Fan *et al.* (2007) defined the EWT as the 'climatological mean water table, a result of long-term mass balance between ... the vertical, atmospherically induced flux across the water table (i.e., groundwater rainfall recharge), and the lateral, topographically induced flow below and parallel to the water table.' They suggested that the EWT was a result of long-term landscape evolution from complex interactions among climate, geology, and biota and that once an EWT was determined

it could be used to estimate such things as aquifer hydraulic parameters. But, they were not explicit about precisely how this could be done.

Fan *et al.* (2007) presented an EWT over much of North America based on rainfall recharge, calculated as the 50-year mean precipitation minus model-estimated surface runoff and evapotranspiration, as input to a simple two-dimensional (2D) steady-state groundwater flow model. At that time, there was no satellite remote sensing component to the EWT model. They found that their simulated water table was generally higher than the observed one (i.e., shallower). They qualified their results by saying their 'goal (wa)s not to describe local groundwater conditions, but to capture ... spatial variability across a continent' resulting from 'long-term and large-scale climatic and geologic forcing'.

Fan *et al.* (2013a) and Fan *et al.* (2013b) updated Fan *et al.* (2007) and expanded coverage of their EWT beyond North America to produce the global EWT they were seeking. They followed the general approach of earlier work, but with several important differences. A major difference was in how values for rainfall recharge were generated for input to the groundwater flow model. Instead of rainfall recharge being calculated the way it was in the 2007 paper, they considered six 'fully coupled vegetation-soil-groundwater model(s)' (i.e., land surface models) and/or databases and used the one in any given case that produced the results closest to observed water table depth (WTD) and wetlands distribution data. Some of these land surface models incorporated satellite data as well as land-based data inputs (Rodell *et al.*, 2004).

Fan *et al.* (2013a) compared their global WTDs with observations at 1,603,781 well sites compiled from government archives and published literature. They found 'a lack of coherent patterns' and noted that there were

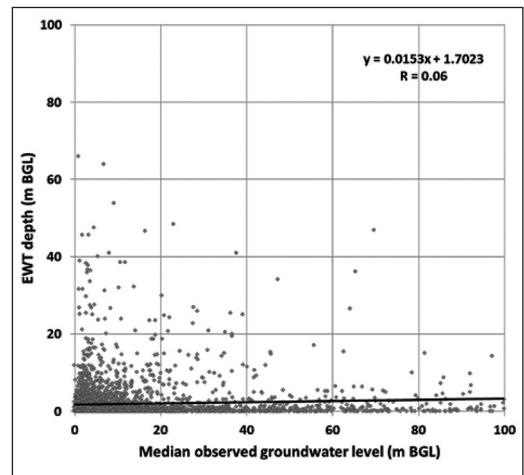
substantial differences between their model results and observations. In particular, their model 'suggests a much higher fraction of WTD' <1 m and >30 m.

### New Zealand EWT comparison

Two attempts were made to validate Westerhoff's results from his interpretation of Fan's simulated EWT for New Zealand using actual water level observations for wells in New Zealand as part of the SAC project. The first was a test case involving long-term observational data from sixty wells around the country. When organized by EWT depth, they clustered into one group of 47 wells having WTDs less than 20 m (19 of these had depths of zero compared to actual depths in observations wells ranging from 0.44 to 18.66 m) and another of 13 wells having WTDs greater than 40 m. In view of this clustering, the data were analysed based on these two clusters of shallow and deep EWT depths. The linear lines of best fit approached horizontal slopes and had  $r^2$  values of 0.10 and 0.19, respectively. This was not indicative of any correlation. The discrepancy between the calculated and observed WTD was substantial in many cases, reaching a maximum of nearly 60 m.

Westerhoff and White (2014) described a second SAC project attempt to validate a simulated EWT in New Zealand. This time, actual groundwater level data from 4,459 wells in the Canterbury Region were used. Results from this comparison did not improve on results from the earlier 60-well test. Westerhoff and White (2014) provided incomplete information on their methodology, but show that the EWT model estimates bore little resemblance to actual groundwater observations. This is evident in their Figure 3.5 (reproduced herein as Fig. 6), a scatterplot produced from their data. The slope of the linear line of best fit in Figure 6 is nearly horizontal (i.e., 0.0153) and the correlation coefficient ( $r$ ) is 0.06. This means virtually no

correlation. As Westerhoff and White (2014) acknowledged, their 'EWT depth estimates compare poorly with groundwater depth observations in large areas of the Canterbury Region'. The EWT model: (1) greatly underestimated actual water table depths; (2) 'calculates relatively few EWT depths in the range of approximately 2 to 30 m'; and (3) produced poor estimates for wells in deeper depth areas. For example, more than 40% of their estimated WTDs were 'less than 1 m' compared with that being the case for only about 5% of observed WTDs. Westerhoff and White (2014) also noted that median and mean observed groundwater depths were 4.4 and 12.2 m BGL, respectively, while EWT median and mean depths were only 0.4 and 1.9 m BGL.



**Figure 6** – EWT depth vs. median observed depth (from Westerhoff and White, 2014).

## Conclusions and Recommendations

### Conclusions

Of the six methods involving satellite remote sensing reviewed, only one (i.e., InSAR) shows potential at this time for characterization of New Zealand aquifers.

The resolution of GRACE satellite gravimetry to determine change in terrestrial



water storage over time is too coarse to apply to any New Zealand aquifers. However, a 10 year 'basin-wide average' for New Zealand as a whole, including all 32 GRACE grid cells covering the New Zealand land mass, was evaluated. Variation in the time series data appears to be consistent with expectations for the annual hydrologic cycle (i.e., more groundwater storage in the winter and less in the summer). Analysis of the data, after adjusting for seasonality, indicates a statistically significant declining trend of 5.6 mm/year.

InSAR is able to provide time series estimates of land surface elevation which may be correlated with changes in aquifer storage and may also be used to estimate hydraulic properties (aquifer storage and confining layer vertical hydraulic conductivity). This potential is worth assessing further with test cases in New Zealand. GNS Science holds 10 years of InSAR data for the North Island that can be analysed. However, where subsidence or uplift is found other information will be needed to determine the role, if any, played by groundwater extraction. There is also a serious limitation in the use of these data for estimation of hydraulic properties – the assumption that horizontal strain and deformation are negligible is unlikely to be warranted and could result in substantial inaccuracy in estimates of hydraulic properties.

Calculation of  $P - ET$  to estimate groundwater rainfall recharge by satellite data involves highly simplifying assumptions which are unlikely to be valid for many New Zealand aquifers. This calculation by remote sensing data alone is not a useful approach. As noted by Kinzelbach *et al.* (2014), 'Unfortunately, both ET and P obtained from remote sensing are inaccurate. Calculating the difference,  $P - ET$ , leads to error propagation, especially when both quantities are of similar magnitude.' Existing land-based rain gauge networks in New Zealand provide better quality data than

satellite remote sensing products do, while the accuracy of AET estimates by satellite remote sensing is questionable at best. Attempts to validate them using flux tower or land surface model results have shown that satellite remote sensing methods may over- or underestimate AET, with underestimation in the range of 10 to 50% more likely. Using such AET values would lead to a substantial overestimation of groundwater rainfall recharge. In addition, few flux tower records are available to validate satellite AET estimates in New Zealand. The continuing availability of satellite platforms and sensors to produce satellite AET products is also uncertain. Thus satellite remote sensing does not appear to make improvements to existing methods used by NIWA to quantify P and ET in New Zealand. In looking at these same issues, Australia has, like NIWA, chosen to rely primarily on hydrologic models for estimating AET.

As with GRACE data, the spatial resolution of satellite remote sensing TIR data is too coarse for the detection of groundwater-stream interactions in New Zealand. Airborne TIR data does have sufficient spatial resolution for this purpose. However, assessment of the utility of the airborne platform was beyond the scope of this objective of the SAC project. There is also possible limited use of satellite TIR data with respect to groundwater inflow to lakes and, in the case of conduit rather than diffuse flow, submarine groundwater discharges on the coast. However, no cases of conduit flow to the sea on the coast of New Zealand have been identified.

Soil moisture affects the partitioning of rain into infiltration, surface runoff, or evapotranspiration. Satellite remote sensing, however, detects soil moisture only in the very near surface of the soil column. Soil moisture has also been correlated with water table fluctuations in shallow aquifers. This is consistent with other

information in the scientific literature about the relationship between soil moisture and shallow groundwater tables under different soil conditions up to 4 metres depth BGL. Efforts to validate soil moisture data have found moderate correlations at best. It is hoped that the Sentinel-1 satellite, launched in April 2014, will improve the resolution of satellite soil moisture data, but that remains to be seen. Therefore, until improved satellite soil moisture capability can be demonstrated to be comparable with in-situ probe data, this technology is not considered useful for characterisation of New Zealand aquifers at this time.

The EWT concept has been developed to obtain a broad sense of patterns on a global scale rather than to accurately model groundwater in any given location. As originally conceived with respect to North America, the EWT model did not utilize any satellite remote sensing data. The current global coverage version uses a land hydrology model, some of which incorporates satellite remote sensing inputs. The recharge data for input to the groundwater flow model are 'meant (only) for inferring large-scale patterns' and are themselves produced by a model (Y. Fan, *pers. comm.*, 2013). The groundwater flow model 'offers a globally continuous but simpler view of water table depth at its natural states' (Fan *et al.*, 2013a). This is a climate equilibrium water table that does not take local geology or groundwater abstraction into account. When better aquifer characterisation data are available for input to the model, model results can be improved by it, but the model itself cannot per se be used to characterise aquifers. Given the ample availability of existing groundwater monitoring networks in New Zealand and very poor comparability of EWT estimated depths with actual observations, the EWT concept does not appear to be a fruitful one to pursue for the purpose of aquifer characterisation in New Zealand.

## Recommendations

Based on this research, it is recommended that no further effort be made to assess or use GRACE satellite gravimetry, satellite remote sensing estimates of  $P - ET$  to attempt to calculate groundwater rainfall recharge, satellite TIR data to attempt to identify areas of groundwater-surface water interaction, satellite remote sensing products to estimate soil moisture, or the EWT concept for attempting to characterise New Zealand aquifers. However, satellite remote sensing technology can be expected to continue to develop and these methods should eventually be re-assessed after substantial improvement in them occurs.

Satellite InSAR technology should be applied in test cases in New Zealand for aquifer characterisation. If subsidence or uplift is identified using this method, it will then be necessary to assess other information regarding what, if any, relationship this has to groundwater abstraction/recharge.

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