New Zealand Rock Properties: Determining Thermal Properties of Shallow Soils

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ABSTRACT

New Zealand's rocks and soils can provide a clean, renewable, and sustainable energy source for heating and cooling of buildings. Incoming solar energy is absorbed and stored by the earth, creating a relatively constant ground temperature year round that can be utilised with a geothermal (ground source) heat pump to provide heating in the winter and cooling in the summer. The amount of heat stored in the rocks and soils are largely influenced by local climatic factors, such as air temperature, sunshine hours, rainfall, and the thermal properties of the rocks and soils.

This paper presents data from a network of shallow ground temperature monitoring sites in different soil types around New Zealand. These temperatures are used to calculate thermal properties such as thermal diffusivity and volumetric heat capacity, which are key properties used in the design of the ground loop configuration for geothermal heat pump installations. This project aims to provide fundamental information to promote the design, development and utilization of geothermal (ground source) heat pumps.

1. INTRODUCTION

Solar radiation penetrates the earth's surface, causing temperature variations through the shallow ground that can provide a source of energy. The depth of penetration of the solar energy depends on the local climate (e.g. solar radiation, ambient temperature variations, wind, rainfall) and site-specific factors, such as local topography, surface cover, and position in regards to the sun (e.g. north-facing). The temperature of the ground is a function of heat transfer by means of radiation, convection and conduction within the soil and rock. Generally three temperature zones can be distinguished (e.g. Popiel et al, 2001): (1) the surface zone where ground temperature is sensitive to diurnal variations, (2) the shallow zone where the ground is sensitive to seasonal weather variations, and (3) a deep zone where the ground temperature is near constant year-round. The amplitude of the ground temperature variations on diurnal and seasonal timescales decreases with depth and is accompanied by a phase shift that increases with depth.

A geothermal heat pump (GHP) utilizes the ground as a heat source in heating mode and as a heat sink in cooling mode. In the heating mode, a GHP absorbs heat from the ground and uses it to warm up spaces such as in houses or buildings. In the cooling mode, heat is absorbed from the conditioned space and transferred to the earth through a ground heat exchanger (GHE). GHPs are an efficient alternative to conventional methods of space conditioning because they utilize the thermal stability of the ground which is essentially an unlimited source and available year round.

High capital cost has been a barrier to increase uptake of GHPs in New Zealand due to the tendency to overdesign ground loop systems based on European or North American design standards (Johnston, 2012). New Zealand requires appropriate and accessible soil/rock property data for local GHP design. This paper examines thermal properties of soils from *in-situ* temperature measurements in two boreholes around New Zealand to provide appropriate and accessible soil/rock property data for local GHP design.

2. GROUND TEMPERATURE DATA

A network of boreholes is being installed around New Zealand to measure ground temperatures at depths down to 9m (Figure 1). This paper presents the data and analyses from the initial two boreholes installed. The first borehole was located at Wairakei (Figure 1), and installed in July 2010 and has been continuously logging temperatures hourly from 31 sensors between 0 m and 7.4 m depth. The lithology is predominately unconsolidated pumice with a thin layer of topsoil (Cole-Baker, 2011).

The second borehole is located at Lincoln (Figure 1) and was installed in December 2012. It contains 12 sensors from 0.3 m down to 9 m (Cole-Baker *et al*, 2013) that have been collecting continuous hourly data until March 2014. The bore was drilled in predominately silt and sand lithology.

Figures 2(a) and(b) show ground temperature data recorded at the Wairakei and Lincoln sites respectively.
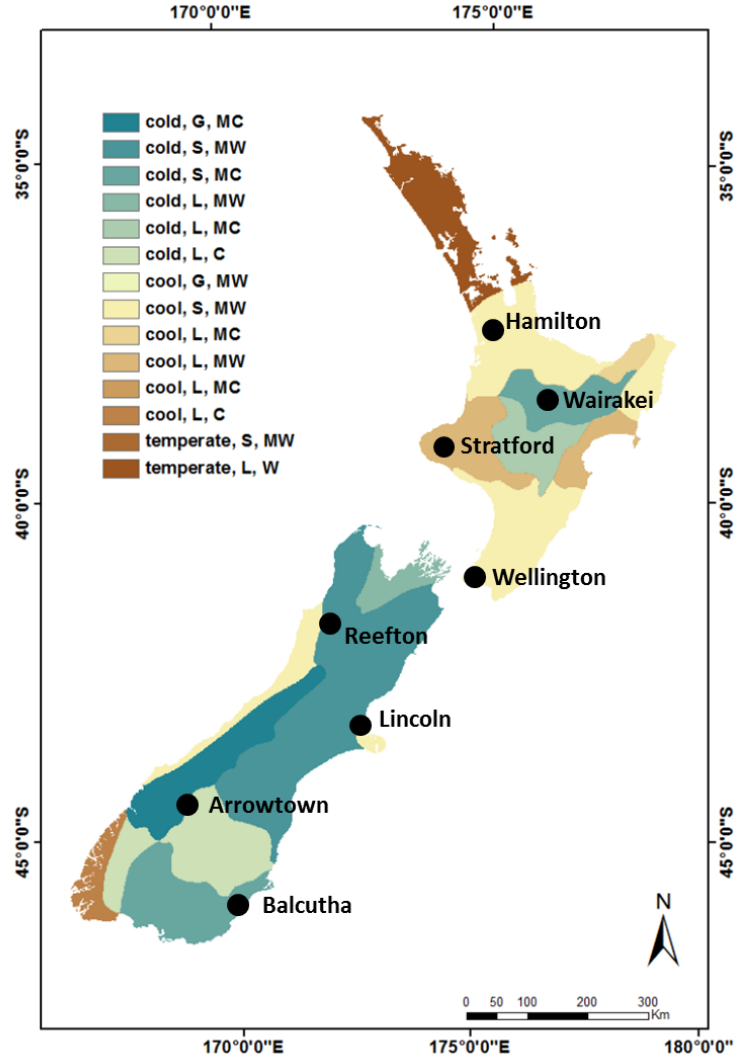
Figure 1: Location of shallow temperature borehole network in New Zealand. The map of New Zealand has been segmented into region of different soil type and climatic zones. Where "cold" indicates winter air temperatures of <2ºC, "cool" suggests winter temperatures of between 2º and 6ºC, and "temperate" indicate winter air temperatures of between 6º and 16ºC. G, S, and L indicate the predominant soils type in the region, where G is coarse gravels, S is sand and silts and L indicates Clay and Loams. C, MC, MW and W indicate the soils temperature, C is cool (<8ºC), MC is moderately cool (8-11ºC), MW is moderate warm (11-15ºC) and W is warm (15-22ºC).

3. METHOD FOR CALCULATING THERMAL DIFFUSIVITY FROM IN SITU TEMPERATURES

In-situ temperature measurements can be used to determine thermal properties, specifically the thermal diffusivity (α, m^{2}s^{-1}), which can be expressed as the ratio of thermal conductivity (κ, Wm^{-1}K^{-1}) and volumetric heat capacity (C_v, Jm^{-3}K^{-1}). Thermal properties of the system can be estimated by modelling measured ground temperatures at depth using an analytical solution to the one-dimensional heat conduction equation (Equation 1; Van Manen and Wallin, 2012):

$$\theta_{(z,t)} = \theta_m - \theta_A e^{\left(-z\sqrt{\frac{\pi}{T\alpha}}\right)} \cos\left(\omega\left(t_y - t_s - \frac{z}{2}\sqrt{\frac{T}{\pi\alpha}}\right)\right) \tag{1}$$

where the boundary condition at the surface is described by a sinusoidal function with a period of T (365.25 days); θ_m and θ_A are the mean ambient temperature and mean amplitude of the ambient temperature (ºC); z is depth (m); t_y is the Julian day of the year, t_s is the Julian day of the year that has the minimum ambient temperature, and ω is the angular frequency given by $2\pi/T$.

Alternatively, thermal diffusivity can be calculated using least squares inversion, by fitting an annually varying sine wave (Equation 2) to the recorded temperature data at different sensor depths.

$$\theta_z = \theta_0 + \theta_A \sin(\phi) \tag{2}$$

An average steady state temperature (θ_0), a maximum temperature variation (amplitude, θ_A) and a time delay (phase, ϕ) can be determined at different depths. The results from Equation 2 are used to calculate the apparent thermal diffusivity using differences in the phase (ϕ, Equation 3) and amplitude (θ_A, Equation 4) at different depths.
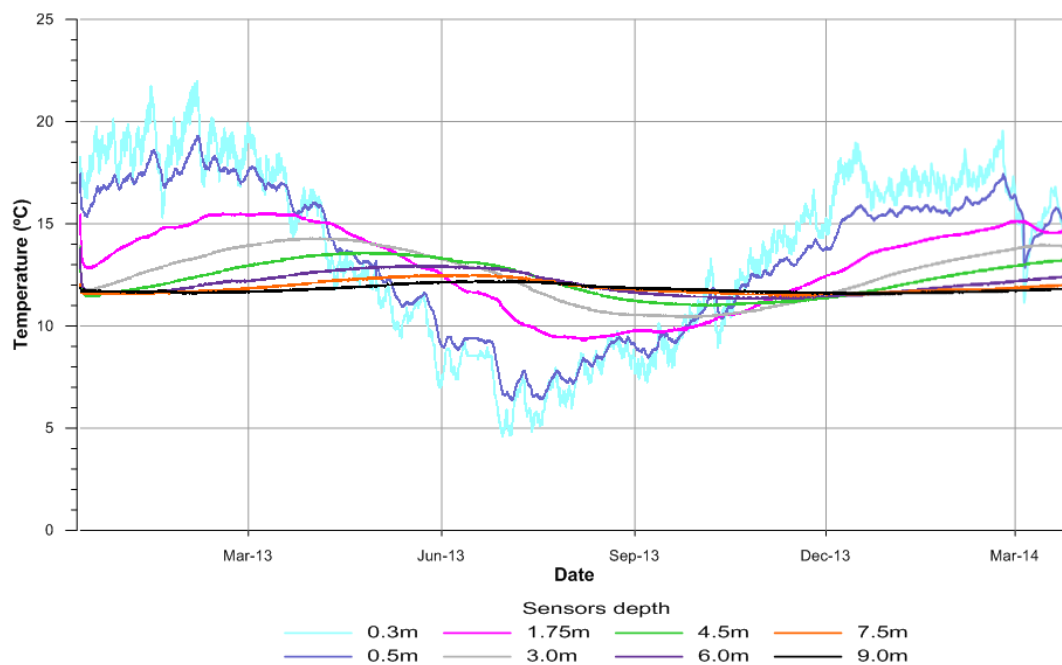
(a)
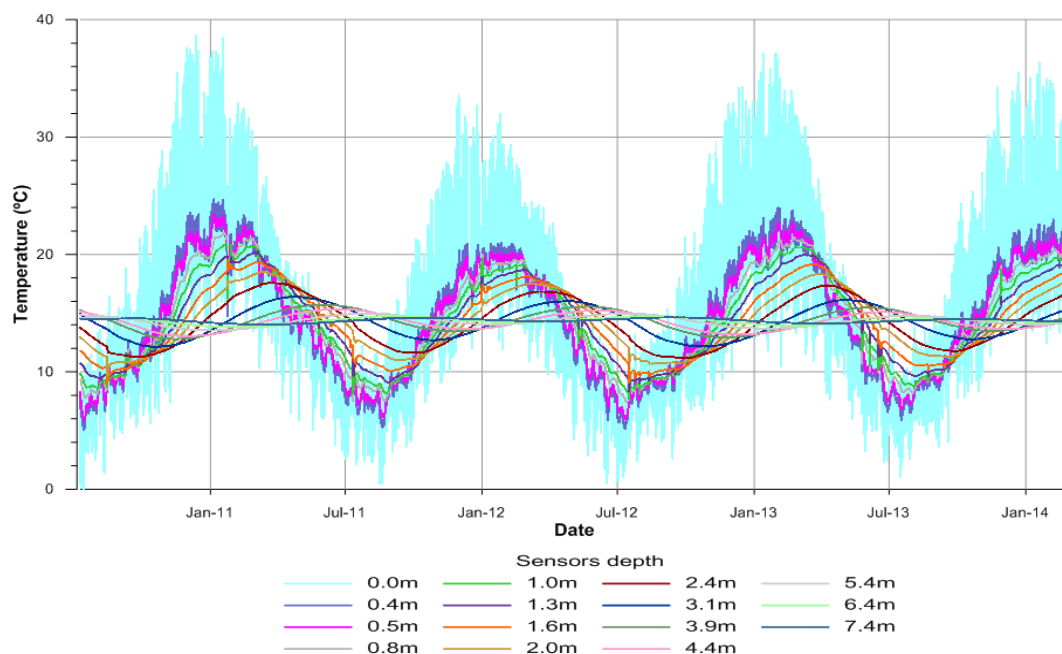
(b)

Figure 2: Soil temperature data recorded at different depths within boreholes. (a) Wairakei and (b) Lincoln

$$\alpha_\phi = \left(\frac{\omega}{2}\right)(z_2 - z_1)^2 \left(\frac{1}{(\phi(z_1) - \phi(z_2))}\right)^2 \tag{3}$$

$$\alpha_A = \left(\frac{\omega}{2}\right)\left(\frac{z_2 - z_1}{\ln\left(\left|\theta_A(\omega, z_1)\right|\big/\left|\theta_A(\omega, z_2)\right|\right)}\right)^2 \tag{4}$$

where z_1 and z_2 are the selected depths. The thermal diffusivity calculated from the phase shift is thought to give a more accurate value (Tabbagh et al, 1999), although in a truly homogenous soil the results from equations 3 and 4 would be equal. The heat transfer in the soil can be calculated from temperature variations at depth using the heat conduction equation with an additional term to account for the effect of rainfall on the heat conduction/convection ratio of the soil (Equation 5).

$$\frac{\partial}{\partial t}\theta(z,t) = \alpha \frac{\partial^2}{\partial z^2}\theta(z,t) + v\frac{\partial}{\partial z}\theta(z,t) \tag{5}$$

where θ is the ground temperature (ºC); and $v = u\, C_{vw}/C_{vs}$; where u is the volumetric flow rate (Darcy's velocity, ms^{-1}), C_{vw} is the volumetric heat capacity of water and C_{vs} is the volumetric heat capacity of the bulk soil.

The solution to Equation 5 for a homogeneous medium is given by Equation 6:

$$\Delta\theta(z,t) = \theta_0 e^{\gamma z} e^{i\omega t} \tag{6}$$

where θ_A is the temperature amplitude at the ground surface; $i^2 = -1$; and $\gamma = \frac{v - \sqrt{v^2 + 4i\omega\alpha}}{2\alpha}$.

Equation 6 allows the temperature at depth to be calculated using the thermal properties of the material. The measured temperatures at sensors depth are fitted using least square inversion to find optimal values for α and C_{vs}.

4. RESULTS AND DISCUSSION

Ground temperature behaviour is generally categorised into three groups (Popiel *et al*, 2001): (1) Temperatures sensitive to diurnal variations, primarily in the top 1 m (surface zone); (2) Temperatures sensitive to seasonal variations, usually down to depths of 7 - 15 m (shallow zone); and (3) near constant ground temperature at depths greater the 15 m (deep zone), approximately 2ºC warmer than average ambient temperature.

Data from the Wairakei borehole shows these three characteristics.

1. Diurnal variation (surface zone): Ground temperatures are sensitive to diurnal effects to 50cm depth (Figure 3).

2. Seasonal variation (shallow zone): Larger scale variations due to seasonal changes are apparent in ground temperatures to depths of 7 m (Figures 2 and 3a).

3. Constant temperature (deep zone): Constant ground temperatures are not reached in the Wairakei borehole, however variations at the bottom are very minimal (± 0.02ºC). This suggests that the "deep zone" is only just deeper than 7.4 m (Figure 4a), where ground temperatures are constant at ~14.4ºC. This is 2.9ºC warmer than the annual average ambient air temperature for the Taupo area (11.5ºC).

This constant temperature is close to the preliminary estimates published by Van Manen and Wallin (2012); and is consistent with published trends that show a constant temperature at depths greater than 15 m as being comparable (± 2ºC) to the annual average ambient air temperature at a given location (Rybach and Sanner, 2000).

The Lincoln borehole shows similar characteristics with the surface zone reaching depths of 50 cm and the shallow zone extends to ca. 9 m depth (Figure 4b). The constant ground temperature of 11.8ºC occurs at depths below 9 m. This is only 0.3ºC higher than the average ambient temperature of the area, which does experience large temperature variations throughout the year (-5ºC – 30ºC).
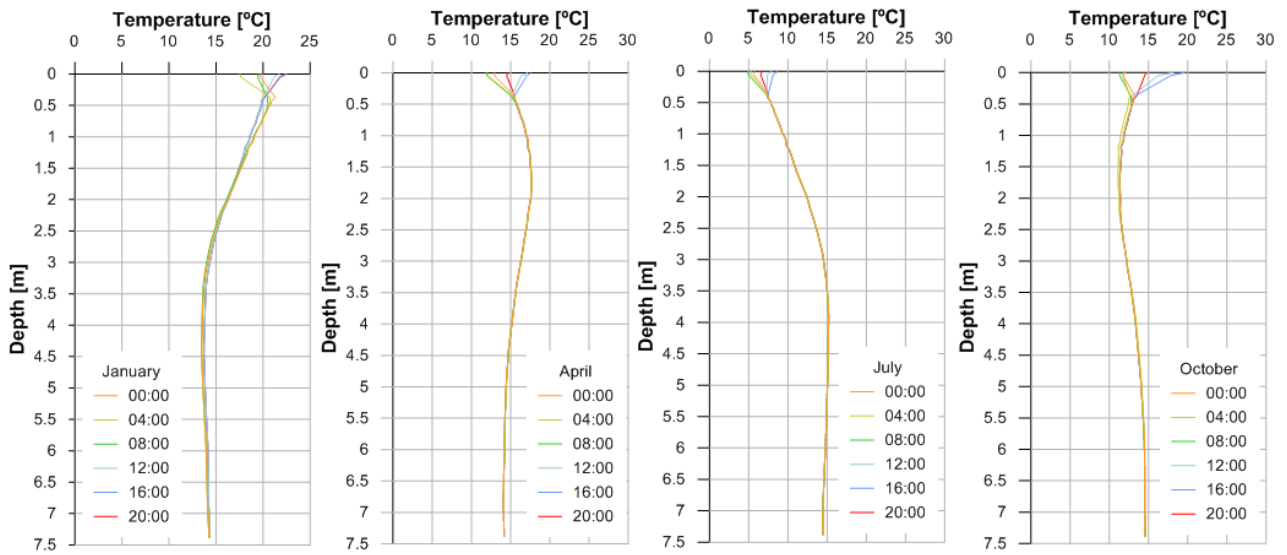
Figure 3: An example of daily average temperature variation for January, April, July and October from the Wairakei borehole. Daily fluctuations are apparent to a depth of 50 cm on average. Seasonal temperature variations with depth are also evident, between depths of 50cm and 7 m.
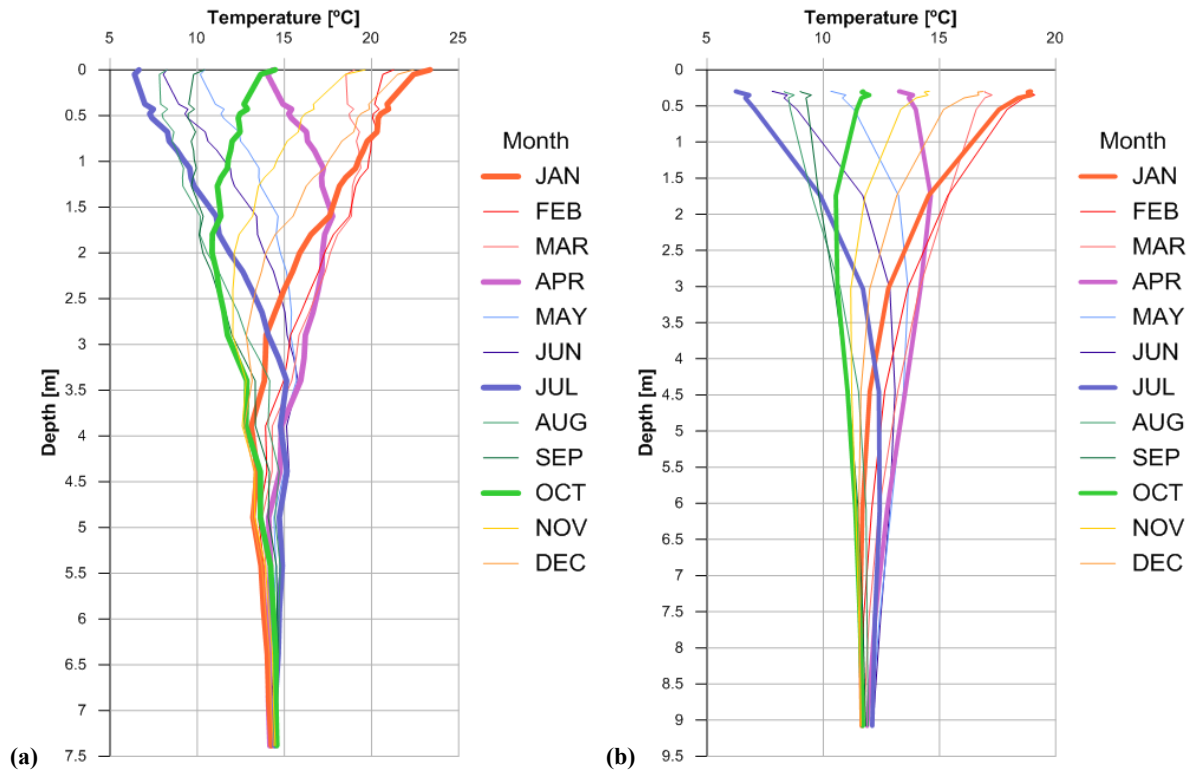

(a)

(b)

Figure 4: Annual temperature variations for (a) Wairakei borehole (averaged data for 43 months); and (b) Lincoln borehole (averaged monthly data over 12 months);

The time lag between surface variations and ground temperature change increases with depth (Figure 2). For example at Wairakei, the minimum surface temperature for 2012 was recorded on June 17th, while the minimum subsurface temperatures were recorded on July 16th, August 19th, November 3rd and April 1st 2013, for depths of 1 m, 2 m, 3.1 m and 7.4 m, respectively. These translate to time lags of 29 days, 92 days, 139 days and 288 days, respectively. From the least square inversions, the phase lag between each depth corresponds to 29 days, 58 days, 100 days and 258.3 days.

Table 1 shows the average temperature (θ_0), temperature variation (θ_A) and phase lag (ϕ) calculated from Equation 2 at selected comparable depths. The shallowest sensor at the Lincoln site is located at 0.3 m deep, so phase delays for both boreholes are calculated from 0.30 m deep to aid comparisons.

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Table 1: Average temperature, θ_0; amplitude, θ_A; and phase, ϕ; delay for selected depths at Wairakei and Lincoln.

	Wairakei			Lincoln		
Depth (m)	θ_0 (ºC)	θ_A (ºC)	ϕ (days)	θ_0 (ºC)	θ_A (ºC)	ϕ (days)
0.3	14.35	6.7	0	12.56	5.8	0
0.4	14.24	6.5	2	12.55	5.3	4
0.6	14.41	6.2	6	12.42	4.7	9
1.0	14.32	5.3	18	-	-	-
1.8	14.38	3.8	43	12.38	2.9	38
3.0	14.36	2.1	82	12.30	1.9	67
4.5	14.34	1.0	139	12.23	1.3	84
7.4	14.37	0.2	250	11.91	0.4	87

Climatic effects are secondary parameters influencing ground temperatures. Rainfall for example has a transient effect on ground temperature that that decreases with depth, depending on the temperature and amount of the rainfall (Figure 5). Rainfall effects can be observed to depths of 2.20m in Wairakei borehole during periods of high rainfall.
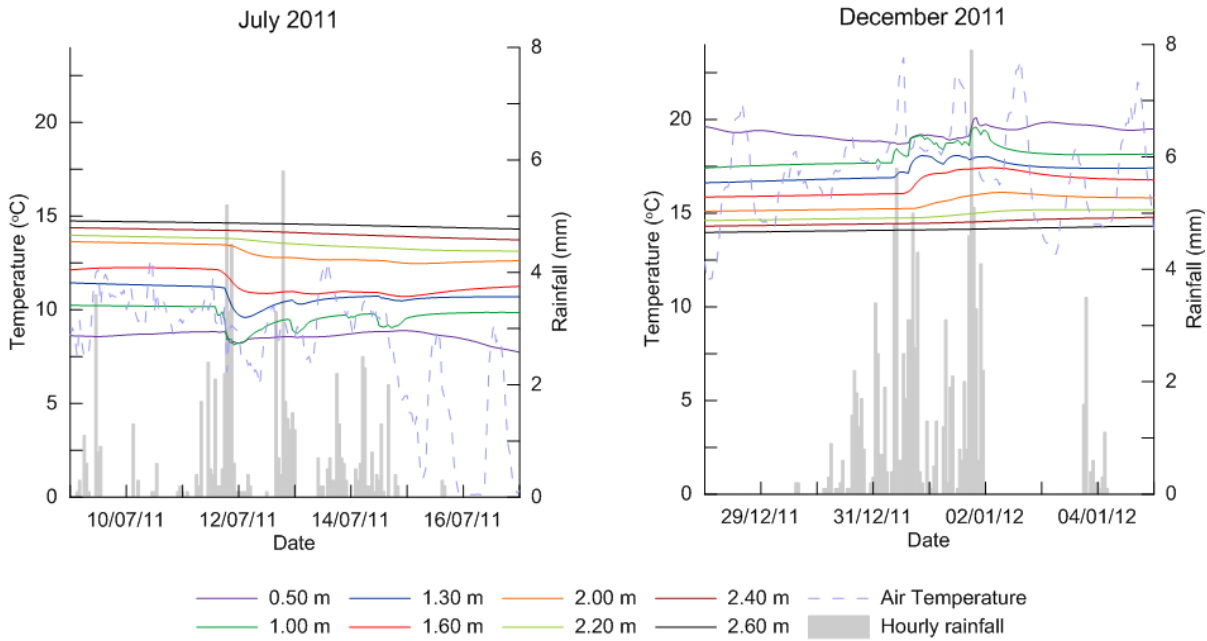
Figure 5: Rainfall induced anomalies in ground temperature data recorded at Wairakei.

Temperature variations at each sensor are fitted using least square inversion (Equation 6) to determine the thermal diffusivity, α, and the volumetric heat capacity, C_v. Local climatic factors such as rainfall are used to determine the volumetric flow rate (Darcy's velocity) and Peclet number (Pe), which provides a measure of the relative part of heat convection to conduction (Huysmans and Dassargues 2005).

$$Pe = \frac{(u C_w L)}{k} \tag{7}$$

where C_w is the volumetric heat capacity of water (4.18×10^6 J m^{-3} K^{-1}), L is the characteristic length (1 m), u the volumetric flow rate, and k is the mean thermal conductivity. Average yearly rainfall for Wairakei and Lincoln are observed to be 972 mm/yr and 594 mm/yr, respectively (NIWA, 2014).

The thermal diffusivity of the soil can be determined from either the observed phase delay or the change in temperature amplitude between depths (Tabbagh *et al*, 1999). Table 2 outlines the average range in thermal diffusivities and volumetric heat capacity estimated for each site through the optimization process.

Table 2: Thermal diffusivity (α) and volumetric heat capacity (C_v) of the ground at Wairakei and Lincoln.

	α_ϕ (m^2/s)	α_A (m^2/s)	C_v (J/m^{3}K)
Wairakei	1.82×10^{-7} – 5.48×10^{-7}	2.20×10^{-7} – 8.51×10^{-7}	2.00×10^6 – 2.79×10^6
Lincoln	1.80×10^{-7} – 6.60×10^{-7}	1.37×10^{-7} – 8.81×10^{-7}	1.98×10^6 – 2.00×10^7

6. SUMMARY

This paper presents ground temperature variations in different soils types in New Zealand. Pumice soils in the Taupo region, shows that the surface zone extends to a depth of 50 cm, while the shallow zone extends to a depth approximately 7.4 m. It is expected that the deep zone starts close to this depth and will be constant throughout the year at ~14.4ºC. The silty / sandy soils of the Canterbury plains near Lincoln, show similar treads, with a surface zone extending to approximately 50cm, while the shallows zone looks to extend to 9m. It is expected that the deep zone starts close to here, with a year-round constant temperature of 11.8ºC. These zones cannot yet be determines for the Raukura borehole.

Shallow ground temperatures show the largest influence of surface temperatures, with the amplitude of the ground temperatures variations decreasing with depth, while the phase delay increases. The effect of rainfall is shown (Figure 5), but not modeled in this paper.

In this paper we have determined ranges of apparent thermal diffusivity and volumetric heat capacity from ground temperatures in two boreholes. Sine waves were fitted to recorded temperatures at different depths within the ground. The phase and amplitudes of the synthetic sine waves were then used to determine values for thermal diffusivity. Volumetric heat capacity was estimated by using least squares inversion. These values will be compared to measurements done on core extracted from the boreholes during drilling

REFERENCES

Atkinson, F. and Seward, A.: Borehole Temperature Array – Installation at the Raukura Climate Station Site. *GNS Science internal report 2014/01* (2014), 18p.

Cole-Baker, J.: Borehole temperature array – design and construction. *GNS Science internal report 2011/01* (2011), 14p.

Cole-Baker, J., Atkinson, F. and Seward, A. Borehole Temperature Array - Installations at Lincoln NIWA site and Arrowtown Golf course. *GNS Science internal report DRAFT* (2013), 22p.

Huysmans, M. and Dassargues, A.: Review of the use of Peclet number to determin the relative importance of advection and diffusion in low permeability environments. *Hydrogeology Journal.* **13**, (2005), 895 – 904.

Johnston, I.W.: Geothermal Energy using ground source heat pumps. *Proceedings,* New Zealand Geothermal Workshop 2012, University of Auckland, Auckland, New Zealand (2012).

NIWA, 2014 Climate Database, http://www.niwa.co.nz/education-and-training/schools/resources/climate. Access in March 2014

Popiel, C.O., Wojtkowiak, J., and Biernacka, B.: Measurements of temperature distribution in ground. *Experimental Thermal and Fluid Science.* **25**, (2001), 301-309.

Rybach, L. and Sanner, B. : Ground Source Heat Pump Systems, The European Experience. *GHC Bulletin* (2000)

Tabbagh, A., Benjoudi, H., Benderitter, H., Determination of recharge in unsaturated soils using temperature monitoring. *Water Resource Research.* **35**, (1999), 2439-46.

Van Manen, S.M. and Wallin, E.: Ground temperature profiles and thermal rock properties at Wairakei, New Zealand. *Renewable Energy.* **34**, (2012), 313-321.