# THERMAL PROPERTIES OF NEW ZEALAND'S ROCKS AND SOILS

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## ABSTRACT

New Zealand's rocks and soils provide a 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 ground source heat pump (GSHP) to provide heating in the winter and cooling in the summer.

Part 1 presents an update of below-ground temperature measurements in several locations around New Zealand. Temperature monitoring boreholes installed at Wairakei (Taupo), Raukura (Hamilton) and Lincoln (Canterbury) are logging in situ temperatures at depth, from the surface down to 13 m. These temperatures can be used to calculate thermal properties of the soils.

Part 2 presents a desktop study of New Zealand's climatic areas, common soil types and geology. Air temperature was spatially combined with soil type, soil temperature and geology to identify areas of unique temperature and ground properties. This regional scale study highlights areas of unique ground and climate properties in which to install future in-ground temperature monitoring borehole.

The data presented in this paper aims to provide fundamental information to improve the design of GSHP ground loops in New Zealand.

## 1. INTRODUCTION

Solar radiation penetrates the Earth's surface, causing temperature variations through the near surface that provides a source of energy. The depth of penetration of the solar energy depends on a number of factors, including 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.

Stored energy can be used for heating and cooling purposes through the use of a Ground Source Heat Pump (GSHP), alternatively known as a Geothermal Heat Pump (GHP) or a Geo-exchange system. The basic principle behind a GSHP is to extract heat from, or reject heat into, the ground or water source using buried vertical or horizontal pipes, through which a heat transfer fluid is circulated (EECA and GNS Science, 2013). This results in a low-cost, environmentally-friendly energy source that can be utilised for space heating/cooling of commercial, industrial or domestic buildings, as well as heating water for swimming pools.

High capital cost is a barrier to increased uptake of GSHP in New Zealand. One factor that contributes to over-inflation of cost is a tendency to overdesign ground loop systems based on European or North American design standards (Johnston, 2012). New Zealand requires appropriate and accessible ground property data for local GSHP design.

This paper examines thermal properties of soils from *in-situ* temperature measurements in several boreholes around New Zealand (Section 2) and a regional scale analysis of New Zealand's climate and ground properties ideal for GSHP installations (Section 3).

### 1.1 Ground Source Heat Pump Ground Loop Design

GSHPs consist of 3 components, (1) the ground loop; (2) the heat pump; and (3) the distribution system. Both the distribution system and heat pump requirements are dependent on the design of the building and its heating/cooling needs. The design of ground loop, in contrast, is primarily influenced by the site location and ground properties.

Efficiency advantages can be gained and ground loops can be much smaller (saving significant upfront capital costs) if a GSHP system can be designed to provide 'balanced loads'(i.e. where the system takes roughly the same amount of heat out of the ground in winter for heating, as it puts back in the ground during summer for cooling). In this case, the system is effectively 'banking' heat energy during summer, and withdrawing it in winter.

To determine the required ground loop size, an analysis of local geological conditions is required. The length of ground loop required is directly influenced by the heat pump capacity, and the ground's resistance and temperature (Johnston, 2012). The length (L) of a vertical borehole containing a single ground loop, for example, is conservatively calculated by Equation 1 (IGSHPA, 2009):

$$L = \frac{HC\left(\frac{CoP-1}{CoP}\right)(R_B + R_G \cdot F_H)}{T_0 - \left(\frac{EWT_{\min} - LWT_{\min}}{2}\right)} \qquad \textbf{[1]}$$

where HC is the capacity of the GSHP at design conditions; CoP is the coefficient of performance of the GSHP at design heating conditions; $R_B$ is the thermal resistance of the borehole; $R_G$ is the thermal resistance of the ground outside the borehole; $F_H$ is the run fraction of the GSHP during heating months; $T_0$ is the steady state ground temperature, and $EWT_{min}$ and $LWT_{min}$ are the entering and leaving water temperature conditions, respectively, on the ground side of the heat pump. HC, $R_B$, $F_H$, $EWT_{min}$ and $LWT_{min}$ are all influenced by the design and need of the build. $R_G$ and T are site-specific and depend on the ground properties. The thermal resistance ($R_G$) of the medium in which the ground loop is placed (e.g. soil or rock) is dependent on its thermal diffusivity (α).Thermal diffusivity can be calculated from a heat equation using annual temperature variations at different depths.

### 1.2 Thermal Diffusivity Studies

Previous studies of ground temperature variations focus on shallow low-enthalpy geothermal systems (e.g. Kurevija & Vulin, 2010), climate change (e.g. Davis et al, 2006) or ground water recharge (e.g. Benjoudi et al 2005). Soil thermal properties are important for all of these applications.

In New Zealand, ground temperature profiles are being used to assess soil thermal properties such as thermal diffusivity, thermal conductivity, and volumetric heat capacity. In the development of low enthalpy geothermal resources these parameters are particularly important for efficient and cost-effective heat recovery using GSHPs. Van Manen and Wallin (2012) published preliminary results from 6 months of data recorded at a borehole located at Wairakei, Taupo. Results show that for an average annual surface temperature fluctuation of 8.63ºC, a thermal diffusivity, α, of $3.48\text{x}10^{-7}$ $m^3s^{-1}$ and a volumetric heat capacity, $C_v$, of $2.35\text{x}10^6$ $Jm^{-3}K^{-1}$ are obtained for a pumice rich soil. Section 2 of this paper presents results from the same borehole with 34 months of recorded ground temperatures in conjunction with preliminary results from two more boreholes located in Raukura and Lincoln.

Section 3 presents a desktop study of different climate and soil regions of New Zealand, aimed to show regions of interest for further ground-temperature monitoring borehole installations.

## 2. TEMPERATURE MONITORING BOREHOLES

This section discusses the collection and analysis of ground temperatures from the first three ground-temperature monitoring boreholes installed in New Zealand.

### 2.1 Ground temperature data

Boreholes with down-hole temperature sensors have been installed at Wairakei, Raukura and Lincoln. The Wairakei borehole was installed in July 2010 and has been continuously logging temperatures with 31 sensors between the surface and 7.4 m below ground surface. The lithology is predominately unconsolidated pumice with a thin layer of soil on the top (Cole-Baker, 2011).

The Raukura borehole was installed in November 2011 and contains 12 sensors installed between 38 cm and 13.3 m below the ground (Cole-Baker *in prep*). Data has been collected between November 2011 and May 2012. The lithology of the site includes silt, loam and sand.

The Lincoln borehole was installed in December 2012 and contains 12 sensors from 30 cm down to 9 m (Cole-Baker & Seward, *in prep*). Data has been collected between December 2012 and June 2013. The bore was drilled in predominately silt and sand lithology.

Figure 1(a) shows 34 months of data recorded at the Wairakei borehole, and figure 1 (b) and (c) show the raw data recorded at Raukura and Lincoln, respectively over a period of 6 months.

### 2.2 Method For Calculating Thermal Diffusivity From In Situ Temperature Measurements

*In-situ* temperature measurements can be used to determine thermal properties, specifically the thermal diffusivity (α, $m^2s^{-1}$), 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 2; Van Manen and Wallin, 2012):

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

where the boundary condition at the surface is described by a sinusoidal function with a period of $T$ (365.25 days); $\theta_m$ and $\theta_A$ are the mean ambient temperature and mean amplitude of the ambient temperature (°C); $z$ 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 a least squares inversion method, by fitting an annually varying sine wave (Equation 3) to the recorded temperature data at different sensor depths.

$$\theta_z = \theta_0 + \theta_A \sin(\phi) \quad \textbf{[3]}$$

An average steady state temperature ($\theta_0$), a maximum temperature variation (amplitude, $\theta_A$) and a time delay (phase, $\phi$) can be determined at different depths. The results from Equation 3 are used to calculate the apparent thermal diffusivity using differences in the phase ($\phi$, Equation 4) and amplitude ($\theta_A$, Equation 4) at different depths.

$$\alpha_\phi = \left(\frac{\omega}{2}\right)(z_2 - z_1)^2\left(\frac{1}{(\phi(z_1) - \phi(z_2))}\right)^2 \quad \textbf{[4]}$$

$$\alpha_A = \left(\frac{\omega}{2}\right)\left(\frac{z_2 - z_1}{\ln\left(|\theta_A(\omega,z_1)| / |\theta_A(\omega,z_2)|\right)}\right)^2 \quad \textbf{[5]}$$

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, although in a truly homogenous soil the results from equations 4 and 5 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 6).

$$\frac{\partial}{\partial t}\theta(z,t) = \alpha\frac{\partial^2}{\partial z^2}\theta(z,t) + \nu\frac{\partial}{\partial z}\theta(z,t) \quad \textbf{[6]}$$

where $\theta$ is the ground temperature (ºC); and $\nu = u\,C_{vw}/C_{vs}$; 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.

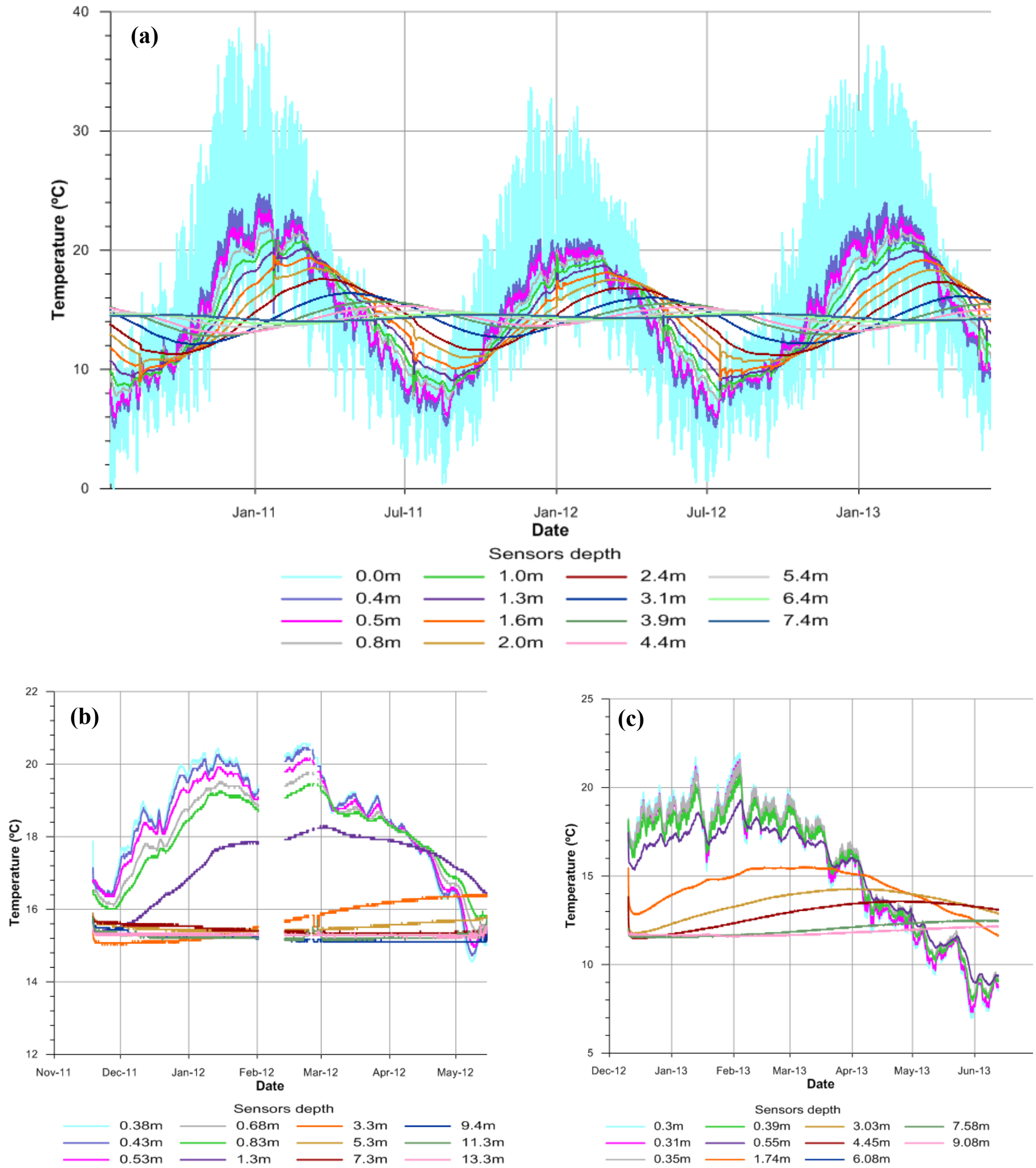


**Figure 1: Raw soil temperature data recorded at the borehole at different depths. (a) Raw data recorded at Wairakei over 34 months; (b) Raw data recorded at Raukura over 6 months; (c) Raw data recorded at Lincoln over 6 months.**

The solution to Equation 6 for a homogeneous medium is given by Equation 7:

$$\Delta\theta(z,t) = \theta_0 e^{\gamma z} e^{i\omega t} \qquad \textbf{[7]}$$

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

Equation 7 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 $C_{vs}$.

### 2.3 Results and Discussion

Ground temperature behaviour is generally categorised into three groups (e.g. 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): In the Taupo area, ground temperatures are sensitive to diurnal effects to 50cm depth (Figure 2).

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 3a), where ground temperatures are constant at ~14.4°C. 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 Raukura borehole shows a surface zone of 50 cm and a shallow zone extending to 9 m depth (Figure 3b). Results from 6 months of recorded down-hole temperatures suggest a constant ground temperature in the deep zone of 15.3ºC, which is 1.5ºC higher than the average ambient temperature in the area.

The Lincoln borehole shows a surface zone of 50 cm and a shallow zone that extends to ca. 9 m depth (Figure 3c). 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). The time lag between surface variations and ground temperature change increases with depth (Figiure 1). 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.

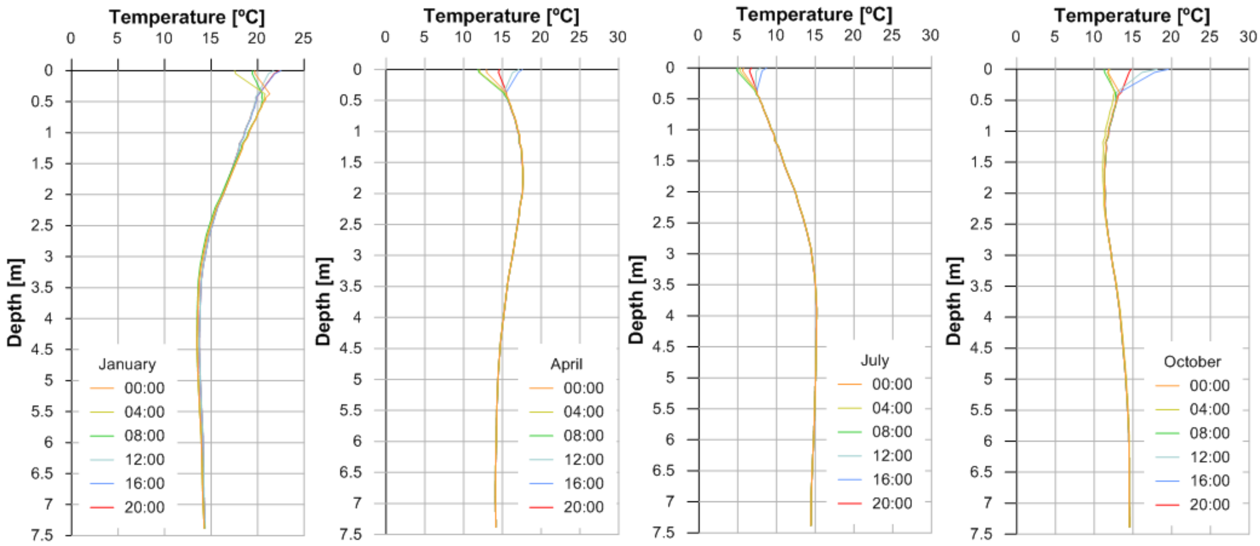


**Figure 2: An example of daily average temperature variation for January, April, July and October from the Wairakei borehole. Daily fluctuations are apparent to a depth of 50 cm on average. Seasonal temperature variations with depth are also evident.**

**(a) Wairakei** **(b) Raukura** **(c) Lincoln**

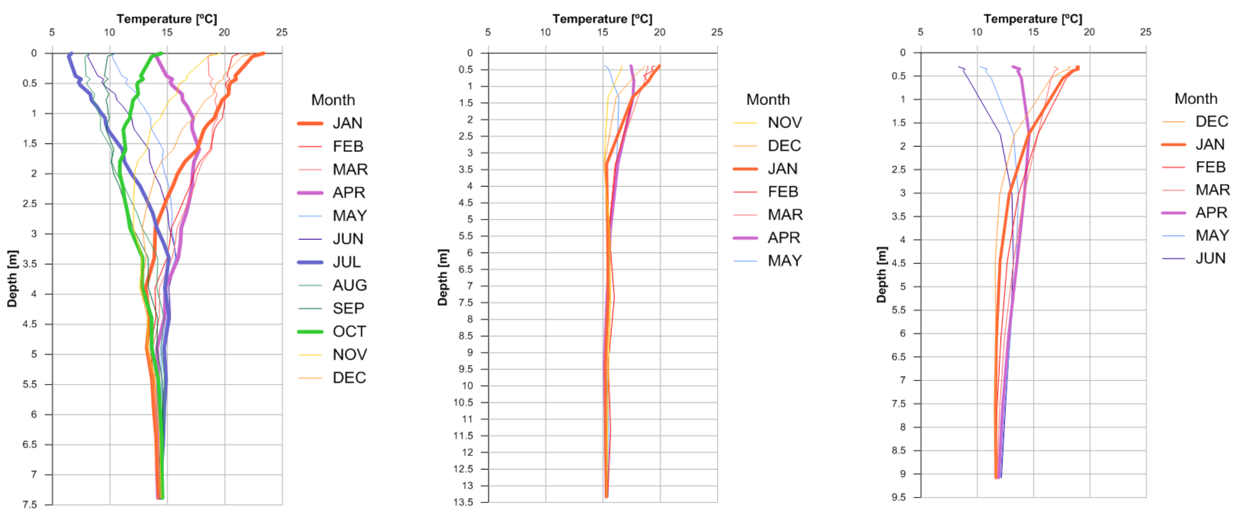


**Figure 3: Annual temperature variations for (a) Wairakei borehole (averaged data for 34 months); (b) Raukura borehole (average monthly data over 6 months); and (c) Lincoln borehole (averaged monthly data over 6 months).**

Table 1 shows the average temperature ($\theta_0$), temperature variation ($\theta_A$) and phase lag ($\phi$) calculated from Equation 3 at selected depths. The average phase delay between the surface and the bottom is 240 days.

**Table 1: Average temperature, $\theta_0$; amplitude, $\theta_A$; and phase, $\phi$; delay for selected depths of the Wairakei borehole.**

| Depth (m) | $\theta_0$ (ºC) | $\theta_A$ (ºC) | $\phi$ (days) |
|---|---|---|---|
| 0 | 14.79 | 8.0 | |
| 0.37 | 14.70 | 7.2 | 8 |
| 0.5 | 14.69 | 6.8 | 11 |
| 1.0 | 14.68 | 5.5 | 29 |
| 2.0 | 14.61 | 3.8 | 59 |
| 3.1 | 14.28 | 2.2 | 99 |
| 7.4 | 14.32 | 0.2 | 240 |

Similar trends are observed in the other two boreholes, although cannot yet be traced to the bottom of the hole due to the length of time over which the data has been collected. Rain and moisture content will affect the transfer of heat over depth within the soil. This effect will be studied in more detail in the future.

Table 2 summarises the thermal diffusivity ($\alpha_\phi$ and $\alpha_A$), and the volumetric heat capacity ($C_v$) of the soils determined for each borehole using equations 4, 5 and 6. These calculations used the average temperature, amplitude variation and phase lag calculated at various depths. Results are given in ranges as the material within the boreholes is not homogeneous and varies with depth. Preliminary results published by Van Manen and Wallin (2012) for the Wairakei borehole are in close agreement with the results shown here.

## 3. REGIONAL GSHP ZONING STUDY

This section outlines a desktop study that was undertaken to identify areas of similar thermal ground and climate properties by analysing New Zealand's air temperature, soil temperature, soil type and geology.

The following objectives were set:

1. Which areas have the greatest air temperature variations? This will aid in inferring if an area's energy demand is predominantly for heating, cooling or a balance of both.
2. Which areas have sufficiently different climate and ground property characteristics? This will help in guiding the location of future ground temperature monitoring boreholes for future studies of thermal properties of soils and rocks.

### 3.1 Data

Air temperature (NIWA, 2013) was used as a proxy measure for climate in this study, although it is acknowledged that properties such as rainfall, sunshine and wind also play a role in the heating/cooling requirement for comfortable living. Additionally, factors such as rainfall (i.e. moisture) will influence the thermal resistance of a soil. This relationship was not explored in this study but will be looked at in future investigations.

Ground temperatures at 30 cm depth and soil particle size were used as a proxy for the thermal conductivity of a soil (κ; the reciprocal of the thermal resistance). These were sourced from Landcare Research (Landcare, 2013). Thermal conductivity ranges were taken from Kavanaugh & Rafferty (1997) and Geothermal Heat Pump Design manual (McQuay International, 2002)

Geology data was sourced from the QMAP 1:1M Geological map of New Zealand (GNS Science, 2012).

These datasets were then classified into broad classes to enable spatial analysis. Table 3 lists the classifications of the data.

### 3.2 Methodology

The spatial analysis of the data consists of overlaying or "adding" different property layers to produce a map of regions with unique conditions.

For example, to determine which regions in New Zealand would benefit from both heating and cooling using a GSHP (objective 1), the climatic datasets for average summer air-temperature and average winter air-temperature provided by NIWA were added to produce a map showing the regions that experience different temperature variations over the year (Figure 4).

To find unique areas in which to install further ground temperature monitoring stations (objective 2), air temperatures were combined with soil type and temperature to produce regional heating and cooling maps, i.e. minimum air temperatures were combined with soil temperatures at 30 cm depth and soil particle size to produce a heating (shallow) map (Figure 5a). Additionally, minimum air temperatures were combined with geology type to produce a heating (deep) map (Figure 5b).

**Table 2: Thermal properties of the ground at Wairakei, Raukura and Lincoln. Values for thermal diffusivity (α), and volumetric heat capacity ($C_v$) are calculated from down-hole temperature measurements at each location.**

| | $\alpha_\phi$ ($m^2/s$) | $\alpha_A$ ($m^2/s$) | $C_v$ ($J/m^3K$) |
|---|---|---|---|
| **Wairakei** | $1.82x10^{-7} – 8.29x10^{-7}$ | $2.20x10^{-7} – 8.51x10^{-7}$ | $2.00x10^{6} – 2.79x10^{6}$ |
| **Raukura** | $1.48x10^{-7} – 3.61x10^{-6}$ | $1.38x10^{-7} – 5.71x10^{-6}$ | $2.00x10^{7} – 2.02x10^{7}$ |
| **Lincoln** | $1.93x10^{-7} – 5.40x10^{-6}$ | $2.03x10^{-7} – 1.35x10^{-6}$ | $1.98x10^{6} – 2.00x10^{7}$ |

**Table 3: Broad classifications of air temperature, soil temperature, soil type and geology used for spatial analysis.**

| | |
|---|---|
| **Air Temperature:**<br>**cold**: $T_{min}$ = < 2 ºC ;<br>**cool**: $T_{min}$ = 2 – 6 ºC;<br>**temperate**: $T_{min}$ = 6 – 16 ºC ; $T_{max}$ = 6 – 16 ºC<br>**warm**: $T_{max}$ = 16 – 22 ºC<br>**hot**: $T_{max}$ = 22 – 26 ºC | **Soil Type:**<br>**L**: clay and loam [ k~0.3-0.4 $Wm^{-1}K^{-1}$]<br>**S**: sand and silt [k~1.3-1.6 $Wm^{-1}K^{-1}$<br>**G**: coarse gravel [k~2.22 $Wm^{-1}K^{-1}$] |
| **Soil Temperature:**<br>**W**: warm [15-22ºC]<br>**MW**: moderate-warm [11-15ºC]<br>**MC**: moderate-cool [8-11ºC]<br>C: cool [<8ºC] | **Geology:**<br>**Q** : quartzite [ k~6.0 $Wm^{-1}K^{-1}$]<br>**G** : gravel, coal, greywacke [k~3.6 – 4.0 $Wm^{-1}K^{-1}$]<br>**S** : sandstone, sand, limestone, schist, phillyte, paragneiss, rhyolite, gneiss [k~2.6 – 3.3 $Wm^{-1}K^{-1}$]<br>**M** : mudstone, claystone, gabbro, argillite, basalt, andesite [k~1.9 – 2.6 $Wm^{-1}K^{-1}$] |

### 3.3 Results and Discussion

#### 3.3.1 Analysis of Seasonal Variation

The World Health Organization recommends a minimum indoor temperature of 16 - 18ºC (EECA, 2013). This falls into the "warm" category (defined in Table 3), however, as no area within New Zealand falls into the "warm" category all year round (Figure 4), most places will benefit from the use of a heating and/or cooling system.

Using the broad classifications of air temperature, the average maximum and minimum seasonal temperatures for New Zealand were combined to highlight areas of greatest seasonal variation (Figure 4).

Four main climatic areas were determined (Figure 4c), and their general type of demand assessed.

1. Extreme variations - areas that experience cold winters and hot summers. These areas are likely to have a high demand that is well balanced for heating and cooling (e.g. Central Otago).
2. Cooler temperatures - areas that generally experience warm summers and cold winters. These areas are more likely to have a higher heating than cooling demand (e.g. Central North Island).
3. Warmer temperatures – areas that generally experience hot summers and cool winters. These areas are more likely to have a higher cooling than heating demand (e.g. Northland).
4. Minimal variations - areas where temperature variations are small, with generally warm summers and cool winters (e.g. West Coast of the South Island). These areas will also be well balanced for heating and cooling, but have a lower demand than in "extreme"areas .

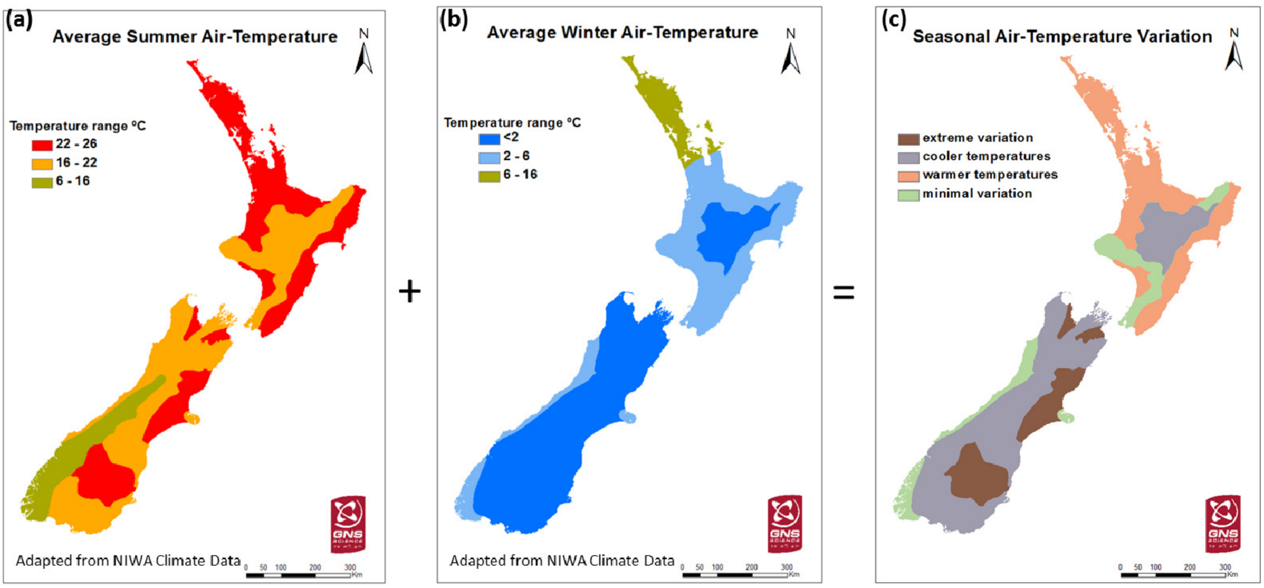


**Figure 4: Summing of the seasonal temperature extremes to highlight areas of greatest seasonal temperature variation. Extreme variations = hot summers, cold winters; Cooler temperatures = warm summers, cold winters; Warmer temperatures = hot summers, cool winters; Minimal variation = warm summers, cool winters.**

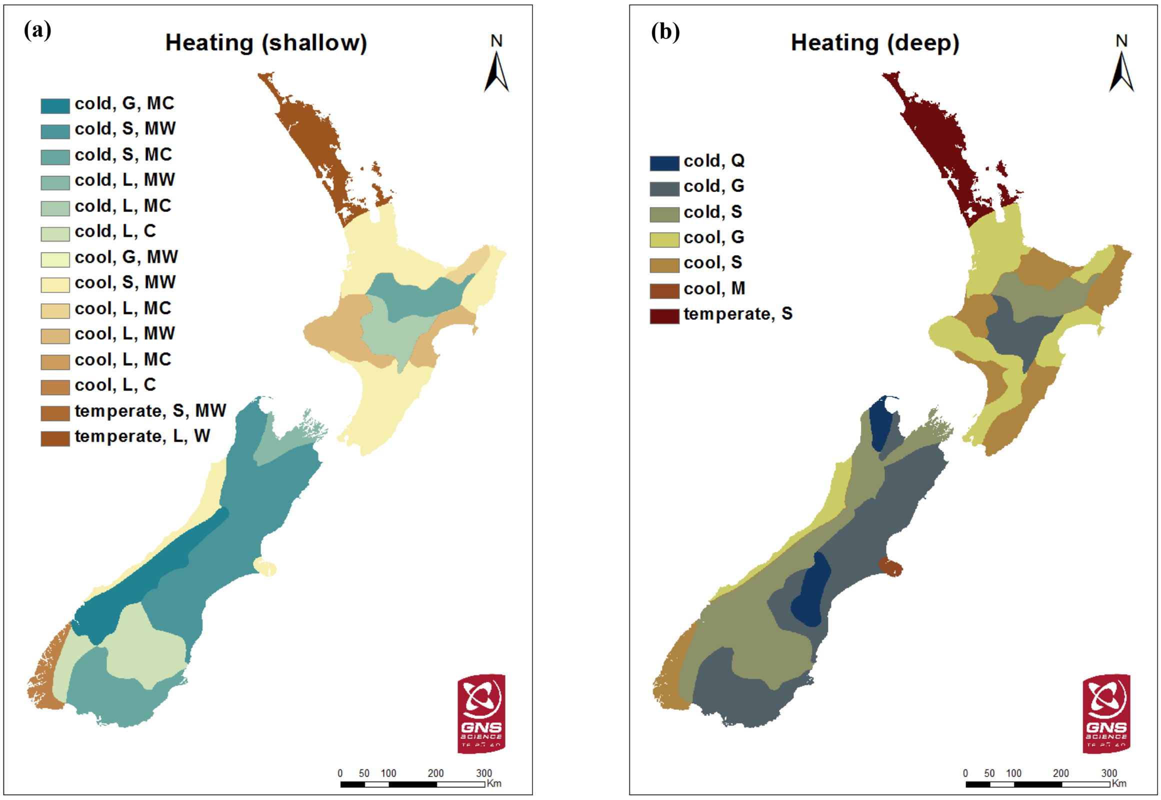


**Figure 5: Heating demand (minimum air temperature) overlaid with geology (deep) and soil (shallow) properties. Definitions used in the map legends are detailed in Table 1.**

### 3.3.2 Analysis of Ground Properties

To identify areas of unique temperature and ground properties, air temperature was spatially combined with soil type, soil temperature and geology. Figure 4 shows the results for the heating scenarios, where minimum average air temperatures were combined with ground properties. The blue to green areas experience "cold" winters (higher heating demand), while brown to red areas have milder winters (lower heating demand).

Figure 2 (a) provides information for horizontal, shallow GSHP ground loop arrays (i.e. 0-10 m depth). Figure 2 (b) provides information for vertical GSHP ground loop arrays (10 – 200+ m).

As well as the balancing of heating and cooling loads (Section 3.3.1), efficiency gains in GSHP system design can be made where the soil/rock has a higher conductivity. For example, gravel soils or greywacke rock (e.g. Alpine Fault) will generally be more conductive than soils containing loam or sand/silt (e.g. Wairarapa).

The different regions identified in figure 5(a) will be used to select future locations for the installation of temperature monitoring boreholes (Section 2) in different climate and soil zones, to determine the efficiency of various soil types at transferring, storing and releasing heat. Further research into deeper temperature variations can also be directed using the results presented in figure 5 (b).

## 4. SUMMARY

This paper looks at thermal properties of New Zealand's soils and rocks inferred from time-series of soil temperatures at a variety of depths. Results from three installed ground temperature monitoring boreholes show the surface temperature zone (the region that is susceptible to diurnal temperature variations) extending to 50 cm deep in all three sites. The shallow zone (zone that varies with seasonal temperature variation) varies between 7.5 m and 9 m due to the soil type where the boreholes are located. The amplitude of the ground temperature response to ambient temperature change decreases with depth, while the phase lag increases with depth.

The temperatures of the deep zone in Wairakei and Raukura are close to the expected values, while the constant soil temperature at Lincoln is close to the mean annual air temperature. These variations in deep zone temperatures will be further investigated as longer time-series datasets become available.

By determining the changes in average temperature, annual temperature variation amplitude and the phase lag at depths over the recorded time-series, the thermal diffusivity and volumetric heat capacity of the soils was calculated.

Effects of other climatic properties, such as rainfall, also have an influence on the thermal properties of the soil within the borehole and will be investigated in future studies.

A desktop study of similar climate and thermal properties of soils and rocks in New Zealand highlighted heating and cooling demand trends for different areas. While all areas could benefit from heating and/or cooling to keep indoor temperatures near recommended levels, some areas would enable more efficient GSHP system design through load balancing. Additionally, areas with more conductive soils and rocks can provide improved conditions for using horizontal or vertical ground loops.

Further investigations into the thermal properties of New Zealand's soils and rocks will greatly increase our understanding of heat transfer in different materials and assist the development of GSHP design, supporting more efficient and cost effective heating and cooling systems throughout New Zealand.

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## REFERENCES

Benjoudi, H., Cheviron, B., Guerin, R., and Tabbagh, A. Determination of upward/downward groundwater fluxes using transient variations of soil profile temperature: test of the method with Voyons (Aube, France) experimental data. *Hydrological Processes* 3735-3745; 101 (1996)

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

Cole-Baker, J.. Borehole Temperature Array - Installation Raukura. *GNS Science internal report 2013* in prep.

Cole-Baker, J. Seward, A. Borehole Temperature Array - Installations at Lincoln NIWA site and Arrowtown Golf course. *GNS Science internal report 2013* in prep.

Davis, M.G., Chapman, D.S., and Harris, R.N. A decade of ground-air temperature tracking at emigrant pass observatory, Utah. *Journal of Climate*. 3722-3731; 19 (2006)

EECA Energywise, Heating and Cooling. http://www.energywise.govt.nz/your-home/heating-and-cooling. Accessed July 2013.

EECA and GNS Science. Geothermal Heat Pumps in New Zealand: An Introductory Technical Guide. *GNS Science Misc serie 54;*ISBM 978-1-972192-44-3 (2013)

GNS Science (2012), 1:1M Geological map of New Zealand, Q-map, http://data.gns.cri.nz/geology/

IGSHPA, *Ground source heat pump residential and light commercial design and installation guide.* International Ground Source Heat Pump Association, Oklahoma State University. (2009)

Johnston, I.W., Geothermal Energy using ground source heat pumps. *New Zealand Geothermal Workcshop 2012 Proceedings*. (2012)

Kavanaugh, S.P. and Rafferty, K. Ground-Source Heat Pump: Design Geothermal systems for Commercial and Institutional Buildings. *ASHRAE. Atlanta Ga.* (1997)

Kurevija, T., and Vulin, D., Determining undisturbed ground temperature as part of shallow geothermal resource assessment. *Rudarsko Geolosko Naftni Zbornik*. 27-36; 22; (2010)

Lardy, M., and Tabbagh, A., Measuring and interpreting heat fluxes from shallow volcanic bodies using vertical temperature profiles: a preliminary test. *Bulletin of Volcanology*. 441-447; 60 (1999)

McQuay International, Application guide *AG31-2008 Geothermal Heat Pump Design Manual* (2002)

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

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

Rybach, I., Sanner, B., Ground-source heat pump systems: the European experience, *Geo-Heat Center Bulletin*. 16-26; 21 (2000)

Landcare Research, LRIS Land Resource Information Systems Portal. http://lris.scinfo.org.nz/

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

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