The Shallow Geothermal Energy Potential in Auckland: An Exploratory Study

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ABSTRACT

Shallow geothermal energy offers a clean, widely applicable, and cost-effective resource. A practical field assessment of this resource is essential for designing a subsurface heat extraction system. A 20 m monitoring well was drilled in Takanini, Auckland and installed with 15 temperature sensors to evaluate its shallow geothermal potential over 12 months.

Temperature profiles exhibited clear seasonal and diurnal variations near the surface, stabilising at approximately 18 °C below 8 m depth. These observations suggest that Auckland's subsurface thermal regime is richer than that of comparable temperate cities such as Melbourne and London. Concurrent monitoring of domestic water temperatures supports preliminary feasibility for geothermal-heated water supply. Ongoing field experiments will further assess the performance of borehole heat exchangers under local geological and climatic conditions. This research will effectively promote the development of sustainable geothermal energy in New Zealand, especially in the broad application of shallow geothermal heat.

1. INTRODUCTION

The growing energy demand for building and household use requires clean and renewable energy exploration (Hassan et al., 2024; Zarco-Soto et al., 2025). While our attention has long been focused on deep geothermal energy, the more accessible and broadly distributed shallow geothermal resource has often been neglected. In recent years, ground source heat pumps (GSHP) and energy piles have attracted increasing attention as emerging technologies in the renewable energy field (Li and Lai, 2015; Mohamad et al., 2021; Sani et al., 2019). In order to assess the feasibility of these technologies in various geographic contexts, exploration of shallow geothermal energy has become both essential and timely (Li and Lai, 2015, Mohamad et al., 2021, Sani et al., 2019).

GSHP systems and energy piles use borehole heat exchangers (BHE) to extract shallow geothermal energy by circulating fluid through a looped piping system (Walch et al., 2021). Combined with a heat pump, the system provides thermal energy for domestic hot water and space heating during winter, while offering building cooling capacity in summer (Gao et al., 2022). Therefore, understanding the near-surface ground temperature and its spatial variability is essential for accurately assessing shallow geothermal resource potential (Retkowski et al., 2015). The absolute value of ground temperature is directly correlated with the energy content of shallow geothermal resources. Meanwhile, the ground temperature distribution provides critical parameters for the design and performance prediction of BHE, affecting the installation cost and operational effectiveness of the entire system (Retkowski et al., 2015). Comparable investigations have been undertaken in Melbourne, London, and China, among other regions (Faizal et al., 2016, Sani et al., 2019, Wang et al., 2019, Yue et al., 2007). Furthermore, precise modelling of ground heat exchange systems and their performance characteristics necessitates comprehensive data on regional ambient temperatures and domestic water consumption patterns (Rammal et al., 2018). Realistic domestic water usage profiles serve as fundamental inputs for experimental regime configuration.

This study provides a preliminary characterisation of ground-temperature profiles and domestic-water temperatures in Auckland, New Zealand, to build a baseline for subsequent shallow geothermal applications.

2. EXPERIMENTAL METHOD

2.1 Location and devices

Given the insufficient knowledge of shallow geothermal conditions in New Zealand, an exploratory study was first carried out in Auckland, which has the largest population in the country. Borehole drilling and temperature data collection were performed in the Takanini district of southern Auckland (at Drill Force NZ Ltd. yard). The specific site is illustrated in Figure 1. The borehole is situated in an open field, unobstructed by buildings or vegetation.

This study focused primarily on measuring domestic water and ground soil temperatures. K-type thermocouples were used as the temperature sensors, featuring a dual-layer PVC protective coating and aluminium shielding wire, providing good corrosion resistance and effectively reducing signal interference during data transmission. The data acquisition system included the TC-08 thermocouple data logger from Pico Technology™, which was operated and monitored via a laptop for data storage and system control. TC-08 supports 8 channels and features built-in cold junction compensation. The PicoLog 6 software, also from Pico Technology™, was used for data recording and visualisation.

Figure 1: Location of the test site.

2.2 Domestic water usage

This research aims to improve awareness and comprehension of shallow geothermal energy utilisation in New Zealand. A fundamental understanding of domestic water temperature profiles and temporal consumption patterns is a prerequisite for effectively integrating this emerging energy technology into residential hot water systems. A continuous monitoring campaign was performed in February 2025 at a typical household (Sadiq Zarrouk's House) to record domestic hot water temperatures across multiple diurnal cycles in an Auckland residence. The experimental setup was comprised of surface-mounted thermocouples on both inlet and outlet pipes of the hot water cylinder, with all sensors properly insulated to minimise thermal interference.

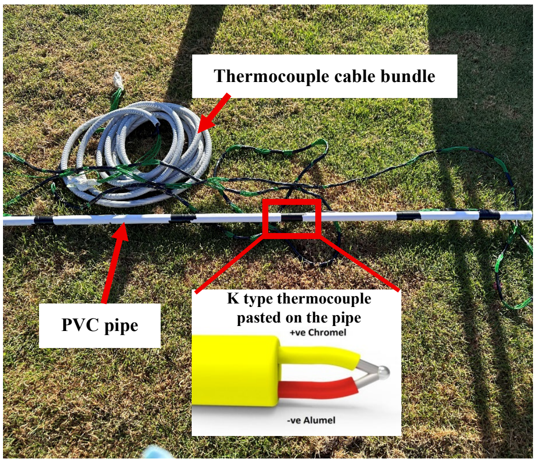
2.3 Borehole ground temperature measurement

Shallow ground temperature is a critical parameter in determining the availability of shallow geothermal energy. Three principal driving mechanisms govern ground temperature: (1) Surface heat flux is the most influential factor on shallow soil temperature, with most of the heat originating from solar radiation. Upon reaching the Earth's surface, the ground absorbs part of the radiation, while another portion is reflected or scattered by clouds back into the atmosphere. The surface then exchanges heat with the environment through air convection and surface moisture evaporation, with heat further transmitted into deeper strata through thermal conduction. Consequently, this mechanism exhibits pronounced daily and seasonal variation. (2) Convective heat transfer induced by groundwater, which depends on factors such as local groundwater level and flow rate. (3) Influence from deeper geothermal conditions, which is typically minor, though it can elevate subsurface temperatures in volcanically active regions (Alqahtani et al., 2023).

In this study, a 20-meter-deep borehole with a diameter of 0.15 meters was drilled at the Drill Force yard in Takanini, Auckland, to investigate the typical depth range of shallow geothermal energy potentially applicable in New Zealand. The well site was chosen because it is in a representative flat area in Auckland for land access and is close to drilling equipment. There is also a >300 m deep groundwater well nearby.

Ground temperatures from the surface to 20 m depth were continuously monitored using 15 thermocouples. As illustrated in Figure 2a, the thermocouples were affixed at fixed intervals along the outer surface of a 20-meter PVC pipe, which has a diameter of 4 cm. The entire pipe assembly was inserted into the borehole, after which cement was pumped through the pipe to complete the backfilling. The backfilling continued until all sensors were fully encased. The ground surface thermocouple was also buried beneath approximately 5–10 cm of backfill material to ensure sensor durability. Figure 2b illustrates the sensor installation and backfilling procedures. Moreover, an additional thermocouple was attached to a household inlet water pipe 2 meters from the borehole to monitor variations in domestic water temperature. All sensors were connected to the data logger, with the data acquisition system housed in an on-site waterproof enclosure. This enclosure was further installed inside a temporary cabinet to mitigate the effects of ambient temperature fluctuations and environmental disturbances.

a.



b.

Figure 2: (a) Ground temperature thermocouple attached to PC grouting pipe; (b) The sensor and the grouting pipe being installed into the borehole.

Figure 3 illustrates a schematic diagram of the borehole and temperature measurement system used in this study. Cement grouting was employed to enhance borehole integrity and minimise thermal contact resistance, thereby improving thermal response characteristics throughout the profile and enhancing measurement accuracy. Multiple studies have shown that soil temperatures below 8m depth remain relatively stable throughout the year (Bady et al., 2021, Faizal et al., 2016, Singh and Sharma, 2017). Therefore, sensors were deployed at 2m intervals between 8-20m depth, while denser 1m spacing measurements were taken above 8m depth to obtain more detailed formation temperature variation data.

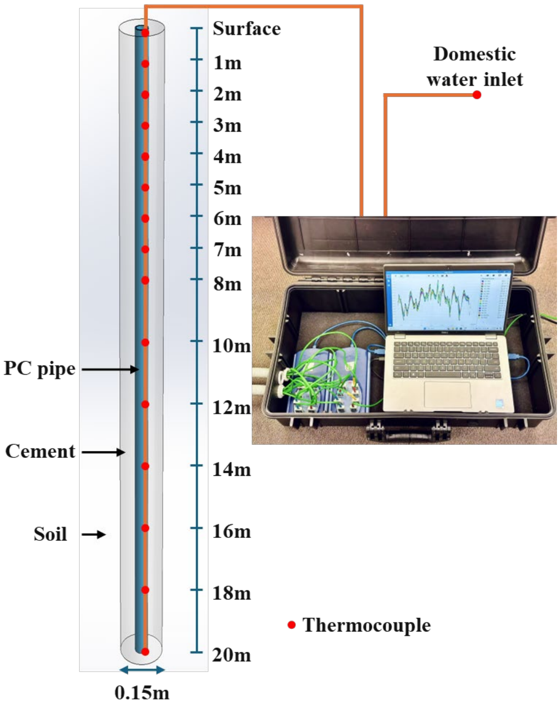


Figure 3: Schematic diagram of the 20m drilling and temperature measurement system.

3. RESULTS AND DISCUSSION

3.1 Domestic water usage

Domestic hot water demand constitutes a major component of building energy consumption (Cui et al., 2024). In GSHP applications, long-term continuous operation leads to a decrease in overall heat exchange efficiency, with higher heat transfer efficiency typically maintained only during the initial phase of operation, and shallow geothermal resources necessitate thermal regeneration periods following continuous extraction (Cui et al., 2024). Therefore, a comprehensive analysis of operational intermittency and temperature requirements proves essential for accurate performance forecasting and assessment of GSHP systems.

According to a recent study by (Whittaker et al., 2022) on domestic water usage patterns, typical weekday water usage durations in households are relatively short (not lasting longer than 4 hours) and exhibit clearly defined peak periods. As shown in Figure 4, the first peak occurs between approximately 6:00 am and 9:00 am, and the second peak appears between 4:00 pm and 7:00 pm. This corresponds to short intermittent operation conditions in shallow geothermal applications. Weekend water usage patterns feature later commencement times, allowing extended nocturnal ground temperature recovery. However, prolonged daytime usage indicates extended continuous operation of the GSHP systems.

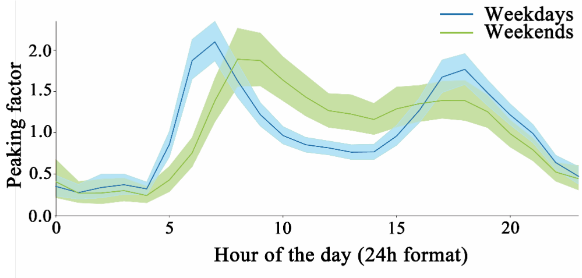


Figure 4: The peaking of water usage on weekdays and weekends (Whittaker et al., 2022).

Measurements in this study led to similar conclusions. Figure 5a and Figure 5b present temperature profiles recorded at Sadiq's house on a weekday and a weekend day, respectively. Monitoring reveals pronounced fluctuations in the hot water pipe temperature during hot water usage, accompanied by slight temperature variations in the cold water pipe. These thermal signatures provide diagnostic markers for potable water consumption profiles. However, it may seem counterintuitive, given that the hot water pipe is already equipped with thermal insulation, but stagnant water still cools to ambient temperature within one hour. The increase in inlet cold water temperature can be attributed to the parallel and closely spaced arrangement of the hot and cold water pipes, where heat is transferred from the hot water through the pipe wall and insulation layer to the external surface of the cold water pipe. Such residual heat transfer through the insulation doesn't necessarily indicate insufficient insulation thickness. Radial heat transfer in pipe insulation consists of two main components: (1) thermal conduction through the insulation, and (2) convective heat transfer on the outer surface of the insulation. The composite thermal resistance integrates both mechanisms, governing radial heat flux as follows (Çengel et al., 2008):

$$Q = \frac{\Delta T}{R_{ins} + R_{conv}} \tag{1}$$

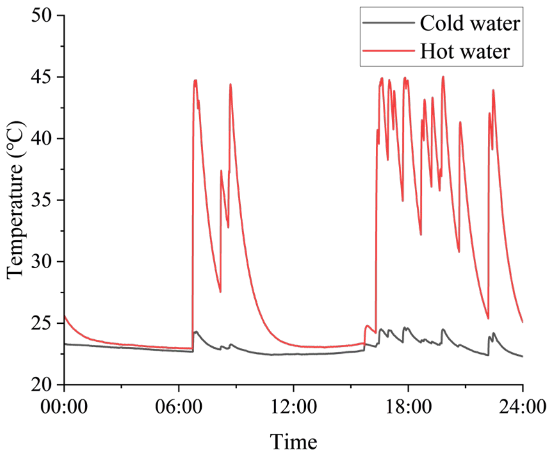
where Q is the heat flux through the pipe insulation, ΔT is the temperature difference between pipe surface and surrounding medium, R_{ins} and R_{conv} indicate the thermal conduction resistance of the insulation material and the thermal convection resistance from the outside, respectively. Enhanced insulation layer thickness diminishes conductive resistance components. Yet concomitant increases in external diameter lead to an increased convective heat transfer area on the outer surface. Consequently reducing the convective thermal resistance at external boundaries. As a result, there exists a critical radius of insulation for a cylindrical body (Çengel et al., 2008):

$$r_{cr} = \frac{k}{h} \tag{2}$$

where r_{cr} is the critical radius of insulation, k is the thermal conductivity of insulation material, and h is the convection heat transfer coefficient. The insulation performance reaches its optimum only when the insulation thickness equals the critical radius r_{cr}. In practical household cylinder systems, precisely adhering to this design criterion is often challenging. This helps explain the rapid temperature drop observed in hot water pipes and the unintended thermal influence on adjacent cold water pipes.

Analysis of household hot water usage data reveals that on weekdays, hot water usage commences around 7 am with multiple draw-offs over 2 hours, then pauses until approximately 4 pm, continuing intermittently until 11 pm. Aggregate weekly analysis indicates 2-hour morning utilisation windows and 6-hour evening demand periods, separated by 8-hour thermal recovery intervals. Weekend usage is more frequent and randomly distributed from 7 am to midnight, showing less regularity, with about 7 hours daily recovery time.

These findings necessitate future ground heat exchange investigations encompassing both brief and extended intermittent operational regimes. Existing research demonstrates that intermittent duration critically influences the composite thermal exchange efficiency of BHE. Prolonged continuous operation reduces efficiency and requires extended ground thermal recovery periods (Bao et al., 2022, Choi et al., 2011).



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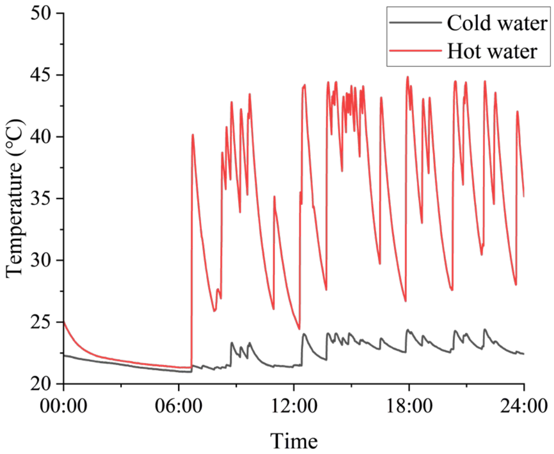


b.

Figure 5: Examples of the temperature and operating time of domestic hot water, (a) weekdays, (b) weekends.

3.2 Ground and domestic water temperature

Affected by solar radiation and surface air temperature, ground temperature generally shows periodic variations with seasonal changes. Therefore, ground temperature monitoring should last at least one year to obtain complete shallow geothermal resources for engineering applications. As of publication, the research has accumulated 3 months of continuous monitoring data, with ongoing measurements planned throughout a full annual cycle; complete findings will be reported in subsequent publications.

Despite comprehensive laboratory calibration incorporating terminal compensation for each thermocouple assembly (Figure 6) to ensure measurement consistency, measurement deviations may still arise during outdoor deployment due to the limited precision and time lag of cold junction compensation, leading to partial sensitivity to ambient temperature fluctuations. This effect is particularly noticeable under daytime solar exposure, rapidly increasing the internal cold junction temperature, leading to artificially high readings at the thermocouple outputs. A similar but opposite bias occurs during nighttime cooling. The reason lies in the thermocouple measurement principle, where the output voltage represents the temperature difference between the measurement and reference cold junctions, with the absolute temperature calculated as:

$$T_p = T_{cold} + T_{dif} \tag{3}$$

where, T_p is the final output temperature at the measurement point, T_{cold} is the absolute temperature measured at the cold junction (data logger), and T_{dif} is the temperature difference measured by the thermocouple. If T_{cold} is inaccurately recorded, it will result in a corresponding error in the computed probe temperature. This study employed a Kalman filter to correct measurements from buried thermocouples, as shown in the following equations (Kordic, 2010):

$$T'_k = T'_{k-1} + K_{k-1} \cdot (T_k - T'_{k-1}) \tag{4}$$

$$K_k = \frac{P_{k-1} + Q}{P_{k-1} + Q + R} \tag{5}$$

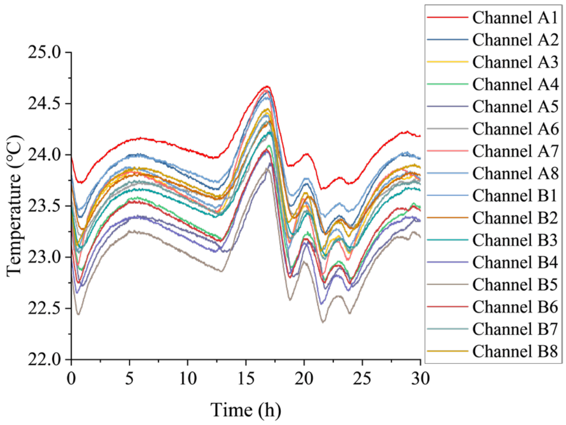
$$P_k = (1 - K_k) \cdot (P_{k-1} + Q) \tag{6}$$

where, T'_k is the current corrected temperature, T_k is the raw measured temperature, and T'_{k-1} is the corrected value from the previous time step. K_k and K_{k-1} are the current and previous Kalman gains. P_k and P_{k-1} are the error covariance estimates at the current and previous steps. Q, the process noise covariance (system prediction uncertainty), is set to 0.01. R, the measurement noise covariance (sensor uncertainty), is set to 2 (Kim, 2023). Figure 7 illustrates the comparative results between the raw data and Kalman-filtered data. This methodology successfully removes spurious subsurface temperature artefacts whilst maintaining authentic long-term thermal evolution patterns.

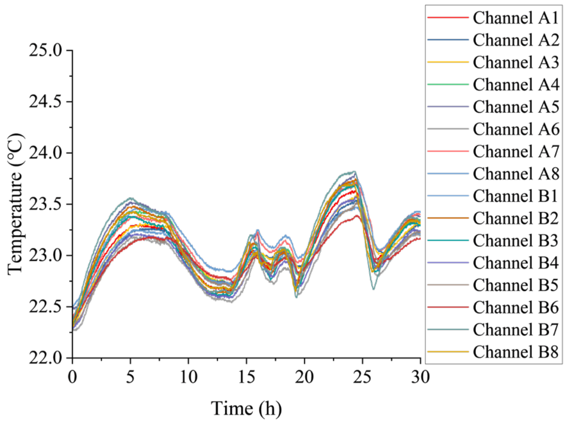
All thermocouples connected to the same data logger share a common cold junction compensation, theoretically resulting in identical errors across all thermocouples on the same unit. Therefore, the following equation is used to eliminate measurement error in the domestic water data:

$$T'_{water} = T_{water} - (T_{6m} - T'_{6m}) \tag{7}$$

where, T'_{water} and T_{water} represent the corrected and measured values of domestic water respectively, T'_{6m} and T_{6m} are the Kalman filter corrected and measured values at 6m depth (thermocouples at 6m and above, along with domestic water thermocouples, are connected to the same data logger).



a.



b.

Figure 6: Laboratory calibration with terminal compensation, (a) before calibration; (b) after calibration

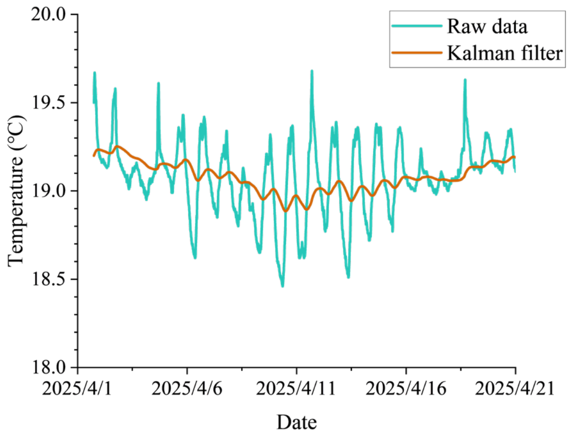


Figure 7: Comparison of raw data and Kalman filtered data

Figure 8 shows the variation in ground temperatures (ground surface to 2 m depth) and domestic water temperature from April to June. It is evident that ground surface temperatures fluctuate significantly due to solar radiation and diurnal temperature differences. The daily temperature variation can be as high as 10 °C. Despite fluctuations between April and June, the overall trend is downward. The average daily temperature decreased from 19 °C in early April to 13 °C by the end of June. These measurements accurately characterise Auckland's thermal climate, establishing critical design parameters for GSHP operational strategies. Domestic water temperatures exhibit comparable thermal behaviour to 1m stratum temperatures, albeit with accelerated cooling kinetics. The thermal profile shows progressive cooling from 22°C to nearly 15°C, maintaining a negative temperature gradient. Beginning in early June, when the water temperature was approximately 17 °C, it has consistently remained below the ground temperature at all depths (Figure 11), except for the 1m depth. This phenomenon arises from water distribution infrastructure being buried at 0.5m depth, where thermal coupling with surface conditions is more pronounced. It is expected that within the next 1 to 2 months, the water temperature may drop below the soil temperatures at all observed depths, potentially falling below 14 °C. Additionally, domestic water temperature is more unstable compared to soil temperature. It contains noticeable thermal spikes caused by convective heat transfer during intermittent water flow.

Ground temperature variation is primarily driven by surface heat exchange. As a result, in winter, the temperature in shallower soil layers drops more rapidly. In contrast, deeper layers exhibit a pronounced lag in temperature change. As shown in Figure 8, the temperature decline at 2 m depth is noticeably smaller than at 1 m. The temperature difference was merely 0.3°C in early April but reached approximately 3°C by late June. This thermal lag becomes more pronounced at 3-5m depths, as shown in Figure 9. In early April, the 3m depth exhibited the maximum stratum temperature (20.6°C). As ground heat dissipated through the surface, temperatures rapidly decreased to approximately 18.7°C. Temperature variations diminished progressively at 4m and 5m depths. By the third week of May, the 3m depth registered lower temperatures than the 4m depth. Commencing June, the 5m depth became the new thermal apex, displacing the 4m. Meanwhile, the temperature of 3m depth started to drop below 6m. Figure 10 provides enhanced visualisation of the downward propagation of the thermal maximum through subsurface strata during winter.

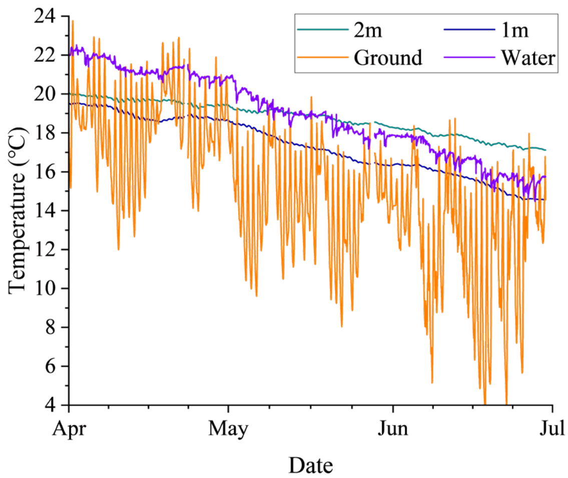


Figure 8: Temperature variations from the ground surface to 2 m depth and in domestic water supply

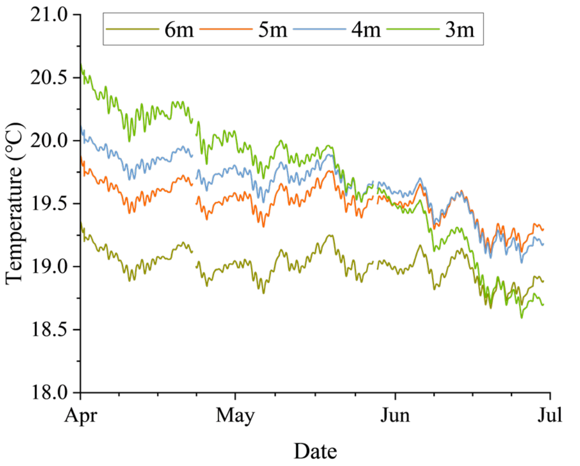


Figure 9: Temperature variation between 3 m and 6 m depth

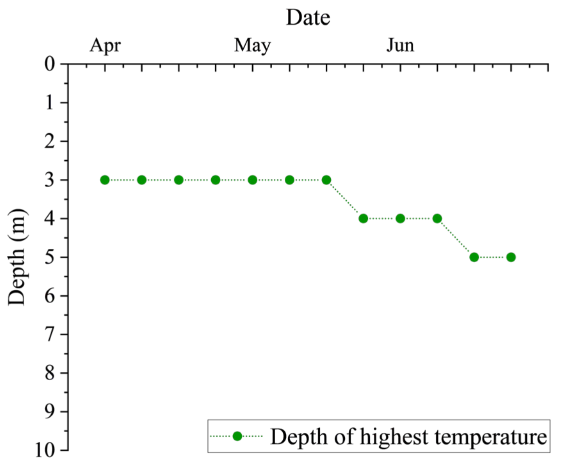


Figure 10: Change in the location of peak ground temperature over time

Deeper temperature data reveals substantial thermal stability below 6m depth, with temperature variation at 6m being less than 0.3°C over 3 months. All eight thermocouples installed from 7 m to 20 m depths share the same data logger, and their temperature fluctuations also show high consistency. Surface thermal exchange has negligible influence at such depths. Thus, these variations are likely due to limitations or noise from the sensors or the data acquisition system.

The distribution of ground temperature is crucial for designing BHE dimensions. Figure 11 presents depth-dependent temperature profiles, with each curve representing the average temperature over its corresponding period. While overall temperatures decrease temporally, curve spacing reflects the temperature variation rate at each depth. Above 7m depth, temperature variation accelerates towards the surface, demonstrating heat transfer from shallow to deep strata. This thermal response behaviour provides mechanistic insight into the observed thermal lag phenomenon. Below 8m depth, uniform curve spacing indicates stable thermal conditions, and minor fluctuations are mainly attributed to measurement error. Furthermore, it can be observed that during winter in Auckland, while temperatures at 6 m show minimal variation, there remains a measurable temperature difference between 6–7 m and deeper layers, which suggests that thermal exchange between 6 m and deeper ground is still ongoing. The thermal equilibrium zone appears to start from approximately 7 m depth. Temperatures in this deeper region remain stable at approximately 17.8 °C. This value is slightly above the average in Melbourne (Faizal et al., 2016, Shah et al., 2019) and significantly higher than in London(Sani et al., 2019).

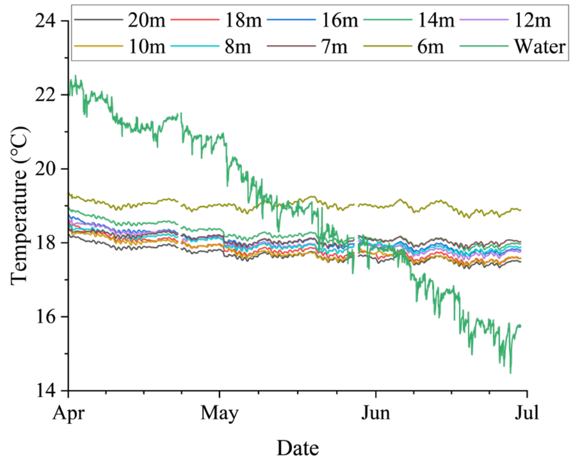


Figure 11: Temperature variation of water and ground between 6 m and 20 m depth

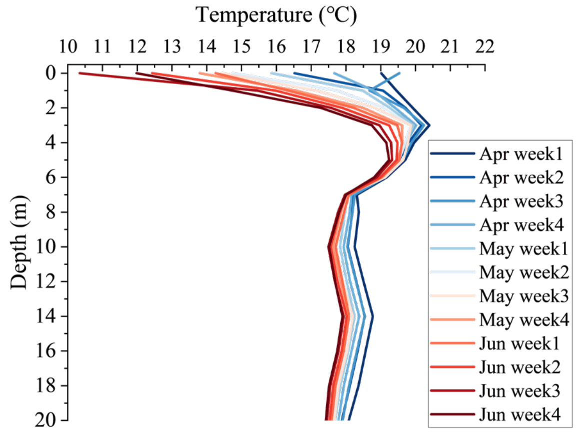


Figure 12: Vertical distribution of ground temperature with depth.

4. CONCLUSION

In this study, long-term ground and domestic water temperature monitoring was carried out in Auckland, New Zealand. A preliminary understanding of the shallow geothermal energy potential in the region was obtained. These results offer a theoretical and empirical basis for future research and applications involving BHE in this region. The main conclusions of this research are summarised below:

- Domestic hot water consumption follows distinct and consistent daily patterns, with peak periods occurring on weekdays in the morning and evening. On weekends, hot water usage increases throughout the day. Weekday conditions may be modelled for future heat exchanger testing using short-term intermittent operation (4–6 h). Extended intermittent cycles (e.g., 12 h) are suitable for representing weekend water use.

- Surface temperatures exhibit high variability, primarily influenced by solar radiation and diurnal cycles. Consequently, borehole heat exchange systems present theoretically viable solutions for residential thermal regulation.

- Ground temperatures continuously declined from April to June, with cooling rates increasing towards the ground surface. The location of the thermal peak gradually migrated from shallow to deeper ground layers during this period. At depths greater than 6 m, temperatures consistently stayed near 17.8 °C, suggesting optimal winter operation employs heat exchange at or below the 6m depth.

- By June, the town's water supply temperature had decreased to 16 °C and continued to decline in winter, while ground temperature stays more stable at around 18 to 19°C, supporting the feasibility of applying shallow geothermal energy for domestic water heating during the winter season. As additional data are collected, a more comprehensive understanding of the shallow subsurface temperature distribution in Auckland will emerge, thereby enabling a more robust assessment of the technological potential of shallow geothermal energy. The optimal performance is expected between late winter and early summer. Furthermore, shallow geothermal energy is plentiful in the Auckland region, which, if efficiently extracted and utilised, can effectively reduce energy demand and operational expenses.

- A limitation of this research is associated with the inherent characteristics of thermocouples, which may introduce noticeable inaccuracies during in-situ measurements. Future work should improve sensors and data loggers by enhancing logger performance and cold junction compensation. Alternatively, replacing thermocouples with thermistors or fibre optics, which are more accurate but more expensive, could yield more accurate absolute temperature readings.

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