UNIVERSIDAD REGIONAL AMAZÓNICA IKIAM

FACULTAD DE CIENCIAS DE LA TIERRA Y AGUA

CARRERA DE GEOCIENCIAS

DETERMINATION OF THE SOIL TEMPERATURE FOR THE POTENTIAL USE OF LOW ENTHALPY GEOTHERMAL ENERGY IN THE TENA CANTON, ECUADOR

Proyecto de investigación previo a la obtención del Título de:

INGENIERO EN GEOCIENCIAS

AUTOR

JUAN JAVIER CELI SALDAÑA

Napo - Ecuador

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Napo - Ecuador

2023

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Certificamos que el trabajo de integración curricular titulado: “Determinación de la temperatura del subsuelo para el potencial aprovechamiento de la energía geotérmica de baja entalpía en el cantón Tena, Ecuador”, en la modalidad de: proyecto de investigación en formato artículo original, fue realizado por: Juan Javier Celi Saldaña, bajo nuestra dirección.

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AGRADECIMIENTOS

Agradezco a Dios por las bendiciones derramadas sobre mi vida y familia que me han ayudado muy fuertemente en este proceso de estudio.

A mi familia que, sin la ayuda de ustedes, definitivamente no hubiera logrado alcanzar este sueño común que nos une inmensamente.

También agradezco a mi tutor, Oswaldo Guzmán y cotutor Bryan Valencia quienes supieron depositar la confianza en mí, guiándome sabiamente para que se materialice este proyecto de investigación. Les agradezco inmensamente.

De la misma manera, a los docentes que a lo largo de este camino supieron tenderme la mano cuando parecía que todo se echaba a perder, muchas gracias.

Igualmente, a todos mis compañeros que luego de extensas pero enriquecedoras jornadas académicas fueron parte de mi vida estudiantil. Gracias por ser buenos colaboradores.

A todas las personas que durante este proceso han sido parte de mi formación académica, les agradezco inmensamente.

Y como no podía ser de otra manera; Agradezco profundamente a esta maravillosa Universidad y a todo su personal docente- administrativo que me abrieron las puertas para formar parte de este selecto grupo de profesionales formados bajo el emblema de Ikiam.

¡Infinitas gracias!

DEDICATORIA

El presente trabajo investigativo lo dedico principalmente a Dios, por ser mi inspiración y mi fortaleza en este arduo pero gratificante proceso hacia mis anhelos añorados.

A mi familia que, gracias al esfuerzo y sacrificio de todos ustedes durante todo este tiempo, se ha logrado un objetivo en común. Su apoyo ha sido la columna vertebral para cumplir esta meta.

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RESUMEN

La geotermia de baja entalpía es un tipo de energía que se obtiene del calor natural almacenado en la parte superficial del subsuelo, el cual aprovecha el diferencial de temperatura entre el subsuelo y la superficie. Se realizó un estudio para determinar la distribución vertical de la temperatura del subsuelo durante un periodo de 150 días en tres lugares del cantón Tena. Se usó datos experimentales para validar un modelo de perfiles de temperatura, a partir de ese modelo se ha estimado perfiles de temperatura en tres puntos previamente seleccionados, que poseen diferentes materiales geológicos dentro del cantón Tena. Los resultados obtenidos se determinaron que las fluctuaciones de temperatura disminuyen a medida que se profundiza desde superficie. En MB, se identificó que a partir de los 5m de profundidad las temperaturas tienden a ser constantes a la media anual del sitio, que es de aproximadamente 25°C. Mientras que en LP y PN, estas se estabilizaron a los 6 y 8m de profundidad, respectivamente. El método indirecto es menos preciso en la zona superficial respecto al experimental. Se identifica la zona superficial a 1m de profundidad, zona poco profunda a 5m y se cree que a partir de los 5m en adelante estaría la zona profunda donde la temperatura permanece constante durante un ciclo anual. La validación de resultados teóricos respecto al experimental mediante la correlación de Pearson muestra una buena correlación. La prueba estadística T entre los dos métodos utilizados, identifica que no existen diferencias significativas con respecto al método directo.

Palabras clave: superficie, zona poco profunda, temperatura del suelo, difusividad térmica del suelo, medición

ABSTRACT

Low enthalpy geothermal energy is a type of energy obtained from the natural heat stored in the superficial part of the subsoil, which takes advantage of the temperature differential between the subsoil and the surface. A study was carried out to determine the subsurface temperature distribution over a period of 150 days at three specific locations in the canton of Tena. Experimental data have been used to validate a temperature profile model and from that model, temperature profiles have been estimated at three previously selected points, which have different geological materials within the canton of Tena. The results obtained determined that the temperature fluctuations decrease as one goes deeper from the surface. In the MB, it was identified that from a depth of 5m the temperatures tend to be constant at the average annual temperature of the site, which is approximately 25°C. While in LP and PN, they stabilized at 6 and 8m depth, respectively. The indirect method is less precise in the superficial area compared to the experimental one. The superficial zone is identified at a depth of 1m, a shallow zone at 5m and it is believed that from 5m onwards there would be the deep zone where the temperature will remain constant during an annual cycle. The validation of theoretical results with respect to the experimental results by means of Pearson's correlation shows a good correlation. The statistical T-test between the two methods used shows that there are no significant differences with respect to the direct method.

Keywords: surface, shallow zone, soil temperature, ground thermal diffusivity, measurement

INTRODUCTION

Low enthalpy geothermal energy or also known as shallow energy is a type of energy that is obtained from the natural heat stored in the superficial part of the subsoil, which it takes advantage of the temperature differential between the subsoil and the surface [1,2]. To this type of renewable energy, the Cartographic and Geological Institute of Catalonia ICGC classifies it between 5 °C < T < 30 °C. Previous studies have shown that, as deeper become from surface, temperatures trend to be constant [3]. Florides and Kalogirou [4] show in a study that temperatures below 5m remain almost constant during a yearly period. In this sense, several authors (e.g.[3,5]) divide the soil into three zones: the superficial zone, which it is sensitive to daily temperature cycles, the shallow zone, which is sensitive to seasonal variations, and finally the deep zone where temperatures remain almost constant.

Very low enthalpy energy can be used through heat exchangers that are generally coupled to geothermal heat pumps for efficient use [6], these interchange heat from the subsoil to the surface or in reverse with the purpose of heating or conditioning an outbuilding in cold or hot seasons, respectively. Nowadays, the use of this geothermal resource has been extended to agro-industrial processes (pasteurization processes, milk fermentation, honey, etc.), agricultural (agricultural nurseries, cocoa drying) among others [7–9].

The report of the 2010 World Geothermal Congress indicates that the use of geothermal energy not only benefits the environment by diversifying access to energy, but also improves the quality of life directly for the population, specifically local communities [10]. To harness this geothermal resource, is necessary to knowledge of temperature of the soil and subsoil and know how those factors control soil temperatures, as well as understanding how these temperatures change a long time and depth from the surface [2,5,11,12].

There are several methods that allow the determination of subsoil temperature profiles, among the most common are calculation methods (indirect methods) using one-dimensional, two-dimensional or three-dimensional equations, which numerous authors (e.g.[5,13–15]) have used to determine temperatures or to contrast said values with other methods. Other method (direct) is the installation of temperature sensors directly in a well previously drilled for this purpose [3,5,6,16].

The values of the thermal diffusivity of the soil is a basic parameter to develop low enthalpy geothermal resources. Generally thermal diffusivity can be obtained by laboratory, analytically or by other methods such as thermal response test (TRT) [5,17,18]. Due to the difficulty of obtaining an undisturbed sample, many authors usually estimate thermal diffusivity by applying the one-dimensional heat conduction equation [16].

At the regional level, there are studies [19–21] by Bottom Hole Temperature (BHT) technique that determine a geothermal gradient for the Marañon-Oriente-Putumayo Basin (one of the oil-rich provinces of South America with abundant hydrocarbon resources of commercial interest) that vary from one another. For example, Hamza et al. [21] calculate a geothermal gradient of 21.4°C/km, while Barba et al. [20] redefine the geothermal gradient as 22.9°C/km, all of them at hundreds of meters depth from the surface. The BHT excludes data for shallow wells due to the variability of climatological processes occurring near the surface. These deep studies help to understand the thermal dynamics of this basin, with a focus on understanding the thermal history of the area for hydrocarbons exploitation purposes.

The use of very low enthalpy geothermal energy in Ecuador is limited, and the few applications that it is given are focused on the use of this energy for heating spas and thermal pools [22]. In the Ecuadorian amazon, no simplified models of temperature distribution in the shallow ground for the Tena canton particularly have been in the literature. The objective of this study is to determine the vertical distribution of soil temperature, from the surface to a depth of 5m, at three different locations in the Tena canton, where the soil and subsoil is composed of different geological materials. In addition, it is pursued to validate the indirect method regarding the results of direct measurements. The results of the research can help to provide reference data for carry out of geothermal heat pump systems for an efficient use of the applications that can be given in this canton (air-conditioning homes, drying of local agricultural products). These would also allow the local municipality to plan the burial of water pipes, human burial sites (cemeteries), among others.

Tena Canton: Territorial description of the study area

The Tena canton is located in the north-central region of the Ecuadorian Amazon, in the Napo province, it has an approximate area of 3904.3 km^2, according to the 2010 INEC population and housing census, Tena has a population of 60,880 inhabitants [23]. It has a range of heights above sea level from 300m to 4200m, which implies that it has a varied tropical weather with an average yearly temperature about 26°C, an average annual rainfall of 3832 mm [24–26].

The geology of the Tena canton is consisting of different lithological units such as metamorphic rocks of the Cordillera Real of Paleozoic age that constitute the general basement [27], intrusive rocks of Jurassic age (Abitagua Granite), sedimentary rocks of Cretaceous age (Hollin, Napo and Tena), Mesozoic metamorphic rocks (Jurassic - Cretaceous), sedimentary rocks of Cenozoic age (Tiyuyacu, Chalcana, Arajuno). Likewise, recent volcanic rocks, Quaternary surface deposits of alluvial origin, also [27,28].

The study area is located in three specific places in the canton of Tena. The selection of the three study sites is because the distribution of the population of the Tena canton is mainly settled on three types of soils composed of different geological materials (carbonate rocks, siliciclastic rocks, and sediments). The first one, called Muyuna borehole (MB), is situated in San Juan de Muyuna Parish belonging to the Tena canton, with geographic coordinates of latitude 0°58'48.43"S and longitude 77°51'1.60"W. This is located on Superficial Deposits (Quaternary), composed mainly of sand, silt, clay, gravel, rounded clasts of different sizes [28,29]. The second one, called Point 2 is located in Puerto Napo (PN) Parish belonging to the Tena canton. It is located at the geographic coordinates latitude 1°2'44.62"S and longitude 77°47'47.68"W. It is within the Napo Formation (Cretaceous: Lower Albian to Senonian), which is considered one of the most important sequences in eastern Ecuador, consisting of a succession of black shales, gray to black limestone, and sandstone calcareous [28–30]. Last one, Point 3 is located in the Los Pinos (LP) sector, which is an urban area of Tena city, it is situated at the geographic coordinates of latitude 0°58'16.65"S and longitude 77°48'51.47"W. It is within the Tena Formation (Maastrichtiens -Paleocene). Baldock [29] describes that this Formation mainly made up shale with sandstone intercalations with very few conglomerates. In the outcrops, one can appreciate the brownish red to reddish brick color, in large part because the lithology is weathered [29,30].

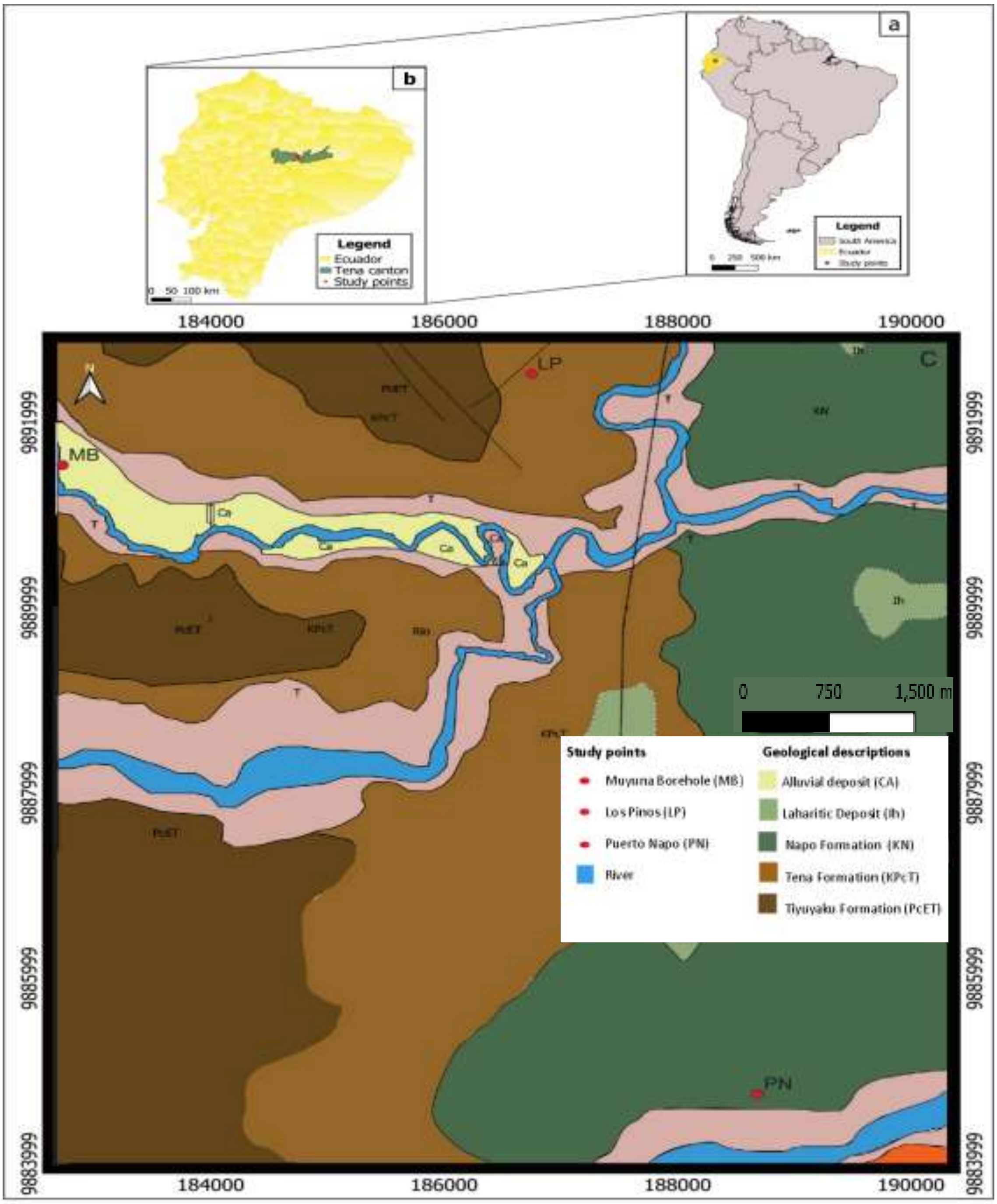

Figure 1. a Location Ecuador in South America. **b** Location of study points in Tena canton. **c** Geological map of the canton of Tena with the study sites

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METHODS

The measurements were made by two methods: Direct and Indirect method [2,12,15,31]. For the study of the distribution of subsoil temperature, was carried out in three places selected in the Tena canton, which are made up of different geological materials. In the point MB, the direct method was used. For it, a 5 m deep borehole with a diameter of 0.10 m was drilled in bare ground for the purpose of very low enthalpy geothermal research, in which high-density polyethylene pipes have been installed, and four temperature sensors were placed inside it, as indicated in Table 1.

A 40-day period was left to recover from the effects of well drilling and temperature stabilization according to Bullard and Luheshi [32,33]. All sensors installed in the well were from the HOBO® MX2202 series, these are factory calibrated, resistant to abrasion and moisture, ideal for systems sensitive to induced voltages and electrical noise, as indicated by the manufacturers [34]. These sensors have a range of -20° to 70°C and an accuracy of ±0.5°C from -20° to 70°C. The record of the temperature data was obtained in an interval of 10 minutes during 150 days (August 2022-January 2023) and for the analysis; the maximum and minimum values of this interval were averaged. The well was filled with bentonite clay for a better precision of the ground temperature values [6]. In addition, a stratigraphic column was made in MB (Figure 2). According to the published literature, a complete annual period of temperature records is normally analyzed. Because these works are carried out in different geographic locations, this implies that these areas have different climatic seasons. However, in the Ecuadorian Amazon there are rainy and dry seasons in short periods. In this sense, during the study period presented here, temperature data have been recorded in both seasons, which would support the temporal amplitude of the records used.

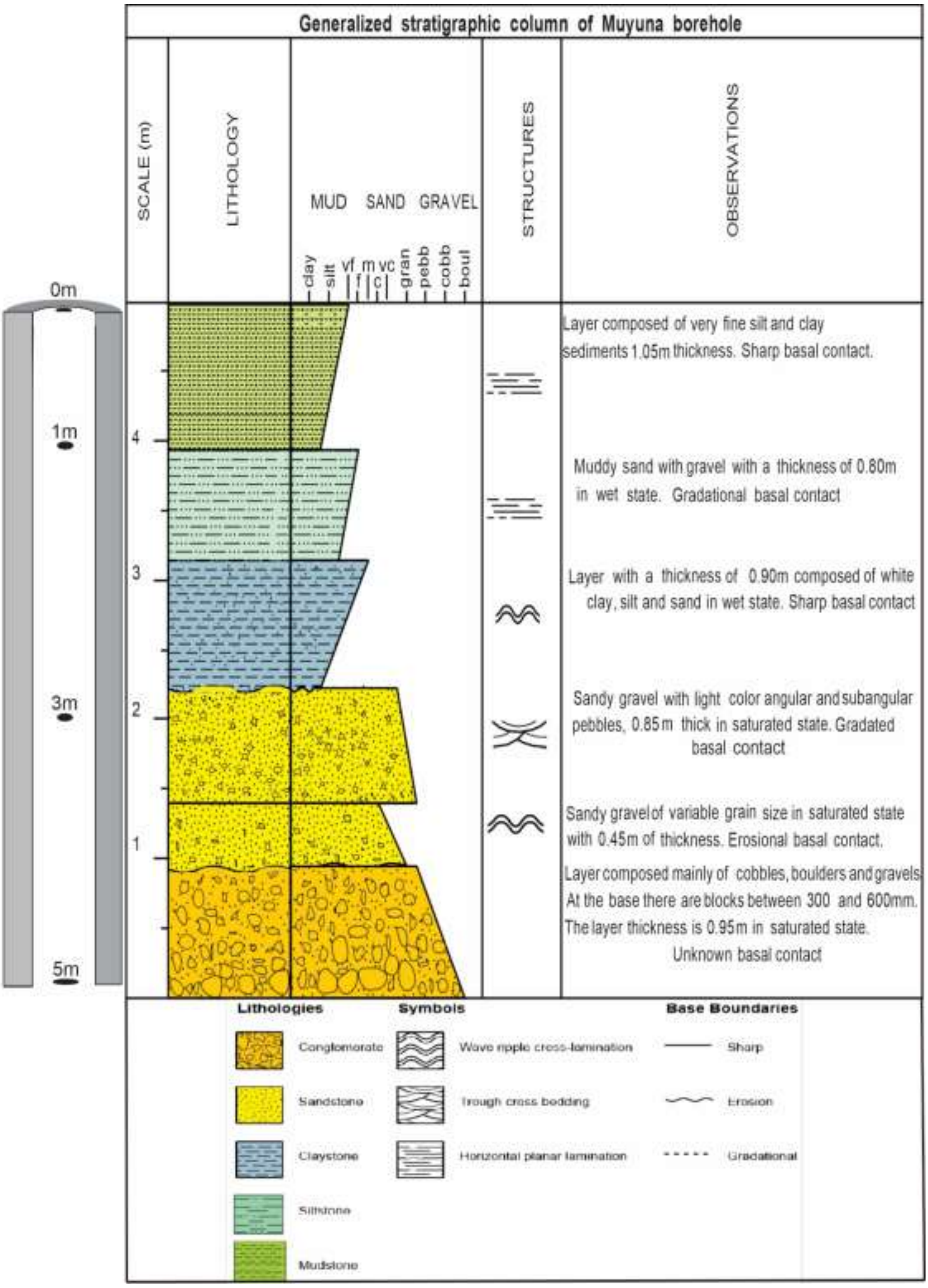

Figure 2. Stratigraphic column of the Muyuna borehole and diagram of the experimental set stand for measuring the temperature distribution in the subsoil

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While for points 2 (PN) and 3 (LP), an estimate of the temperature profiles was obtained of the subsoil by a mathematical correlation established by Kasuda and Achenbach [15] and other authors have implemented it in various works [2,4,14,16,35], stablishing other way for the estimation of subsoil temperature profiles at different depths, using equation (1). These study points were analysed by observing exposed rocks at the surface and cross-checking with information from geological maps of the Tena canton [28,36,37].

$$T_{soil\,(D,\,tyear)} = T_{mean} - T_{amp} * \exp\left(-D\sqrt{\frac{\pi}{365*\alpha}}\right) * \cos\left(\frac{2\pi}{365}\left(t_{year} - t_{shift} - D\sqrt{\frac{\pi}{365*\alpha}}\right)\right) \quad (1)$$

Where:

- $T_{soil(D,year)}$= Soil temperature in °C at depth D and time of year.
- T_{mean} = Average surface temperature in °C (average air temperature).
- T_{amp}= Range of surface temperature [(maximum air temperature - minimum air temperature) /2].
- D= Depth below the surface (surface=0).
- α= Soil thermal diffusivity in m^2 /day.
- t_{year} = Current time (day).
- t_{shift} = Day of the year of minimum surface temperature.

For the application of equation (1), climatological station Ikiam University data were used. Meteorological dataset recorded about 7 years (2016-2022).

Table 1. Borehole and equipment installation details

Location	Deep/Diam (m)	Ground heat exchangers	Filling material	Thermometers position (m)	sampling locations (m)
Borehole Muyuna	5/ 0.1	PE100, PN16, 50 X 3mm 1 x 5 m	Bentonite clay	0 ; 1; 3; 5	1; 3; 5

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According to Marquez et al. [38], taking into account the thermal diffusivity by tables, it is possible to estimate the maximum and minimum temperature at vary depths by developing equation (1).

$$T_L = T_{mean} - T_{amp} * \exp\left(-D\sqrt{\frac{\pi}{365*\alpha}}\right) \quad (2)$$

$$T_H = T_{mean} + T_{amp} * \exp\left(-D\sqrt{\frac{\pi}{365*\alpha}}\right) \quad (3)$$

Where:

- T_L= minimum temperatures of the subsoil
- T_H= maximum temperatures of the subsoil

Equations (2 and 3) were applied to estimate the maximum and minimum temperature profiles at points 2 and 3. Thermal ground diffusivity values was calculated based by analytical solution of the one-dimensional Fourier heat conduction equation [39], which have been widely used for the estimation of the thermal diffusivity [40,41], considering the medium as a homogeneous soil

$$\frac{\partial T}{\partial t} = \alpha.\nabla^2 T = \alpha.\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \quad (4)$$

Where:

- α= Thermal diffusivity.
- $T = f(x,t)$ is the temperature at time t and a given position $P(x,y,z)$
  Because the heat is assumed to be unidimensional
- $\frac{\partial^2 T}{\partial y^2};\frac{\partial^2 T}{\partial z^2} = 0$, such that
- $\frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial x^2}$
  x is replaced by D = is the depth from the surface which is taken as positive down

Previous studies (e.g. [16,38]) determine the thermal diffusivity of the subsoil from equation (4), using meteorological data from climatological stations. This equation was applied to estimate the thermal diffusivity at 1, 3 and 5m depth respectively in MB.

$$\alpha = \frac{\omega\cdot(D)^2}{2[\left(ln\frac{T_{amp}}{T_H - Tm}\right)]^2} \quad (5)$$

ω (angular frequency; rad/s)= 2π/*P*, *P* is the period of the sinusoid, that to the annual temperature cycle is 365 days

The determination of the density of the heat flux in MB was carried out through flux heat equation [17,42].

$$q = -ʎ\frac{\partial T}{\partial D} \quad (6)$$

Where, q is heat flux per unit area, ʎ is the coefficient of thermal conductivity of the soil, T is the temperature of the soil, and D is the depth of the subsoil from the surface. The thermal conductivity value of 0.9 W/m.K for 1m and 1.8 W/m.K for 3m and 5m of depth in the soil type of MB is obtained from [43].

The entire set of data recorded from the subsurface temperature profiles obtained by the two methods used was analyzed using the Excel program. In addition, Levene's test [44] is used to determine if there is a significant difference in variances between 1, 3 and 5m depth in MB and the following hypotheses are put forward: Null hypothesis (Ho): There are no significant differences in temperatures between the three depths. Alternative hypothesis (H1): There are significant temperature differences between the three depths. Likewise, A T-test is used to compare the temperature values reported by the indirect method with those observed in the MB, and it is hypothesized that there would be no significant differences between the two methods used.

RESULTS

Air temperature and rainfall summary from data recorded at the Ikiam University climatological station is shown in Figure 3.

In this Figure, rainy and less intense seasons can be identified. During this period of measurements, the data show a maximum temperature of 40°C in September 2019 and a minimum of 14.98°C in October 2016. With respect to rainfalls, it is identified that most of the precipitation is concentrated in the months of April, May, June and July, which are the rainiest months. It is not possible to establish a precise dry season, however, according to the graph it can be seen that the month of August is the one with the least rainfall with an average of 214 mm, except in the year 2017, which had a record of 597.6 mm.

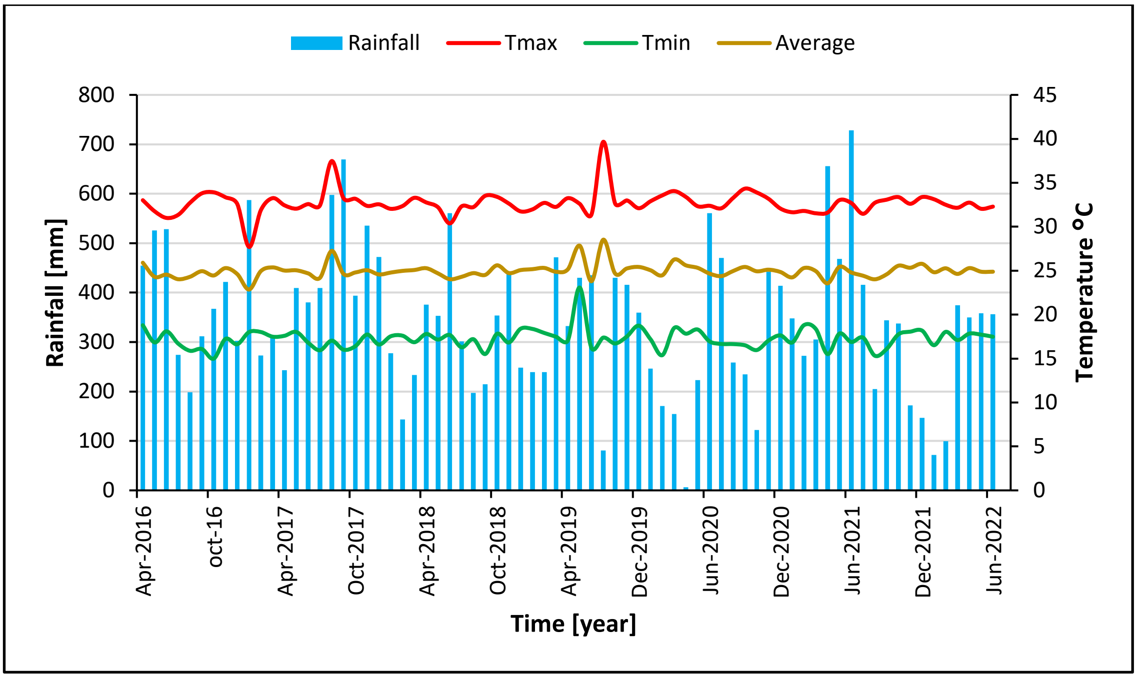

Figure 3. Air temperatures and rainfall yearly recorded at the weather station of the Ikiam Amazon Regional University for 7 years period

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The results of the temperature distribution during 150 days period (August 13, 2022 – January 13, 2023) from surface to 5m depth in MB are represented in Figure 4. During this period, it is observed that the temperatures at 5m depth it remains almost constant during this time, while at 3m it tends to vary slightly, but at a depth of 1m the temperature difference between 5m and 1m is almost 1°C in January. The temperatures at 0m (surface) vary significantly in relation to the previous ones, and it remains in phase with the ambient temperature. It is observed that the daily temperature cycles penetrate up to 1m deep. Amplitude wave decline as deeper from the surface. It can also be observed that maximum daily rainfall in this period occurred at the end of August and beginning of September.

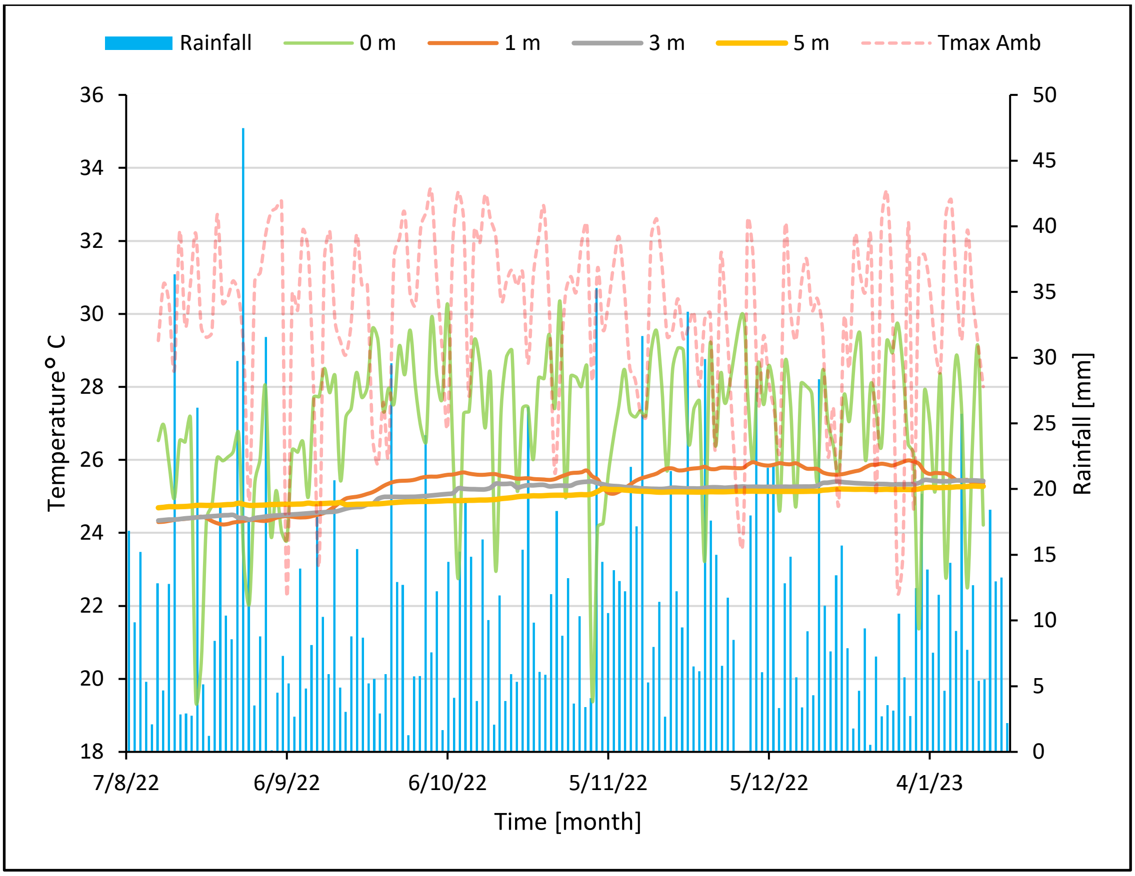

Figure 4. Subsoil temperature distribution in relation to time-depth in the Muyuna borehole from 13/08/22- 13/01/23 to 1, 3, 5m depth

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The behavior of average monthly temperature distribution of the ground in MB during 5 months is shown in Figure 5. The area close to the surface (between 0m - 1m depth) is observed to be in the temperature range between 24.5 and 27.5°C. As one goes deeper from the surface, it is observed that temperature tends to decrease reaching an almost constant temperature about 25°C at 5m depth.

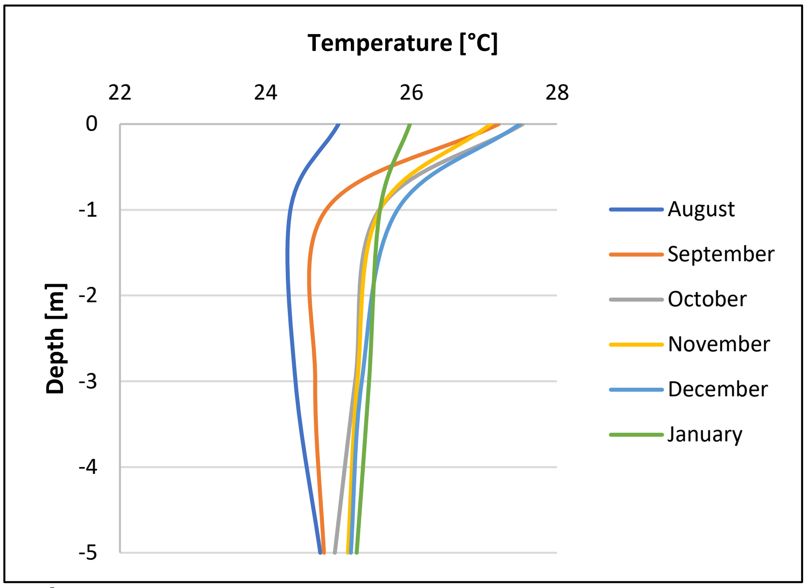

Figure 5. Average monthly temperatures as a function of depth during 150 days
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The temperature variation with respect to depth during 24 hours is plotted in Figure 6. It is noted that the daily temperature cycle reaches up to 1m depth in this type of soil. The surface temperature reaches its maximum value at 12pm and its minimum at 6am.

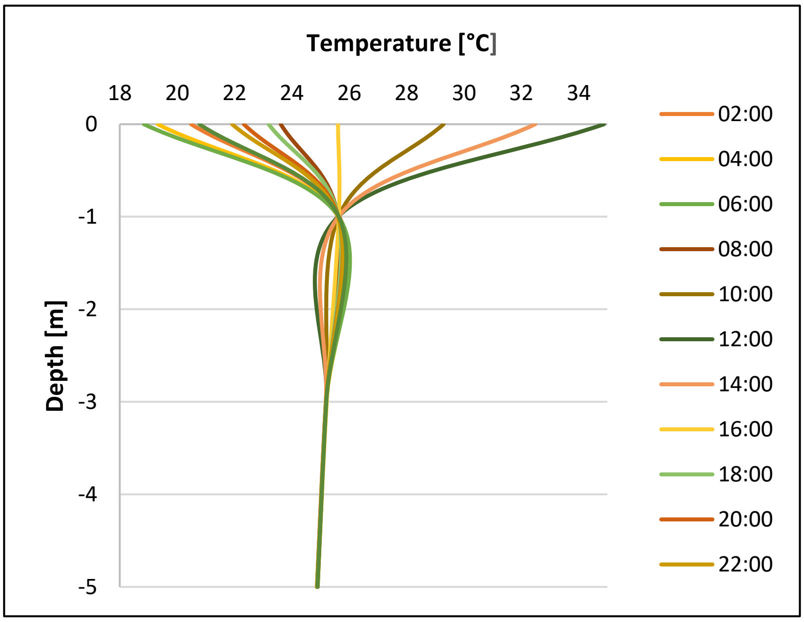

Figure 6. Temperature variation cycle with depth and time on 10 October 2022 during 24 hours in Muyuna Borehole
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Figure 7 shows the results of the heat flux density calculation for MB. The heat flux density is plotted at 1m, 3m and 5m depth over a period of 150 days. At 1 m depth, the rate of heat exchange from or to the surface is higher than at 3 m depth and higher than at 5 m depth. It is observed that at 5m, the oscillations of heat exchange are lower in relation to the previous ones, maintaining this range of oscillations throughout the study period without significant changes. The representation of negative heat flux density values indicates that heat is being transferred from the subsoil to the surface and positive heat flux density values indicate that heat is being transferred from the surface to the subsoil. The analysis is presented in the discussion section.

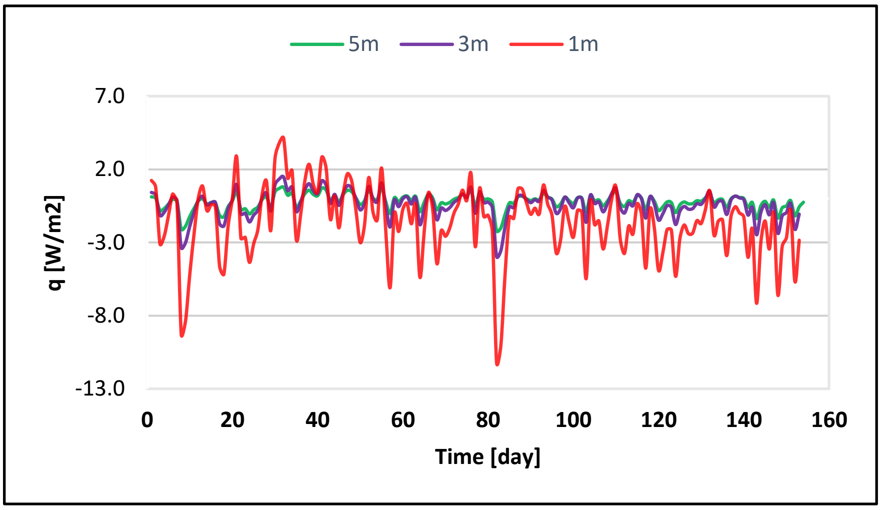

Figure 7. Heat flux density in the ground layer 0m (surface) – 5m as a function of the 150 days period
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Table 2. Thermal diffusivity values in Muyuna Borehole

Depth [m]	Temperature [°C]	Condition	Thermal Diffusivities [m²/s]	Thermal Diffusivities [m²/day]	Standard deviation [σ]
1	25.12	wet	2.13E-08	1.83999E-03	0.0003735
3	24.9	saturated	1.00E-07	0.00863164	0.00033255
5	24.99	saturated	1.98E-07	0.01708269	0.00200918

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Table 2 shows the thermal diffusivity values for the MB. These values were obtained using equation (5), it can be observed that the values change at different depth levels, as well as temperature. This will be discussed in detail below.

To validate the temperature values of the indirect method [15] against the experimental one, it was necessary to use statistics to support the results (Figure 8). From the experimental data collected for 150 days at three depth levels in MB, against the estimated data for the same period and location, a Pearson's statistical correlation is performed to determine the relationship between the methods used. To evaluate the accuracy of the model, RMSE is used, as well as the R^2 to observe how well the model fits the observed data. The values of the statistical analyses obtained are shown in table 3.

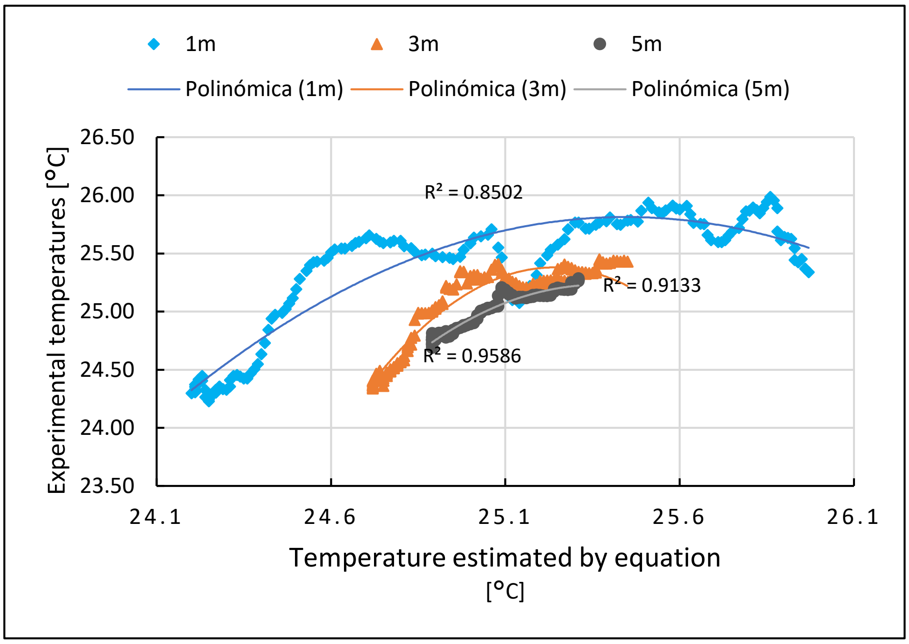

Figure 8. Validation of the indirect vs. direct method used in the Muyuna borehole at different depth levels.

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Table 3. Statistical analysis

S.Analysis	1m	3m	5m
Pearson´s correlation	0.7593	0.8679	0.9616
RMSE	0.46	0.2	0.09
R^2	0.8502	0.9133	0.9586
Fitting coeficients			
a2	-0.9608	-3.6289	-2.1596
a1	48.895	183.19	109.57
a0	-596.26	-2286.6	-1364.6
Variance			
Levene´s test	p value	2.2x10^-16	
T -test	p value	0.41	

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Figure 9 shows average yearly maximum and minimum subsoil temperature profiles at different depths in bare soil for three measurement points in the Tena canton by the indirect method. Calculations were based on thermal diffusivity available in the literature [43,45–47]. For Puerto Napo (limestone) 1.33E-6 $m^2.s^{-1}$, for Los Pinos (clay/silt wet) 5E-7 $m^2.s^{-1}$, and for the Muyuna borehole (gravelly sand - saturated gravel) 1.98E-7 $m^2.s^{-1}$ thermal diffusivity value obtained in this study.

Figure 9A shows the behavior of the subsurface temperature up to 10 m depth. At 1m depth maximum temperature was 29.05°C and minimum temperatures was 21.18°C. Likewise, at 3m depth maximum is 26.07°C and minimum temperature was 24.16°C, while at 5m depth maximum was 25.34°C and minimum was 24.9°C. It can observed tend to flatten from 5m in MB. In addition, the experimental temperature values obtained during the 150 days are shown. In Figure 9B (PN) the maximum temperature at 1m depth was 31.2°C and the minimum temperature is 19°C, at 3m maximum temperature was 28.6°C and minimum temperature was 21.6°C, and at 5m It can observed maximum was 27.1°C and minimum was 23.1°C. Since 8m depth onwards, these values tend to flatten out as one goes deeper from the surface, stabilizing at approximately 25°C during yearly period. Meanwhile, in Figure 9C (LP), the maximum temperature was 30.24°C and minimum temperature values was 20°C at 1m depth, at 3m the maximum was 27.22°C and the minimum temperature was 23.02°C, respectively. The maximum was 25.9°C and minimum temperature was 24.3°C at 5m depth. Temperature variation stabilizes from 6m depth, with subsoil temperatures remaining almost constant at around 25°C at that location throughout the yearly period.

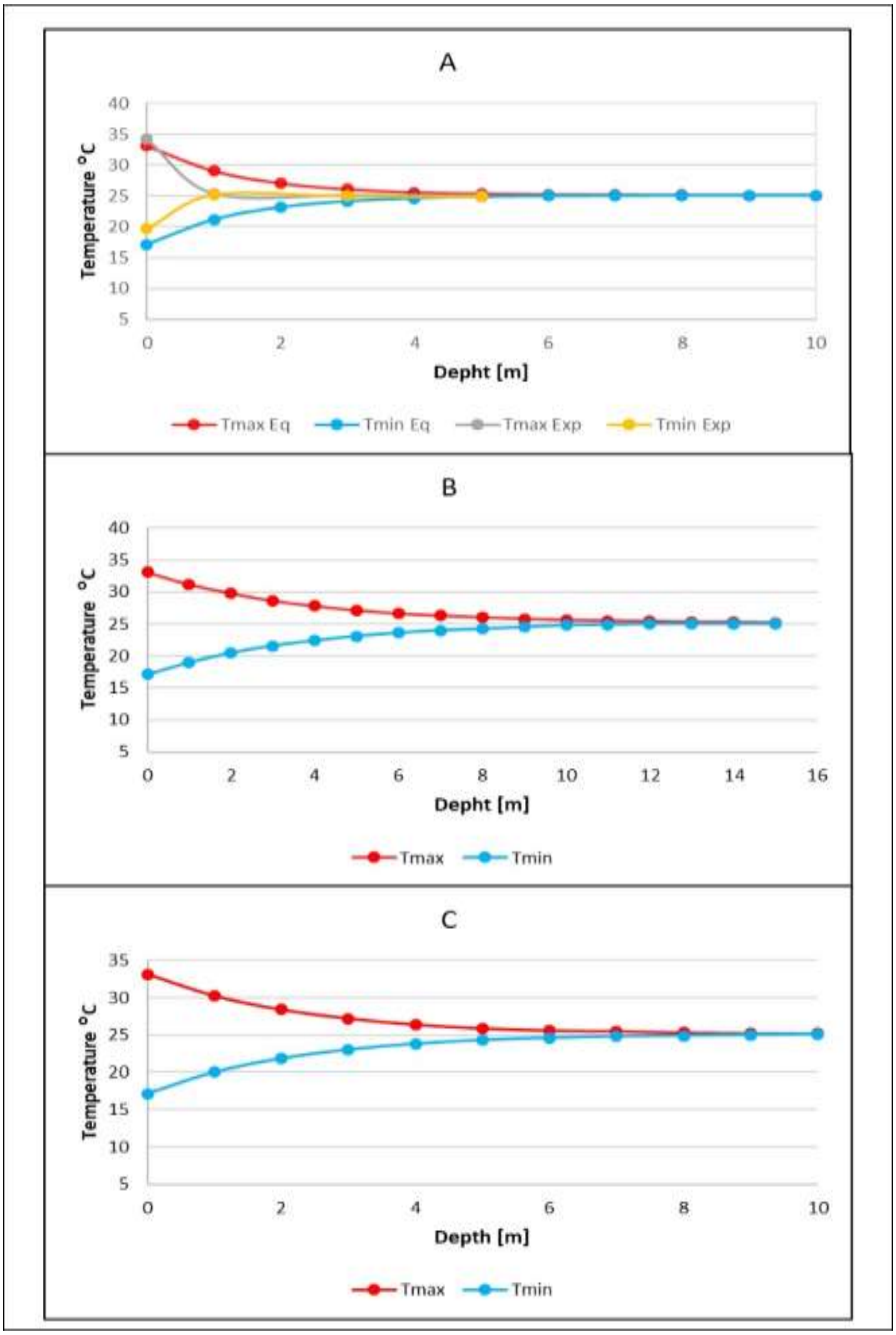

Figure 9. Average yearly maximum and minimum subsoil temperature profiles in 3 points Tena canton by indirect method: **A)** MB, **B)** PN, **C**) LP

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DISCUSSION

Knowing the thermal properties of the subsoil is essential for the exploitation of very low enthalpy shallow geothermal resources. As evidenced in the previous paragraphs, soil temperature profiles vary with respect to the other soil types constituted by different geological materials analyzed in Tena canton. According to Hillel [48], these temperature variations respond to regimes of meteorological changes acting on the atmosphere-surface that are characterized by a regular periodic succession of days and nights and climatic seasons. However, the regular cycles are often disturbed by phenomena such as cloudiness, cold waves, heat waves, rain or snowstorms and periods of drought [49]. In addition to those mentioned, the natural properties of the soil such as diffusivity and thermal conductivity of the soil, humidity, play a major role in temperature variations, without neglecting also to expose the geographical conditions specific to the site.

According to the data obtained by the climatological station of Ikiam University during a period of 7 years, which are represented in Figure 3, intense rainfall has been observed during the months of April, May, June and July in excess of 500 mm per month, and of lesser intensity in the month of August around 200 mm. With regard to temperature, an average ambient temperature of 25.12°C has been obtained for the period April 2016-June 2022.

Vertical Temperature profiles of the Muyuna borehole by direct method

The set of data recorded during the period of 150 days in the MB at various depths shown in Figure 4. It is evident that temperature fluctuations decrease as one goes deeper from the surface due to the thermal inertia of the soil, which, Ng [50], defines as the "property of a material that expresses the degree of slowness with which its temperature reaches that of the environment". Below 1m, these fluctuations are hardly noticeable. For example, at surface level - for the purposes of this study it was taken equal to 0m - average maximum values of approximately 35°C were obtained, while at 5m depth the maximum average stabilized at around 25°C, observing a difference of 10°C at only 5m depth.

In Figure 5, it can be seen that from a depth of 5m, the temperatures during the 150 days tend to the average annual temperature of Tena, which is 25.12°C. During this period, average temperature was 25.01 °C a 5m of depth. According to the trend, it can be identified that from a depth of 5m, these values would be almost constant. This is corroborated in Figure 9, in which it is plotted up to 10 m depth. The opposite happens at the surface zone of the soil, where there are wide variations in temperature. At the surface level it is observed that temperature is higher than the air temperature of the place, this is because the sun's rays first heat the surface of the Earth, causing the soil in turn begins to radiate heat by heating the air near the surface. It is then that the surface of the ground has higher temperatures than at near-surface levels [51,52].

Figure 6 shows an approximate temperature difference of 14°C between the maximum and minimum temperature elapsed in one day (24 hours). The daily temperature cycle reaches approximately 1m depth. Kalogirou and Florides [53] indicate that, at a surface level, the surface thermal conductivity affects largely depending on how high or low the conductivity value is, the degree of affectation will be. Consequently it is observed that surface zone of MB extends to 1m, while the shallow zone extends to 5m depth and from 5m onwards would be the deep zone in which, according to several authors (e.g.[5,6,54]) temperatures are insensitive to climatic variations.

Effect of surface temperature variations on heat flux at Muyuna Borehole

Data obtained at MB reveal significant variations in heat flux at different depths over a period of 150 days. At 5 m depth, the heat flux remains relatively constant, ranging from $-1 W/m^2$ to $1 W/m^2$. While at 1 m depth, the rate of heat exchange from or to the surface ranges from 4 to $-11 W/m^2$. According to the literature, when the surface soil temperature increases, either due to direct solar radiation or climatic factors, there is an increase in the heat flux to the subsurface. This is because the temperature difference between the surface and the subsoil creates a thermal gradient, causing heat to be transferred from the warmer to the cooler zone [31,55]. On the other hand, during periods of lower surface temperatures, heat flow is transferred from the subsurface to the surface. To analyse the relationship of surface temperatures to heat flux in MB, a lagged cross-correlation analysis is performed (Figure 10). The analysis allowed us to identify the time span it takes to affect these surface temperatures at different depths. For example, at depths of 1m, 3m and 5m, a time lag of 3, 13 and 23 days was observed, respectively. The deeper one goes into the subsoil, smaller the heat flux oscillations become. Some soils have the capacity to retain heat, as is the case of clay (see Figure 2), which has a low thermal conductivity, which would act as an insulator in MB, causing the heat flow to slow down and take longer to propagate to greater depths.

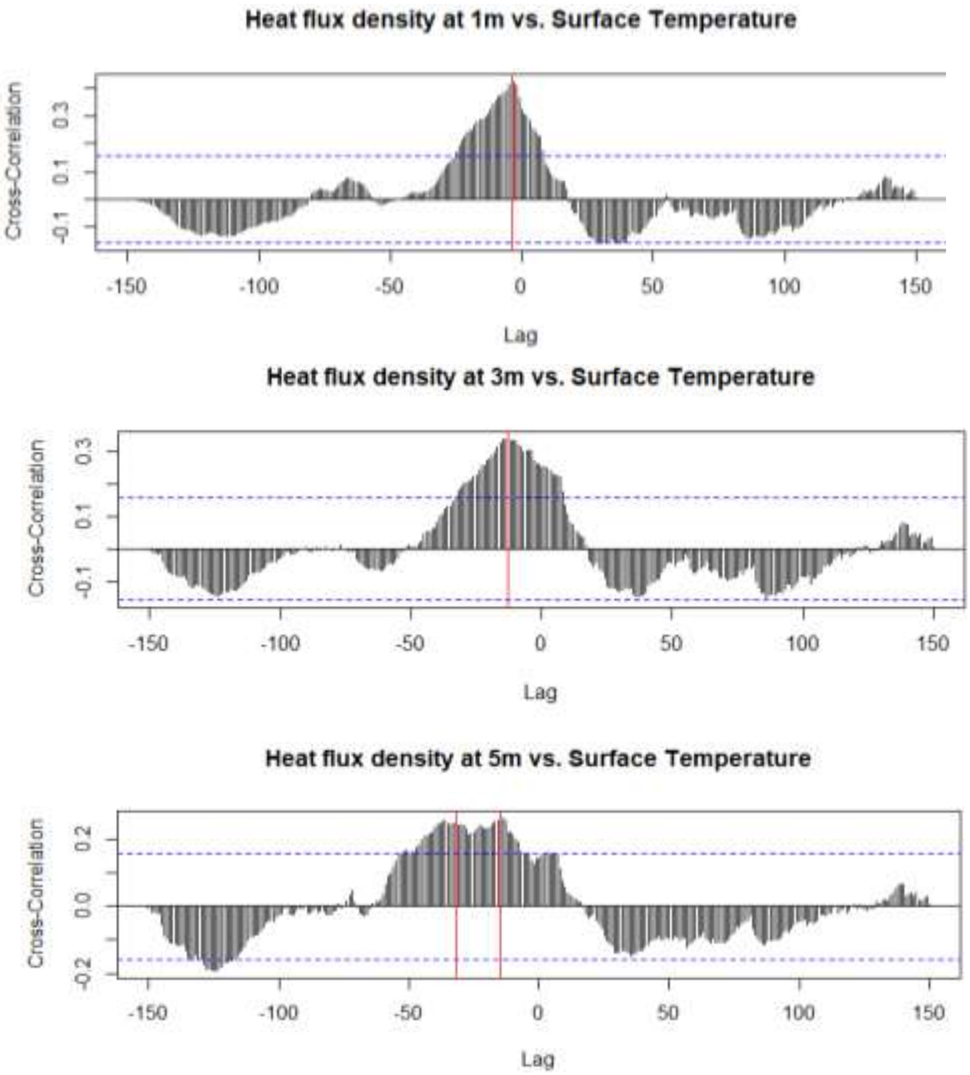

Figure 10. Time lag of heat flux regarding to surface temperatures in Muyuna borehole in different depths
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Vertical temperature distribution three points by indirect method

Graph 9A shows graphs obtained by experimental measurements and indirect measurements in MB. It can be seen that the one obtained indirectly does not have good precision, at least in the surface area, with respect to the experimental one. This is due to the fact that it assumes the uniformity of the soil. In addition, it assumes a sinusoidal variation in the surface and does not consider the vegetation cover and solar radiation, which means that the data obtained near the surface area in MB are not similar to those observed experimentally. But from a depth of 3m, they are in good agreement with each other. This is because the weather effects that occur on the surface are no longer progressing with intensity. The limitations of this method in the surface zone are a barrier to being able to accurately predict surface zone temperatures.

The profiles temperatures calculated in PN and LP show (Figures 9B and 9C) a difference in the depth of temperature stabilization. In PN, temperatures tend to the annual average temperature of the site from 8m depth, while in LP temperatures tend to 25°C from 6 m depth. If the lithologies of the different study sites are analyzed, it is observed that: The lithology of MB and LP tend to be similar, given that in the superficial part of the well it has siliciclastic soils that are the ones that make up LP sector. Only that the geological material is lithified in this sector as opposed to MB which is sediment, that is to say it has not suffered lithification. This would be a major factor in the closeness of the temperature values at both study sites. This argument can also be supported if one can observe in the sector of PN, constituted by carbonates, that from a depth of 8m the temperature values tend to be constant. The differences between different geological materials are evident. The lithology in the shallow zone is one of the factors that directly affect the temperature of the different soil types and from the deep zone onwards, Florides and Pouloupatis [3] mentions that, temperature distribution in the deep zone will depend directly on the lithological characteristics, but not the geographical location or climate.

Ground Thermal diffusivity

As could be observed in the stratigraphic column of the MB (Figure 2), this site from 2.75m to 5m depth is made up of layers of sandy gravels and gravels with blocks between 70mm to 600mm in a saturated state, identifying this zone have high permeability. Calculations of thermal diffusivity carried out in MB by equation (5) at different depths show that the thermal diffusivity of the soil changes at the three depth levels at which temperature measurements were taken. For example, at 1m depth the thermal diffusivity value at that level was 2.13 E-8 $m^2.s^{-1}$, while at 3m depth its value was 1E-7 $m^2.s^{-1}$ and at 5m depth a thermal diffusivity value of 1.98E-7 $m^2.s^{-1}$ was obtained.

The available values of thermal diffusivity for these types of lithological materials in saturated state in the literature [43,45–47] are in the range from 1E-6 to 7.5E-7 $m^2.s^{-1}$. If one compares the diffusivity values calculated in the borehole with those suggested in the literature for this soil type, they vary significantly. For example, assuming a single thermal diffusivity value for the entire borehole profile, the literature suggests a thermal diffusivity value of 7E-7 $m^2.s^{-1}$ for saturated gravel, but as it has been shown that the value obtained for gravel in a saturated state at 5 m depth at this point is only 1.98E-7 $m^2.s^{-1}$. This would be a limitation when applying the indirect method for the estimation of temperature profiles because the soils are not homogeneous. The range of thermal diffusivity in this type of geological material is wide, and these values will depend on the mineralogical constitution of the soil, temperature, granulometry, depth, density and moisture content [56].

Validation of the indirect method with respect to the experimental method.

To validate the indirect method, the results of Pearson's statistical analysis obtained 0.75, 0.86, and 0.96 at 1, 3, 5m depth, respectively. Values that according to [57] can be considered as a good correlation between variables, as these values are close to one. Also, the coefficients of determination (R^2= 0.85, 0.91, 0.95) at three different depths show a non-linear dependence. Furthermore, in general terms the calculated RMSE indicates a good accuracy of the model.

Statistical analysis

Finally, the analysis of variances was carried out with the help of Rstudio. The Levene's test indicates that there are significant differences temperature variances between 1m, 3m and 5m depth in the Muyuna borehole with a P value=$2.2x10^{-16}$, rejecting the null hypothesis. The comparison of temperature variances between both methods using the T-test reported temperature values comparable to those observed experimentally, with a significance of P=0.41, therefore the null hypothesis is not rejected. Statistically it is known that if the p value > 0.05, it is considered that the results would not have a significant difference [58,59]. It is true that this result does not determine the certainty of the mathematical method in relation to the experimental one, however, it could be inferred that there is a good percentage of probability that supports the hypothesis put forward.

CONCLUSIONS

This study has presented the vertical distribution of ground temperatures from surface to 5m depth at three sites in the canton of Tena in order to understand the thermal dynamics at these sites. The direct method employed in MB, a temperature data log was obtained for 150 days, which after processing, average temperatures of 25.32°C, 24.9°C and 25.01°C were observed at 1m, 3m and 5m depth, respectively. At 5m depth, a stabilization of the temperature was noted at around 25°C, which is almost equal to the average annual temperature of the Tena canton that is 25.12°C. Meanwhile, for PN and LP, the stabilization of the temperature was observed at 8m and 6m of depth, respectively by indirect method. By means of the experimental method it is identified that the superficial zone in MB reaches up to 1m depth, the shallow zone reaches 5m and the deep zone would be below 5m.

The validation the indirect method regarding the experimental method by statistical analysis. Pearson's statistical correlation showed a good correlation between the variables of the methods used. The accuracy of model by RMSE shows a good accuracy, and coefficient of determination R^2 shows a good fit. In general, the indirect method shows a general agreement with respect to the experimental one. The analysis of variance between the two methods used, identifies that there are no significant differences with respect to the direct method. However, this mathematical method allows estimations of temperature values that contribute to have a general knowledge of temperature variations in different types of soil, given the difficulty of having a homogeneous soil in the environment and the limitation of specifying its physical properties. Therefore, it is necessary to plan investigations in other soil types using both methods, in order to have a broader database for future applications of very low enthalpy geothermal energy in the Tena canton.

ACKNOWLEDGEMENTS

The authors would like to thank the hydrometeorological services laboratory of the Amazonian Regional University Ikiam for supplying dataset weather of the Tena canton. Likewise, AAPG Foundation's L. Austin Weeks Undergraduate Grant program by the grant 2022

REFERENCES

1. Cárcel Carrasco FJ, Martínez Márquez D. LA ENERGÍA GEOTÉRMICA DE BAJA ENTALPÍA. 3C Tecnología_Glosas de innovación aplicadas a la pyme. 2015;4: 96–108. doi:10.17993/3ctecno.2015.v4n3e15.96-108
2. Florides G, Kalogirou S. ANNUAL GROUND TEMPERATURE MEASUREMENTS AT VARIOUS DEPTHS. 2004.
3. Florides GA, Pouloupatis PD, Kalogirou S, Messaritis V, Panayides I, Zomeni Z, et al. The geothermal characteristics of the ground and the potential of using ground coupled heat pumps in Cyprus. Energy. 2011;36: 5027–5036. doi:10.1016/j.energy.2011.05.048
4. Florides G, Kalogirou S. Ground heat exchangers-A review of systems, models and applications. Renewable Energy. 2007. pp. 2461–2478. doi:10.1016/j.renene.2006.12.014
5. van Manen SM, Wallin E. Ground temperature profiles and thermal rock properties at Wairakei, New Zealand. Renew Energy. 2012;43: 313–321. doi:10.1016/j.renene.2011.11.032
6. Florides G, Kalogirou S. First in situ determination of the thermal performance of a U-pipe borehole heat exchanger, in Cyprus. Appl Therm Eng. 2008;28: 157–163. doi:10.1016/j.applthermaleng.2007.03.026
7. ICAEN. Geoíndex - Geotèrmia superficial. Institut Cartogràfic i Geològic de Catalunya. 2021 [cited 16 Mar 2022]. Available: https://www.icgc.cat/ca/Administracio-i-empresa/Eines/Visualitzadors-Geoindex/Geoindex-Geotermia-superficial
8. Lund JW, Freeston DH, Boyd TL. Direct utilization of geothermal energy 2010 worldwide review. Geothermics. 2011;40: 159–180. doi:10.1016/j.geothermics.2011.07.004
9. Yadav K, Sircar A. Application of low enthalpy geothermal fluid for space heating and cooling, honey processing and milk pasteurization. Case Studies in Thermal Engineering. 2019;14. doi:10.1016/J.CSITE.2019.100499
10. Surana T, Atmojo JP, Subandriya A. Development of Geothermal Energy Direct Use in Indonesia. Proceedings World Geothermal Congress. 2010.
11. Tong C, Li X, Duanmu L, Wang H. Prediction of the temperature profiles for shallow ground in cold region and cold winter hot summer region of China. Energy Build. 2021;242. doi:10.1016/j.enbuild.2021.110946
12. Teleszewski TJ, Krawczyk DA, Fernandez-Rodriguez JM, Lozano-Lunar A, Rodero A. The Study of Soil Temperature Distribution for Very Low-Temperature Geothermal Energy Applications in Selected Locations of Temperate and Subtropical Climate. Energies (Basel). 2022;15. doi:10.3390/en15093345
13. Krawczyk DA, Teleszewski TJ. Optimization of geometric parameters of thermal insulation of pre-insulated double pipes. Energies (Basel). 2019;12. doi:10.3390/en12061012
14. Mihalakakou G, Santamouris M, Asimakopoulos D. Modelling the earth temperature using multiyear measurements. Energy Build. 1992.

15. Kasuda T, Achenbach R. Earth Temperature and Thermal Diffusivity at Selected Stations in the United States. 1965; 1–233. Available: https://nvlpubs.nist.gov/nistpubs/Legacy/RPT/nbsreport8972.pdf
16. Arias-Penas D, Castro-García MP, Rey-Ronco MA, Alonso-Sánchez T. Determining the thermal diffusivity of the ground based on subsoil temperatures. Preliminary results of an experimental geothermal borehole study Q-THERMIE-UNIOVI. Geothermics. 2015;54: 35–42. doi:10.1016/j.geothermics.2014.10.006
17. Teleszewski TJ, Krawczyk DA, Fernandez-Rodriguez JM, Lozano-Lunar A, Rodero A. The Study of Soil Temperature Distribution for Very Low-Temperature Geothermal Energy Applications in Selected Locations of Temperate and Subtropical Climate. Energies (Basel). 2022;15. doi:10.3390/en15093345
18. Gehlin S. Thermal Response Test Method Development and Evaluation. 2002.
19. Henry SG, Pollack HN. Terrestrial heat flow above the Andean subduction zone in Bolivia and Peru. J Geophys Res. 1988;93. doi:10.1029/jb093ib12p15153
20. Barba DP, Barragán R, Gallardo J, Salguero A. Geothermal Gradients in the Upper Amazon Basin derived from BHT data. International Journal of Terrestrial Heat Flow and Applications. 2021;4: 85–94. doi:10.31214/ijthfa.v4i1.58
21. Hamza VM, Dias FJSS, Gomes AJL, Terceros ZGD. Numerical and functional representations of regional heat flow in South America. Physics of the Earth and Planetary Interiors. 2005;152: 223–256. doi:10.1016/j.pepi.2005.04.009
22. INER. Proyecto 17: Plan de líneas de investigación para el desarrollo de la geotermia. 2015.
23. INEC. Estructura de la población ¿QUÉ EDAD TENEMOS LOS HABITANTES DE NAPO? ¿CUÁNTOS SOMOS Y CUÁNTO HEMOS CRECIDO? 2010.
24. Gad Municipal de Tena. PDOT-CANTON-TENA-2014-2019. 2014 [cited 20 Dec 2022]. Available: https://odsterritorioecuador.ec/wp-content/uploads/2019/04/PDOT-CANTON-TENA-2014-2019.pdf
25. MAGAP-PRAT. "LEVANTAMIENTO DE CARTOGRAFÍA TEMÁTICA ESCALA 1:25.000, LOTE 1." 2015.
26. GADP Chontapunta. PLAN DE DESARROLLO Y ORDENAMIENTO TERRITORIAL DE LA PARROQUIA CHONTA PUNTA PLAN DE DESARROLLO Y ORDENAMIENTO TERRITORIAL PARROQUIA: CHONTA PUNTA "Con voluntad y entusiasmo generamos el desarrollo de nuestro territorio" Agosto-2015. 2019.
27. Paucar S. Compilación Breves descripciones de las Hojas geológicas 1:100000 del Ecuador continental. 2021.
28. DGGM-INEMIN. 69.- Hoja geológica Tena - escala 1 100.000. 1986 [cited 21 Dec 2022]. Available: https://drive.google.com/file/d/1cCB2N0Um2W_IGBOIrhviBEOzs6But3us/view?pli=1
29. Baldock John W. Geología del Ecuador. Boletín de la explicación del mapa geológico de la república del Ecuador. Escala 1:1000000. División de Investigación Geológico-Minera. 1982; 9–19.
30. Sauer Walther. Geología del Ecuador. Ministerio de Educación. 1965.

31. Ochsner TE, Sauer TJ, Horton R. Soil heat storage measurements in energy balance studies. Agronomy Journal. 2007. pp. 311–319. doi:10.2134/agronj2005.0103S
32. Luheshi MN. Estimation of formation temperature from borehole measurements. 1983.
33. Bullard EC. The time necessary for a bole hole to attain temperature equilibrium. Phil Mug. 1946. doi:https://doi.org/10.1111/j.1365-246X.1947.tb00348.x
34. HOBO. HOBO® Pendant® MX Temp (MX2201) and Temp/Light (MX2202) Logger Manual. 2017 [cited 13 Nov 2022]. Available: www.onsetcomp.com
35. Prangnell J, McGowan G. Soil temperature calculation for burial site analysis. Forensic Sci Int. 2009;191: 104–109. doi:10.1016/j.forsciint.2009.07.002
36. DGGM - INEMIN. 44.- Hoja Geológica Puerto Napo - escala 1 100.000. 1986.
37. Abarca Karen. Mapa Geológico de Tena entre Muyuna y Ongota (1:5000). 2022.
38. Andújar J, Martínez M, Gómez S. Ground thermal diffusivity calculation by direct soil temperature measurement. application to very low enthalpy geothermal energy systems. Sensors (Switzerland). 2016;16. doi:10.3390/s16030306
39. Poirier DR, Geiger GH. Conduction of Heat in Solids. Transport Phenomena in Materials Processing. 2016; 281–327. doi:10.1007/978-3-319-48090-9_9
40. Tabbagh A, Bendjoudi H, Benderitter Y. Determination of recharge in unsaturated soils using temperature monitoring. Water Resour Res. 1999;35: 2439–2446. doi:10.1029/1999WR900134
41. López Santos A, Zermeño González A, González Barrios JL, González Cervantes G, Cadena Zapata M, Campos Magaña SG. Medición de la profundidad de flujo de calor y difusividad térmica en suelos con texturas diferentes por dos métodos de análisis. Investigación y Ciencia de la Universidad Autónoma de Aguascalientes. 2014; 17–25. doi:10.33064/IYCUAA2014623621
42. Sauer TJ, Horton R. Soil heat flux. Micrometeorology in Agricultural Systems. wiley; 2015. pp. 131–154. doi:10.2134/agronmonogr47.c7
43. Pahud D. Geothermal energy and heat storage. 2002.
44. Datatab. Levene Test • Simply explained | DATAtab. [cited 20 Apr 2023]. Available: https://datatab.net/tutorial/levene-test
45. Llopis G, Rodrigo V. Guía de la Energía Geotérmica. Madrid; 2008.
46. Dalla Santa G, Peron F, Galgaro A, Cultrera M, Bertermann D, Mueller J, et al. Laboratory Measurements of Gravel Thermal Conductivity: An Update Methodological Approach. Energy Procedia. Elsevier Ltd; 2017. pp. 671–677. doi:10.1016/j.egypro.2017.08.287
47. El Ámbito De La Ciudad De Santa Fe CE, Alejandro Daniel Eberhardt Guillermo Juan Chiarella Paulo Tejada Estefania R. VIABILIDAD Y PERTINENCIA DE LOS SISTEMAS DE ACONDICIONAMIENTO AMBIENTAL POR GEOTERMIA DE BAJO Eje 2: Tecnología para la construcción sustentable. 2018.
48. Hillel Daniel. Introduction to soil physics. Academic Press; 1982.
49. Hillel Daniel. Introduction to environmental soil physics Daniel Hilel. Elsevier Science. 2004.

50. Ng SC, Low KS, Tioh NH. Newspaper sandwiched aerated lightweight concrete wall panels - Thermal inertia, transient thermal behavior and surface temperature prediction. Energy Build. 2011;43: 1636–1645. doi:10.1016/j.enbuild.2011.03.007
51. Earth Observatory Nasa. Global Warming. Jun 2010 [cited 19 Feb 2023]. Available: https://earthobservatory.nasa.gov/features/GlobalWarming/page2.php
52. US Department of Commerce NNWS. NWS JetStream - The Transfer of Heat Energy. National Weather Service. [cited 19 Feb 2023]. Available: https://www.weather.gov/jetstream/heat
53. Kalogirou S, Florides G. Measurements of Ground Temperature at Various Depths. 2004. Available: https://www.researchgate.net/publication/30500372
54. Popiel CO, Wojtkowiak J, Biernacka B. Measurements of temperature distribution in ground. Exp Therm Fluid Sci. 2001. doi:https://doi.org/10.1016/S0894-1777(01)00078-4
55. Larwa B, Kupiec K. Heat transfer in the ground with a horizontal heat exchanger installed – Long-term thermal effects. Appl Therm Eng. 2020;164. doi:10.1016/j.applthermaleng.2019.114539
56. Dai B, Zhang Y, Ding H, Xu Y, Liu Z. Characteristics and Prediction of the Thermal Diffusivity of Sandy Soil. Energies (Basel). 2022;15. doi:10.3390/en15041524
57. Laerds Statistics. Correlación producto-momento de Pearson: cuándo debe ejecutar esta prueba, el rango de valores que puede tomar el coeficiente y cómo medir la fuerza de asociación. [cited 20 Apr 2023]. Available: https://statistics.laerd.com/statistical-guides/pearson-correlation-coefficient-statistical-guide.php
58. Arias MM, Molina M. Lectura crítica en pequeñas dosis ¿Qué significa realmente el valor de p? Rev Pediatr Aten Primaria. 2017;19: 377–81.
59. Institute for Work Healthy Workers. Statistical significance. Apr 2005 [cited 21 Feb 2023]. Available: https://www.iwh.on.ca/what-researchers-mean-by/statistical-significance