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Deliverable Contributors:

1. Lysandros Katsifarakis

2. Konstantinos Katsifarakis

Has been reviewed and approved by: Konstantinos Katsifarakis

Table of Contents

Introduction

Renewable energy sources have been constantly gaining interest during the past decades. That is due to a number of reasons, such as the fear of the depletion of fossil fuels and the protection of the environment. Renewable energy sources include solar and wind energy, geothermal energy and more.

The use of geothermal energy can be done at a larger or a smaller scale. When it is used in a smaller scale (domestically), this can be done with the use of a geothermal system that includes a heat pump and other parts. There are some different categories of geothermal systems, with the main ones being the closed-loop and the open-loop systems. In the Aristotle University of Thessaloniki (A.U.Th.), and specifically in the building of the department of Hydraulics and Environmental Engineering (building of Hydraulics), of the Faculty of Civil Engineering, such a system was initially created.

In order for any geothermal system to be able to function there are some prerequisites. For an open-loop system, first of all water needs to be available. This water is in most cases obtained not from sources on the surface of the earth, but from ones located inside the earth, from underground aquifers.

Although it is not usually thought of in this way, the ground that we step on, as well as the layers of it below the surface, are often full of smaller or larger pores. These pores do not remain empty but are filled with air and more often than not with water. An underground aquifer consists of the amount of water present inside a certain volume of ground.

Some of these aquifers are located closer to the surface of the ground and some of them deeper in it, and in some cases very significantly so. The water in the underground aquifers cannot be accessed as easily as that in the lakes and the rivers, however, it remains a very valuable fresh water resource around the world. Actually, many areas around the world are being provided with water partly or exclusively via water extracted from underground aquifers.

In order for the water in the underground aquifers to be used the usual process is this. A well has to be created by specialized machinery. The well needs to be of sufficient depth. The walls of the well must be properly stabilized (if needed) and a water pump can be then placed in it. The water from the ground fills the well and then gets pumped out of it through pipes.

An interesting phenomenon that takes place when water is pumped out of an underground aquifer is that the water level at the point where the pump is located and in a large area around it can drop, in certain cases significantly so. This can be important for a wide variety of reasons, environmental, economical, reasons related to health and safety and more. This phenomenon of a local change in the level of water is not really to be found in water masses on the surface of the earth, but is very common in the aquifers inside of it.

The water inside the earth can also move in any direction. The movement of water on the surface of the earth is known to most people, however this is not the case with underground water. Due to the nature of the space where the water is located in the ground, its movement is usually different. It is, in most cases, very significantly slower. However, in certain types of grounds, the pores are actually so large so as to resemble pipes. Especially in those the way the water flows can be similar to the way it does on the surface. These types of grounds, though, are not the norm.

What is here worth noting is the fact that in many areas the existence of underground aquifers is, practically, a given. The main difference among them is the depth in which they are located, the types of ground at the level of the water and above, the amount of water present and its quality.

The porosity of the ground and its ability to store water

The total amount of empty space in a material can be referred to with the term porosity. The porosity of the soil dictates the amount of water that can be stored in it and is, in general, a very important characteristic of the soil. The porosity can vary significantly and it is greatly affected by the soil texture, its structure and the total amount of organic matter in it.

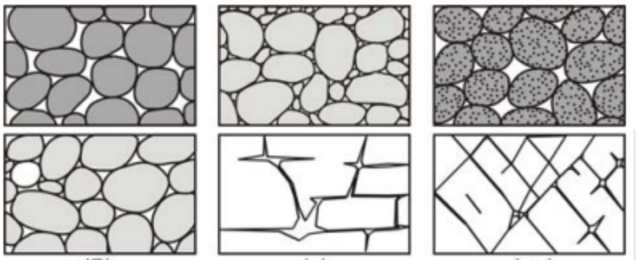


Figure 1. The images depict what could be observed if different soils were examined closely. The porosity in all of them can be clearly seen (Source: Meinzer, 1923)

Regarding soil texture: Soils such as sand naturally have larger pores than others, such as clay. Thus the porosity in coarse-grained soils is typically higher than this of the fine-grained ones. In the coarse-grained soils, though, the pores can be less interconnected.

Regarding soil structure: Soils that are well-structured allow water to infiltrate in them more easily and have a greater ability to store water in general. The poorly structured soils, on the other hand, usually have a smaller amount of pores in them, thus their ability to store water is also inferior.

Regarding the organic matter in the soil: Organic matter binds soil particles together and it also contributes in the creation of larger pores which are more interconnected. Thus, the presence of organic matter in the soil can lead to greater porosity and a greater ability of the soil to store water.

The ability of the ground to store water can have an effect in various environmental processes. For example, the groundwater recharge is affected by it. Moreover, the ability of the ground to store water can play a role in phenomena like floods, since a higher ability of the ground to absorb water can lead to a smaller amount of it running off on the surface and, thus, can lead to less severe flood events.

All in all, a ground with greater porosity can have larger amounts of water stored in it. This in turn can lead to larger amounts of water being available and more easily available, as well.

Pumping water from the ground

Specialized mechanical equipment is used in order for water stored in underground aquifers to be extracted and used (domestically, agriculturally etc). These pieces of equipment work by creating a pressure differential, which in turn forces the water to flow to the surface. This process is called pumping and the mechanical equipment making it possible, water pumps, or simply pumps.

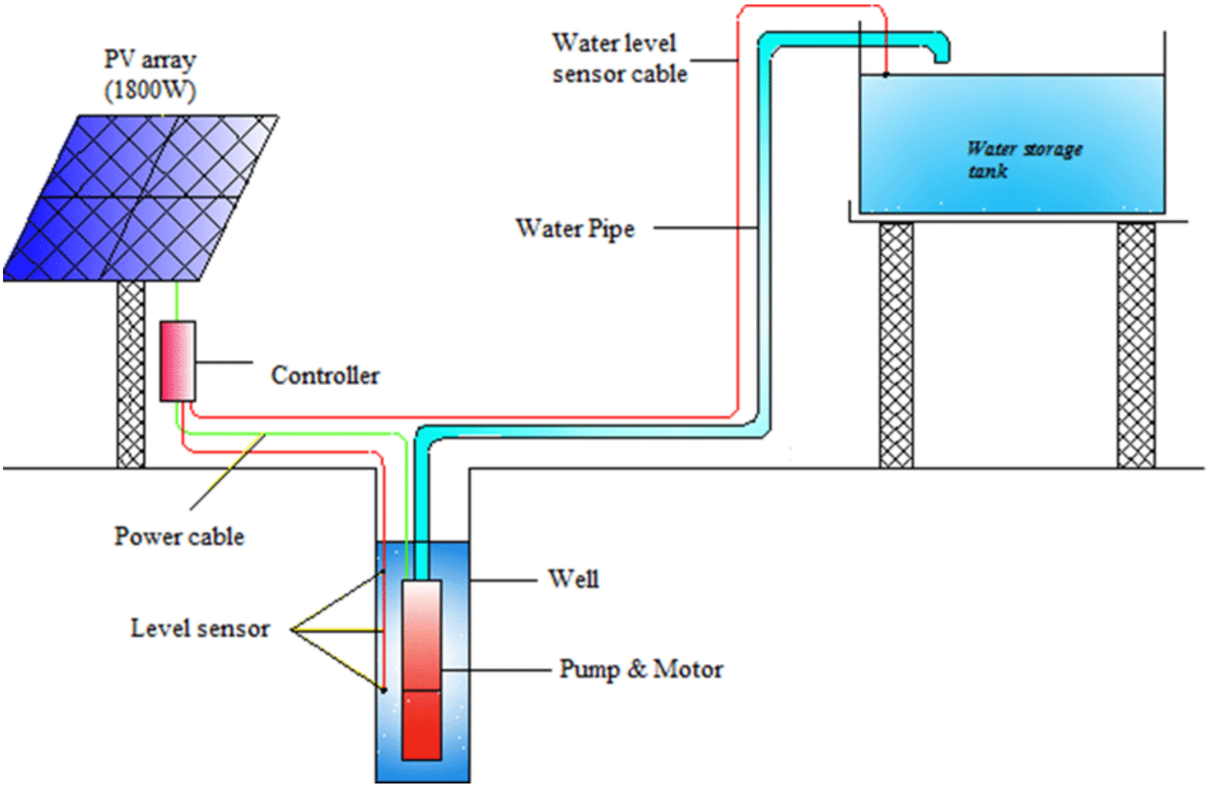


Figure 2. A diagram showing a water pumping system powered by solar energy. The water pump in it is a submersible pump (Source: Elias Salilih, 2020)

A variety of water pumps is available, submersible pumps, jet pumps and even hand pumps. The first ones work by getting submerged into the water and they can usually be found in deep wells. The second ones, the jet pumps, need to be installed on the ground. They can be found mostly in use in shallow wells and they function by using suction to draw water from the wells. Lastly, the hand pumps are mostly either a remnant of previous eras or in use in remote areas where there are shortages in available electric energy. As their name implies, they are operated manually.

Although water can be present inside the ground, the amount that can be provided by an underground aquifer is not the same in all cases. It is dependent on various factors, such as the permeability of the soil, the rate in which water is replenished in the aquifer, the depth of the well constructed in it and more. It is worth mentioning here that over-pumping water from an aquifer can have detrimental effects like leading to a severe drop in the water table, leading to the depletion of the aquifer, or even leading to saltwater intrusion (this can happen in coastal areas). Additionally, since the amount of water present in the ground affects the mechanical properties of the ground, an extensive drop in the water table could potentially lead to land subsidence and, thus, threaten any constructions in the area.

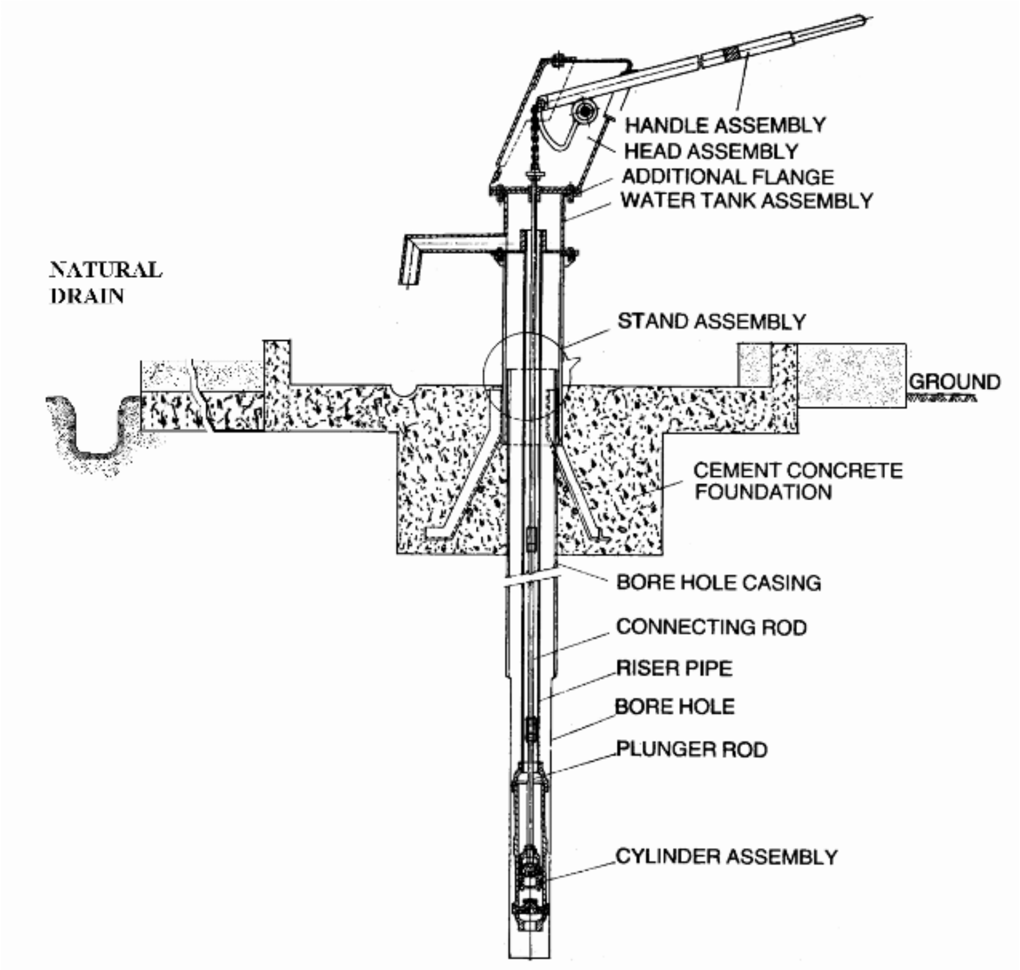


Figure 3. Diagram showing a hand pump (Source: Abdel Bagi Siraj et al, 2010)

Lastly, the over-pumping of water from an underground aquifer can have negative environmental effects, as well. For example, it can lead to the depletion of surface water resources, it can affect ecosystems that are dependent on groundwater, or even lead to the contamination of the aquifer by pollutants present in the ground.

How the groundwater level drawdown can impact the properties of the soil and cause land subsidence

Land subsidence is the term used to describe the downward vertical movement of the surface of the Earth. This phenomenon can be caused by both, natural processes and as a result of human activities. Natural causes of land subsidence can be earthquakes and the collapse of caves located underground. In the phenomenon of land subsidence there is practically very little or insignificant horizontal movement of the soil taking place.

Regarding the main causes of land subsidence linked to human activities, the over-extraction of groundwater should be among the most common ones. Pumping water from an underground aquifer can lead to a drop in the level of the water in it, which is called groundwater level drawdown, or, more simply, drawdown.

The presence of water in the soil affects its properties, thus the groundwater level drawdown can change how the soil in the area behaves, and sometimes very drastically. When water is no longer present in a ground mass, the pores of the soil that it previously filled become empty. This can decrease the ability of the soil to resist the load that it is under, and thus make it unable to retain its current structure. Consequently, it will get compressed and its volume will decrease. This then will affect the layers of the ground above, causing them to move downwards and, thus, land subsidence will occur.

Figure 4. Examples of land subsidence (Source: Majid Mohammady et al, 2019)

Land subsidence can seriously damage buildings and infrastructure, as well as the environment in the area where it takes place. Moreover, if this phenomenon takes place in agricultural regions, it can lead to lower crop yields, as well as even loss of fertile lands. If the phenomenon occurs in coastal areas, this phenomenon can lead to inundation of certain areas during high tides or during storms.

How is groundwater level drawdown calculated

When pumping water from an underground aquifer a drawdown can occur. However, the drawdown does not take place over the whole aquifer, at least to the same extent. It is stronger at the points where water is extracted from the aquifer and decreases gradually around them.

The non-uniform sustained decrease in the level of the water at a large enough scale in a mass of water can be observed almost exclusively in underground aquifers, for a simple reason. In them the water can usually move at much slower speeds than in rivers, lakes etc. When water is being pumped from a lake for example, from the very spot where the draining is happening a drop in the water level could start forming. However, the surrounding water would then be in a higher level and it would naturally flow towards the lower level area. This would then very rapidly replenish the water missing and bring the water level back up. In such a case, even if a small drop in the water level would form, it would most likely not be significant and would also be totally local.

On the other hand, in the underground aquifers, the water usually can move at a much slower pace. In them, when water gets pumped from the aquifer, a very local drawdown starts appearing and the surrounding water starts again flowing to this area. However, it usually cannot move fast enough there. Consequently, the initially local drawdown remains and even starts expanding around the well via which the water is being extracted. Depending on the amount of water getting extracted from the aquifer, the duration of the extraction, the total amount of water in the aquifer, the rate in which the water in the aquifer gets replenished, certain properties of the ground and how fast the water can move in the aquifer, a drop in the water level starts occurring and spreading, until the water level reaches a maximum, non-uniform drawdown, affecting the maximum possible area around the well. If the water is pumped from an aquifer by several different wells, if the flow rate from a well is not steady and if a pump is not working constantly the whole phenomenon of the groundwater level drawdown is similar, but also more complicated at the same time.

What was described above can be seen in the following figures. In the first one, an underground aquifer is depicted and a well through which water is being constantly extracted from it. The initial level of the water in the ground was a bit lower than the surface of the ground.

The aquifer extends at a certain depth below this initial level. This depth is symbolized with “H” and it can be measured in meters. Through the well a certain amount of water is constantly being extracted. This is symbolized with “Q_0” and it can be measured in m^3/h. Due to water being extracted from the well, the water level just around it has dropped, and right there it is at its lowest point. At a certain distance from the well there are the closest points to it where the water level has not been affected at all by the pumping that has been going on. This distance is symbolized with “R” and can be measured in meters. At distances greater than R, the water level in the aquifer is, of course, also unaffected and at the initial level. Between the points around the well, where the water level is at the lowest point, and the points at a distance R around the well, where the water level has not been affected at all, there are countless other points where the water level has been affected, but just to some extent. The closer these points are located to the well, the more the water level there has been affected. The drawdown at any point is symbolized with “s” and can be measured in meters. The water level from the points around the well to the point at distance R from it forms a shape resembling a part of an ellipse.

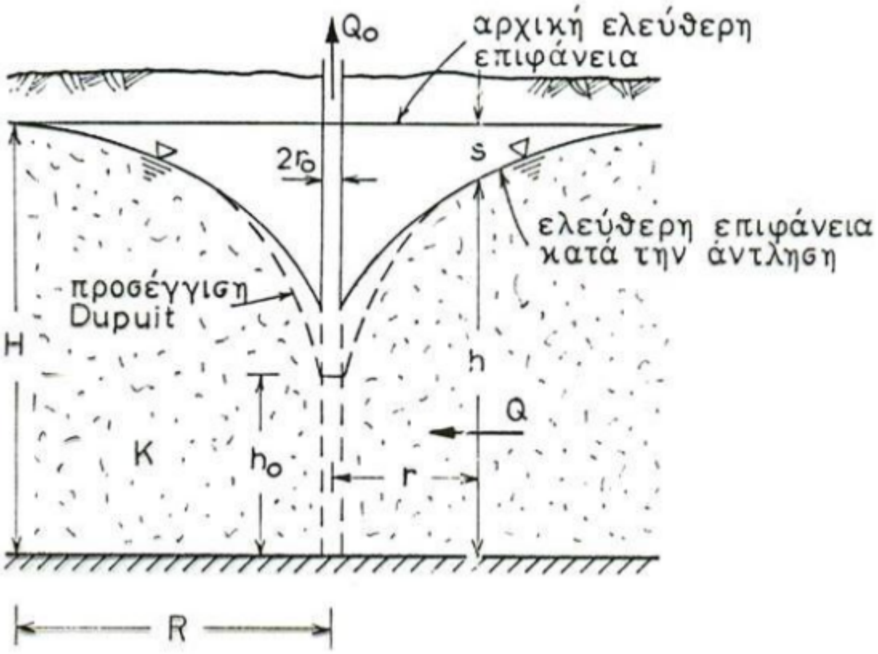


Figure 5. The drawdown in the level of the water in an underground aquifer caused by water being constantly pumped from a well (Source: P. Latinopoulos, 1986)

The more complex version of what was previously described is shown in the following figure. In it, water is shown to be pumped by two different wells.

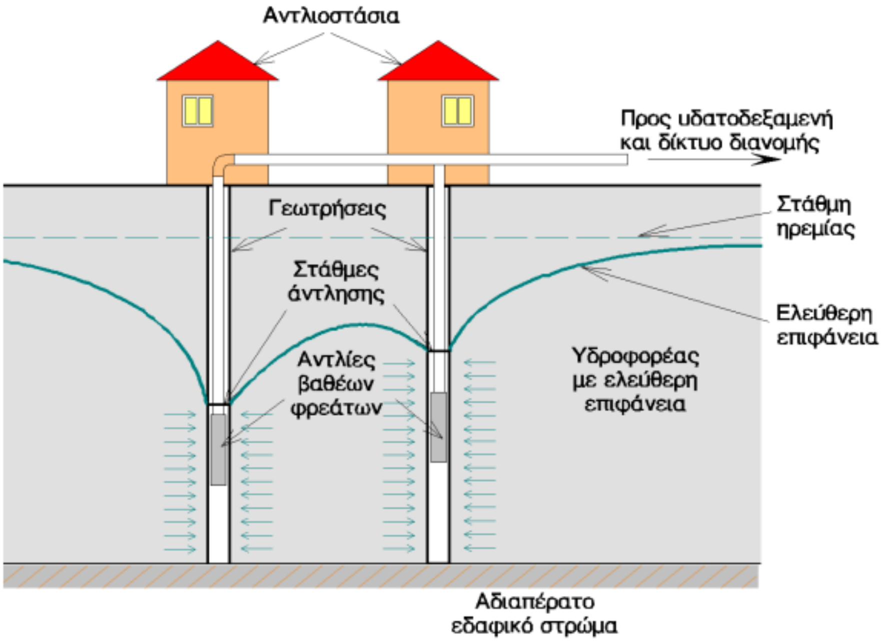


Figure 6. The drawdown as it could be when water is being extracted constantly by two wells (Source: D. Tolikas, 1997)

Depending on the type of aquifer and after making the assumption that all the properties of the soil are the same throughout the aquifer, there are certain equations that make it possible for one to calculate the drawdown from around the well to any point in the aquifer.

For an aquifer like the one below the building of Hydraulics and for a single well extracting water from it constantly, the (final) drawdown can be calculated by the equation:

$s = [\ Q_0 / (2\pi T)\ ] * \ln(R/r) \qquad (1)$,

in which "r" symbolizes the distance from the center of the well at which the drawdown needs to be calculated.

The case of the pilot installation

Using soft criteria it was estimated that there is an aquifer at the area below the building of Hydraulics. The estimation was totally correct and an underground aquifer proved to be there. Unfortunately, a proper geophysical research was not able to be executed, since the area is densely built, and the machinery needed in order to take ground samples at an appropriate depth could not be deployed in the area. It was only feasible to examine the top layers of the soil, until the depth of about 6 meters from the surface.

Therefore, after the open-loop geothermal system was created when it was time to test it, it was shown that the well could not provide the heat pumps with adequate amounts of water, so that they could function properly. That presented a serious challenge and, in order to find a way to overcome it, there were two solutions available.

The first solution would be to maintain the geothermal system an open-loop system, while making the well deeper, so that more water in the underground could be reached and provided to the heat pumps. The second solution would be to keep the main parts of the geothermal system as they are, namely the heat pumps, and change the pipes in the ground, so as to form a closed-loop system.

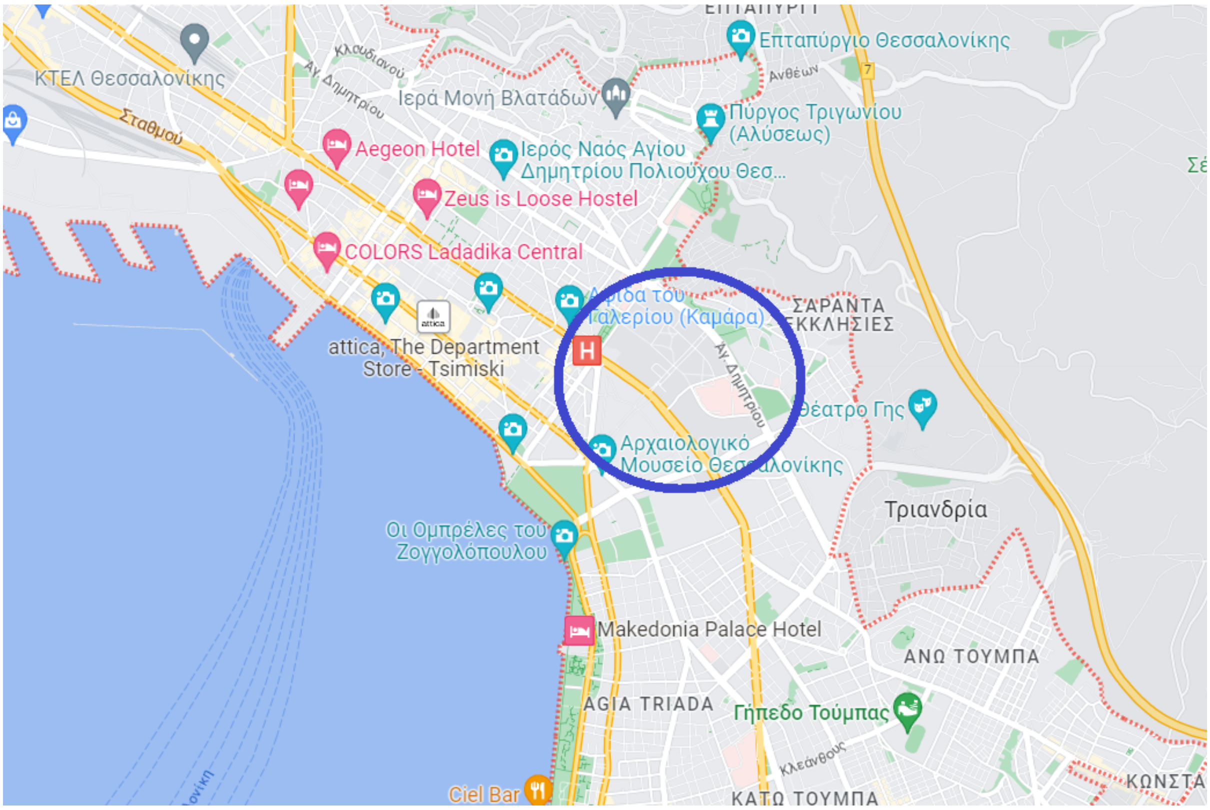


Figure 7. Part of the map of Thessaloniki. The Aristotle University of Thessaloniki is located within the dark blue area (Source of the map: google map)

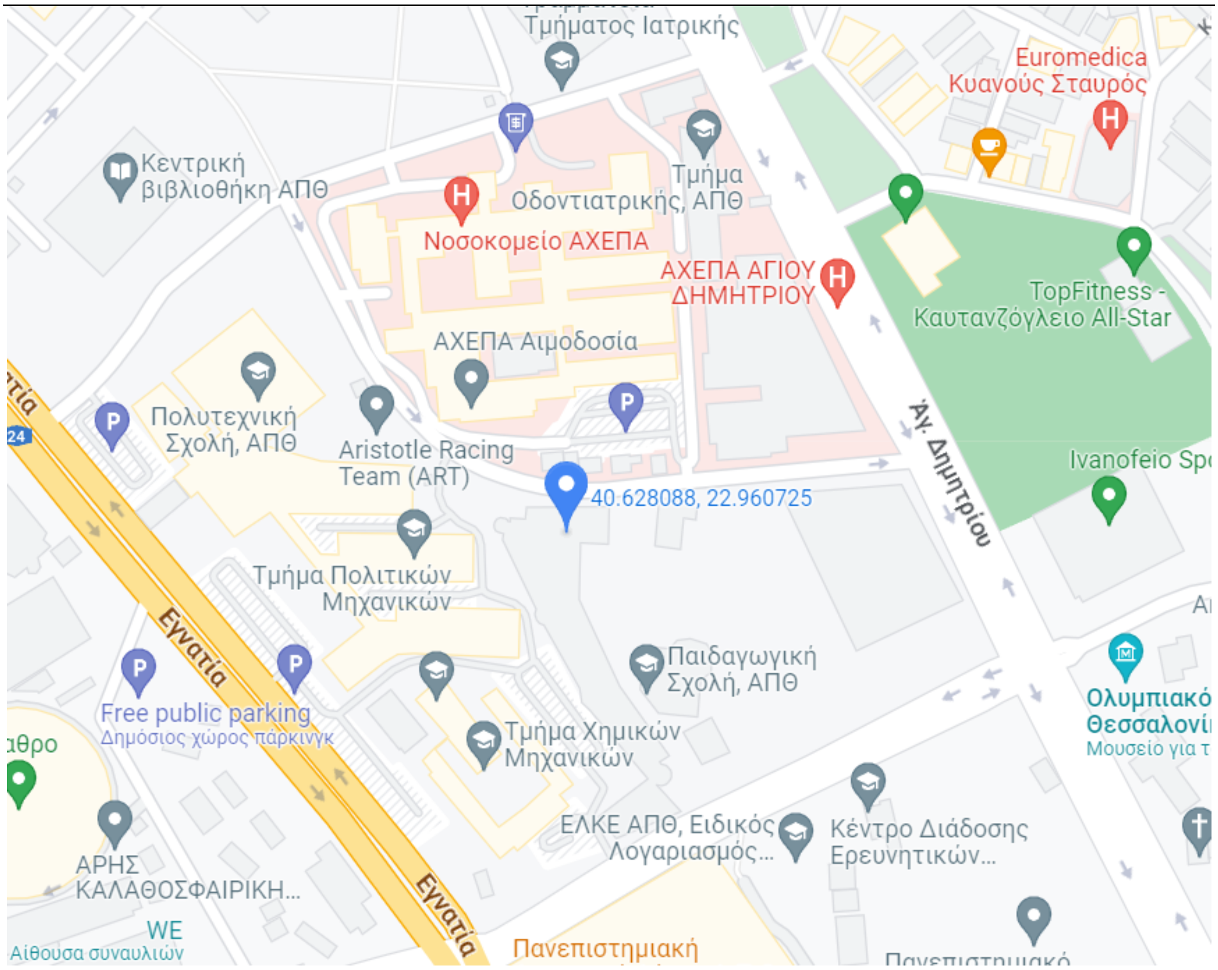


Figure 8. Part of the Aristotle University of Thessaloniki. The blue pointer indicates the location of the building of Hydraulics (Source of the map: google maps)

Since it was shown that there would not be enough water for the system available to be pumped, if the system remained exactly as it initially was, it would be without a point to study the best pumping protocol, how measurements regarding it should be performed and other data regarding the protocol and the pumped water. Thus, our effort was allocated into the following study. This study examines whether an open-loop system with a deeper well would be an acceptable solution in the area, or if it could lead to possible land subsidence and thus endanger the nearby buildings.

It is worth noticing here that the danger of land subsidence has to do, in this case, with the possible groundwater level drawdown below each building. The closer a location is to a well the greater the drawdown is expected to be. Therefore, for each building it is totally acceptable to calculate the drawdown below its point that is the closest to the well. If the drawdown below this point is not too great, then the whole building can be considered to be safe from land subsidence.

Data from the well construction and the initial flow rate

During the drilling that took place for the construction of the well initially, a geological cross-section of the soil at that location was acquired and it is presented in the following figure. In it is shown that the top layer is not a high quality soil. Moreover, below this layer, almost exclusively, clay soil was found.

It is not known whether or not the soil around the whole area is exactly the same. It can be an indication, though, of what could be expected. It is also worth mentioning that both the top layer and the layer of the clay soil are susceptible to land subsidence. Actually, the vast majority of the cases of land subsidence happen upon structures built on clay soil. These facts alone should make the one examining about possible land subsidence in the area alarmed.

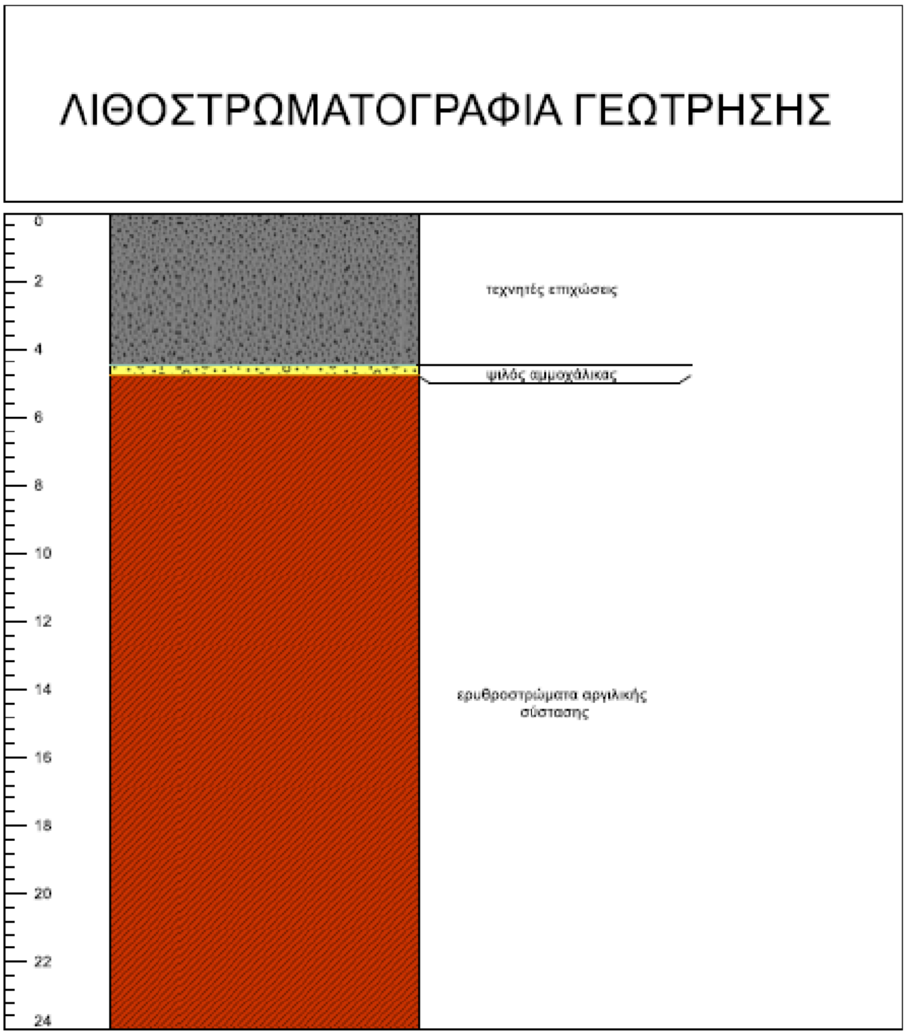


Figure 9. Lithostromatology of drilling.(Department of Geology at Aristotle University of Thessaloniki)

The following figure shows the flow rate from the well that was initially constructed. As it is shown, unfortunately, the well could not sustain the required flow. The pumping test was repeated several days later and the results were the same.

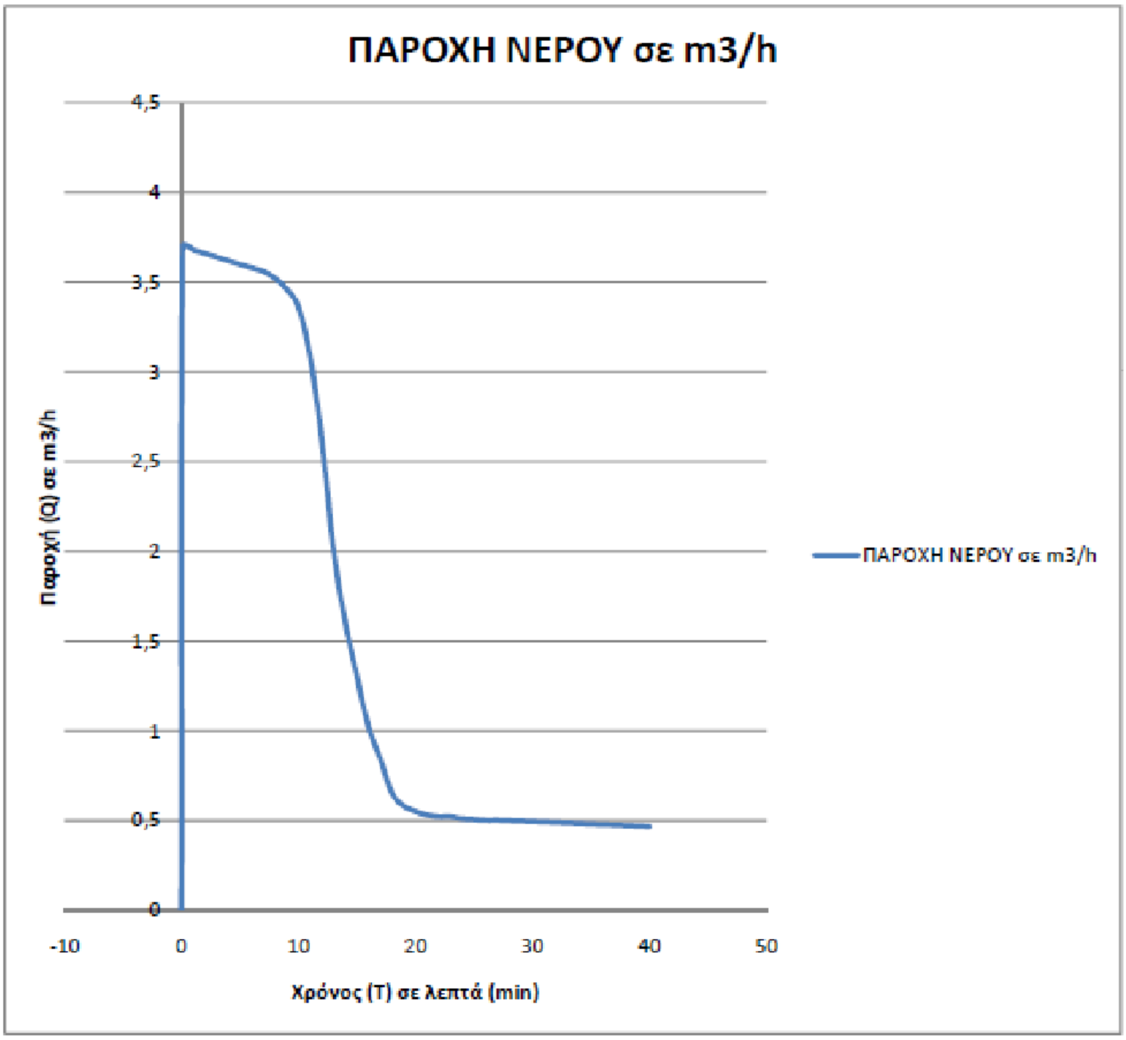


Figure 10. The flow rate diagram from the test that was conducted

Study of possible harms if a deeper well would be constructed

The well, during the initial phase, was constructed in a location close to the building of Hydraulics, at a distance of about 10 meters. This was by design for two reasons. First of all, because the water from the well had to be transported inside the building of Hydraulics, and secondly because there are several other buildings in the area and only certain locations where the construction could take place.

Since this is a densely built area, there are several other buildings in short distance. A very significant drawdown of the groundwater level could possibly affect several of them. The buildings close to the well are the following: a) the building of Hydraulics, b) the new building of the School of Engineering, c) the kindergarten of A.U.Th., d) the main complex of buildings of the School of Engineering, e) the Pedagogical School and f) the AHEPA Hospital. The distance of those buildings to the well is respectively and approximately: 10m, 10m, 30m, 50m, 50m and (from the main buildings of the hospital) 70m.

In order for the drawdown to be estimated at the aforementioned distances from the well a model could be created. Our model is based on the assumption that the soil throughout the whole area where the aquifer is located is uniform and has the same properties. Thus, equation 1 can be used.

Moreover, water was found at about 4 meters below the surface of the ground. After extracting water from the well for some time, there was practically not any water being extracted. The well was created to be 24 meters deep. So, it could be assumed that by extracting the average amount of water per time unit from the well the drawdown around it would be 20 meters. Having this piece of information the value of “T” in equation 1 can be calculated for each different value of “R”. This would be an estimation and the real value of “T” could be smaller, thus the following scenarios were examined for the value of “T” as it is derived in the way previously described and also for the half value of that.

Since the “R” in equation 1 is not known, the calculations were performed multiple times, each time with a different, yet typical value for “R”. What is more, different calculations were performed for different values of the water extracted from the well, the “Q_0”.

It is important to mention here this: for all the following calculations, a drawdown (“s”) greater than or equal to 40m is considered to be dangerous and a drawdown greater than or equal to 30m is considered potentially dangerous.

For R = 500m and Q_0 = 20m^3/h:

The initial calculation of the value of T is:

T = 0.12379m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	100,60	72,35	59,21	59,21

For T' = T/2, it is:

T' = 0.06189m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	201,19	144,69	118,42	101,12

For R = 500m and Q_0 = 10m^3/h:

The initial calculation of the value of T is:

T = 0.12379m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	50,30	36,17	29,61	29,61

For T' = T/2, it is:

T' = 0.06189m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	100,60	72,35	59,21	50,56

For R = 500m and Q_0 = 5m^3/h:

The initial calculation of the value of T is:

T = 0.12379m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	25,15	18,09	14,80	14,80

For T’ = T/2, it is:

T’ = 0.06189m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	50,30	36,17	29,61	25,28

For R = 1000m and Q$_0$ = 20m^3/h:

The initial calculation of the value of T is:

T = 0.13507m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	108,52	82,63	70,60	70,60

For T’ = T/2, it is:

T’ = 0.06754m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	217,05	165,27	141,19	125,33

For R = 1000m and Q$_0$ = 10m^3/h:

The initial calculation of the value of T is:

T = 0.13507m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	54,26	41,32	35,30	35,30

For T’ = T/2, it is:

T’ = 0.06754m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	108,52	82,63	70,60	62,67

For R = 1000m and Q_0 = 5m^3/h:

The initial calculation of the value of T is:

T = 0.13507m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	27,13	20,66	17,65	17,65

For T’ = T/2, it is:

T’ = 0.06754m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	54,26	41,32	35,30	31,33

For R = 2000m and Q_0 = 20m^3/h:

The initial calculation of the value of T is:

T = 0.14636m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	115,23	91,34	80,23	80,23

For T’ = T/2, it is:

T’ = 0.07318m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	230,46	182,67	160,45	145,82

For R = 2000m and Q$_0$ = 10m^3/h:

The initial calculation of the value of T is:

T = 0.14636m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	57,61	45,67	40,11	40,11

For T’ = T/2, it is:

T’ = 0.07318m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	115,23	91,34	80,23	72,91

For R = 2000m and Q$_0$ = 5m^3/h:

The initial calculation of the value of T is:

T = 0.14636m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	28,81	22,83	20,06	20,06

For T' = T/2, it is:

T' = 0.07318m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	57,61	45,67	40,11	36,45

For R = 3000m and Q_0 = 20m^3/h:

The initial calculation of the value of T is:

T = 0.15279m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	118,69	95,83	85,20	85,20

For T' = T/2, it is:

T' = 0.07648m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	237,38	191,66	170,40	156,40

For R = 3000m and Q_0 = 10m^3/h:

The initial calculation of the value of T is:

T = 0.15279m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	59,35	47,92	42,60	42,60

For T’ = T/2, it is:

T’ = 0.07648m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	118,69	95,83	85,20	78,20

For R = 3000m and Q_0 = 5m^3/h:

The initial calculation of the value of T is:

T = 0.15279m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	29,67	23,96	21,30	21,30

For T’ = T/2, it is:

T’ = 0.07648m^2/h.

Thus, it can be calculated:

r (m)	10	30	50	70
s (m)	59,35	47,92	42,60	39,10

By examining the previous numerous cases it is obvious that there is no scenario in which it could be said with certainty that no nearby building would be in danger of land subsidence if a deeper well was constructed in the area and more water was going to be extracted from it. Thus, it would be wiser to reject this solution and the creation of a closed-loop system is best to be chosen.

In addition to the safety concerns, there are a few more reasons why making the well deeper could be disadvantageous. First of all, as the depth from which groundwater is being extracted increases, the energy consumption and, consequently, the operation cost, increases, as well. If it exceeds a certain limit, the operation of the geothermal system is not viable, from a financial point of view. Moreover, there is no environmental benefit anymore, either, except if the electricity is produced from renewable sources, such as photovoltaics. Additionally, the licensing process in Greece, regarding the license of a swallow well, can be too slow (according to our experience).

Consequently, the creation of a closed-loop system was implemented, since it appeared clearly to be the most favorable of the two available solutions.

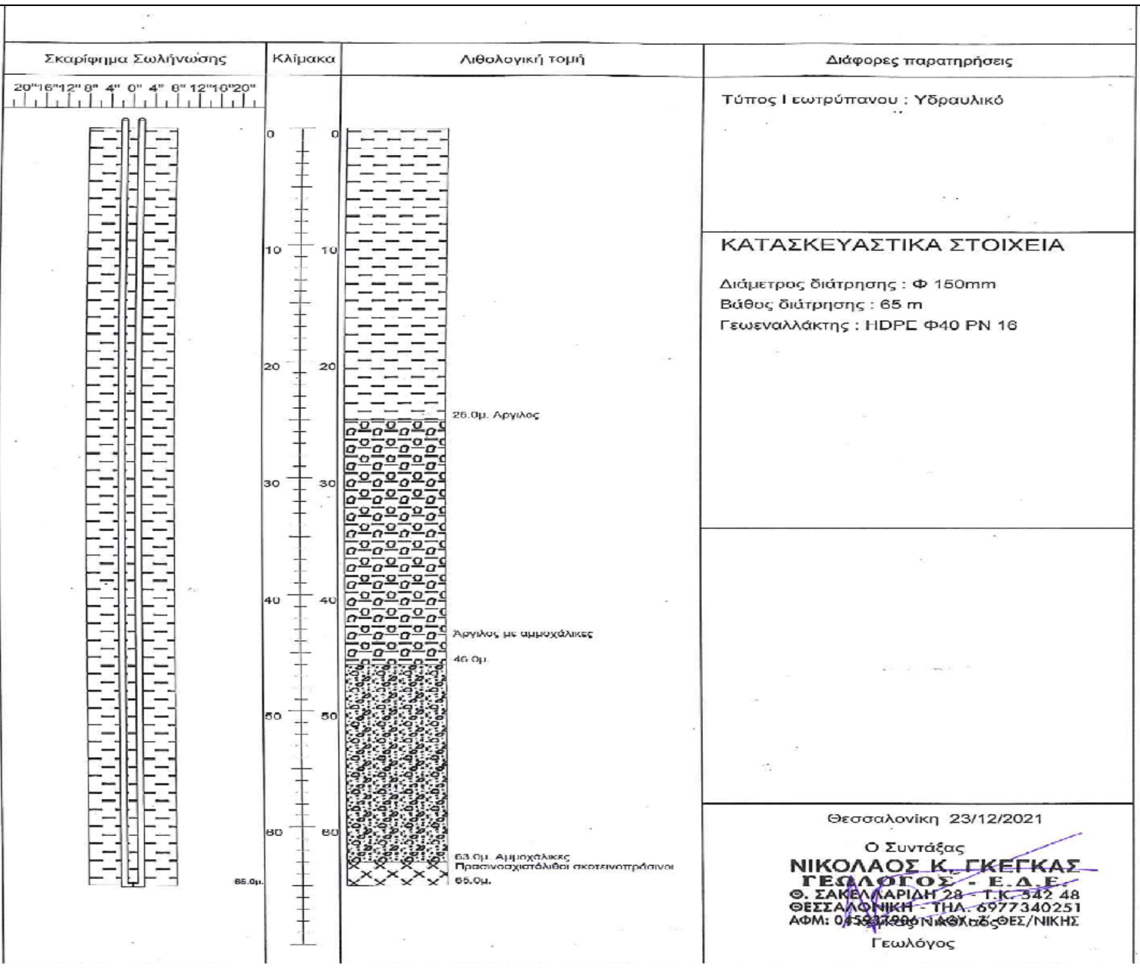
The construction of the closed-loop system

After the construction of a closed-loop system (geo-heat exchanger) was selected, it had to be designed and properly placed in the available area around the building of Hydraulics. The selected area was at the university lot, at a distance of less than 50 meters from the building. The initial plan was to construct 9 vertical boreholes, with a length of 100 meters each. In each borehole a geo-heat exchanger would be placed, consisting of a polyethylene tube U Φ40 PN 16 (SDR 11). In addition, a coaxial heat exchanger, with length equal to 50 meters, would be constructed, in order to compare its efficiency to the classical ones. The locations of the initial plan are shown in figure below.

Figure 11. The locations where the vertical system would be constructed

During the first drillings, a hard rock layer was found approximately at a depth of 65 meters, as shown in the cross-section of the following figure. Penetrating this layer would result in substantial delays and would cause nuisance to the users of the adjacent university installations. For this reason, it was instead chosen to have 14 boreholes constructed, each with a length of 65 meters, instead of 9 boreholes of 100 meter length each. The total constructed borehole length was equal to 960 meters, namely it was roughly equivalent with the planned system.

The boreholes were filled with suitable heat conducting grout (conductivity 1.5W/(m·K), starting from the bottom of each borehole.



Τύπος Γεωτρύπανου : Υδραυλικό

ΚΑΤΑΣΚΕΥΑΣΤΙΚΑ ΣΤΟΙΧΕΙΑ

Διάμετρος διάτρησης : Φ 150mm
Βάθος διάτρησης : 65 m
Γεωεναλλάκτης : HDPE Φ40 PN 16

Θεσσαλονίκη 23/12/2021

Ο Συντάξας
ΝΙΚΟΛΑΟΣ Κ. ΓΚΕΓΚΑΣ
ΓΕΩΛΟΓΟΣ - Ε.Δ.Ε.
Θ. ΣΑΚΕΛΛΑΡΙΔΗ 28 - Τ.Κ. 542 48
ΘΕΣΣΑΛΟΝΙΚΗ - ΤΗΛ. 6977340251
ΑΦΜ: 0[illegible] ΔΟΥ Ζ΄ ΘΕΣ/ΝΙΚΗΣ
Γκέγκας Νικόλαος
Γεωλόγος

Figure 11. Cross-section of a typical borehole and the geological strata

By the aforementioned adaptations the final system was able to be constructed. Thus, the whole system became operational.