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The Hydraulic and Hydrogeochemical Characteristics of Hard-Rock Aquifer in Southern Johor, Malaysia

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Abstract

Malaysia is known as a country with a significant amount of surface water. It has a high amount of annual rainfall. Despite Malaysia's large surface water reserves, increased water demand has made supply scarce. Other sources of water, including ground water, are needed to meet the demand. Nowadays, groundwater exploration in Malaysia has been done extensively to explore the nature of groundwater and its aquifer. The aim of the study is to determine the hydraulic characteristics and the hydrogeochemical characteristics of hard-rock aquifer in Southern Johor, Malaysia. This study will provide information about the nature of the hard-rock aquifer in southern Johor, which will help with groundwater exploration in the future. A well known as SP-TW1 is being drilled in a specific area of Gunung Pulai's southwest. The depth of the drilled well is 126 m. Then, a televiewer survey is done to determine the lithology of the well. A series of pumping tests are also done in the well. After the pumping tests are done, a step-drawdown test, constant discharge test and recovery test are done to determine the hydraulic characteristics of the drilled well. The groundwater is also taken as a sample, and it has been sent to a lab to determine the hydrogeochemistry of the well. Based on the pumping test analysis that has been done, the average hydraulic conductivity of the well is 0.0161 m/d, the average transmissivity is 3.088 m^2/d and the average storativity is 0.95. According to the data plotted, the drilled well is also determined to be a double-porosity aquifer and fractured aquifer. The total dissolve solid recorded is 200 mg/L and the groundwater sample from the SP-TW1 well mainly contains calcium-bicarbonate (Ca-HCO_3) which makes it alkaline.

Keywords: *Groundwater, Hard-Rock Aquifer, Hydrogeochemistry, Pumping Test*

1.0 Introduction

Malaysia is well known as a tropical country with a humid climate. It is recorded that Malaysia received an annual rainfall of 2500 mm to 3000 mm with an average rainfall of 2300 mm/year[1]. The country has significant amount of surface water reserves, including rivers and lakes. In fact, in Malaysia, more than 90% of freshwater resources are derived from surface water[1]. However, water scarcity still occurs due to the population growth in Malaysia. Several factors, such as technological advancement in agriculture and industrialization as well as urbanisation have contributed to water scarcity in Malaysia[2]. Thus, Malaysia is exploring groundwater as a conjunctive water

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resource to cater to the demand. According to Heng[1], the total groundwater available for usage is estimated to be 120 billion m^3. This suggests groundwater has great potential as a conjunctive water resource in the future.

As of now in Malaysia, mainly groundwater is used for agricultural purposes and the country is in the middle stage of development. In order to prove how groundwater and surface water can be used together during the off-season to irrigate paddy and other seasonal crops at Meranti, Kelantan, the Drainage and Irrigation Department (D.I.D.) has successfully completed a pilot project there[3]. Also, water is being developed for irrigation at Kampung Kandis, Bachok, Kelantan, as well as at Banggol Katong, Terengganu, as part of a fishermen resettlement program[3]. Also, recently completed studies suggest that groundwater is used to meet irrigation and domestic water supply demands in the Kedah, Perlis, Kelantan, Kemasin, and Terengganu river basins[4].

In the light of growing water demand and the unreliable supply of surface water (rivers), the people have shifted their attention to groundwater. It's becoming increasingly important to discuss the use and conservation of groundwater in society, in both the public and business sectors[3]. Although it has been an important topic, there is still limited development for groundwater usage in Malaysia, and the reasons are:

- limitation in recognizing the vast potential of groundwater resources,
- the misconception that groundwater utilization is not sustainable,
- minimal information on the groundwater resource, and
- limited local expertise in the field of groundwater management.

It is common for hydrogeologists to view well siting in hard rock terrain as a game of chess. By selecting the right tools and using the right strategies, they should be able to achieve a positive outcome. In reality, this is often a delusion. In groundwater supply investigations, resources are insufficient to adequately characterize the complex nature of hard rocks. Most hydrogeologists have difficulty predicting the hydraulic properties of hard rock aquifers due to their fractured, discontinuous, and incredibly heterogeneous nature. Furthermore, a single prospective borehole's chemical quality cannot also be adequately predicted due to heterogeneous and discontinuous fracture mineralization as well as heterogeneous and discontinuous fracturing[5]. Throughout this paper, the hydrogeochemical properties can differ widely even within a single lithology, largely due to fracture residence times and hydrodynamics that differ from one another[5].

Hard rocks were previously overlooked as a potential source of groundwater. This was due to their limited permeability and expensive drilling costs. However, recent geo-hydrological studies have revealed that some sites produce sustainable yields. Furthermore, rapid down-the-hole hammer drilling procedures have made groundwater research and development work easier[6]. Water well drilling success rates in hard rock areas have also grown as a result of systematic geo-exploration. Table 1 presents, a comparison of the hydrogeological characteristics of granular and hard (fractured) rock aquifers.

Hard rocks have a lower permeability and are less porous. Boreholes in weathered and fractured rock aquifers are widely known to fail more frequently and produce low specific yields, according to this explanation. The weathered zone overlies a fractured layer in most hard rock aquifers, which are considered dual aquifer

Table 1. Comparison of granular and fractured hard rock aquifers[6]

Aquifer Characteristics	Aquifer Type	
	Granular Rock	**Fractured Rock**
Effective porosity	Mostly primary	Mostly secondary through joints, fractures etc.
Isotropy	More isotropic	Mostly anisotropic
Homogeneity	More homogeneous	Less homogeneous
Flow	Laminar	Possibly rapid and turbulent
Flow predictions	Darcy's law usually applies	Darcy's law may not apply, cubic law applicable
Recharge	Dispersed	Primarily dispersed with some point of recharge
Temporary head variation	Minimal variation	Moderate variation
Water quality variation	Minimal variation	Greater variation

systems. In this sort of aquifer, there is a scarcity of data on the characteristics that determine secondary permeability. Furthermore, little is known about the occurrence, distribution, and recharge of groundwater. All of this makes it difficult to choose a modelling method for analyzing hydrogeological issues. Because rocks are less porous and permeable, the rocks that are drilled and gathered from the well may also be devoid of water. The procedure of collecting boulders from a hard rock aquifer will take time and money, making groundwater exploration in this type of aquifer more difficult.

Hard rock aquifer hydraulic parameters can be estimated both in the lab and in the field. However, values derived from rock samples in the laboratory are not representative of the formation. In Table 2, a list of commonly used field methods is listed. The method chosen will depend on the purpose of the research. Packer tests, slug tests, and tracer tests are preferred for small-scale problems, such as water seepage into mines and tunnels and contamination transport. For detailed investigations of local scales, cross-hole pneumatic injection tests are recommended. The pumping test method should be utilized for estimating aquifer parameters as well as groundwater development and management on a regional basis.

In hard rocks, structural analysis is critical in the planning of pumping tests and the interpretation of test results because the geometry of the fractures has a considerable impact on flow characteristics and pumping test data.

In tropical region such in Malaysia, most of the hard rock aquifers are categorized as unconfined aquifers[7]. As an indication of the best model to use to interpret the data collected, a diagnostic plot should be compared to a set of typical diagnostic plots like those depicted in Figure 1. The diagnostic plot in Figure 1(b) shows that the unconfined aquifer has the same characteristics as the double porosity aquifer. A double-porosity model can be used to represent the behaviour of fractured aquifers for regional groundwater investigations. A detailed explanation of the double porosity model has been provided by Streltsova-Adams[8] and Gringarten[9]. Three types of distributions of matrix blocks are examined, horizontal slabs (strata type), spherical blocks, and cubes. The model assumes two regions, porous block, and fracture, each having different hydraulic and hydraulic-mechanical characteristics. The alternative aquifer-aquitard system is equivalent to the fissured medium with horizontal fractures[10]. The block consists of fine pores that are separated by fractures. Fluid is supplied to fractures via these blocks, which act as uniformly distributed sources of fluid. Researchers have also employed such a methodology to analyze fractured oil reservoirs using some modifications[11].

Hydrogeochemistry also differs significantly from borehole to borehole within a hard rock aquifer over distances of only a few metres, depending upon whether a transmissive fracture is encountered. In addition, fracture walls vary in their ability to interact with water and rock, so water rock composition is affected, among other factors, by fracture mineralogy (surface area to volume, residence time) and fracture minerals. Groundwater flows mostly through fractures in crystalline (igneous and metamorphic) rocks. As a result, there is less contact area between water and the rock matrix than in porous media. Furthermore, crystalline rocks frequently contain silicate minerals, which have poor solubility. As a result, the salinity of groundwater in these rocks is often low (TDS < 500 mg/l). Groundwater in arid and semi-arid regions, on the other hand, may have a high salinity.

This paper explores some aspects of the philosophy of sitting successful wells in hard rock aquifers and suggests a way to characterize such heterogeneous aquifers based on their hydrogeochemistry as well as their hydraulic parameters. According to the present study, ‘hard rock

Table 2. Field test methods for estimation of hydraulic characteristics of hard rock aquifers[6]

Purpose of Investigation	Size of area under Investigation	Distribution of fractures	Test Method
Geo-technical investigations; mine drainage; waste	A few km^2	Random	Packer (Lugeon) test, slug test, tracer injection test
		Systematic fractures of 1, 2 or 3 sets	Modified packer test, cross-hole hydraulic test; tracer injection
Groundwater development; water	>100 km^2	Random and closely	Pumping test
Geothermal and petroleum reservoirs	A few km^2	Random	Well interference test, tracer injection test

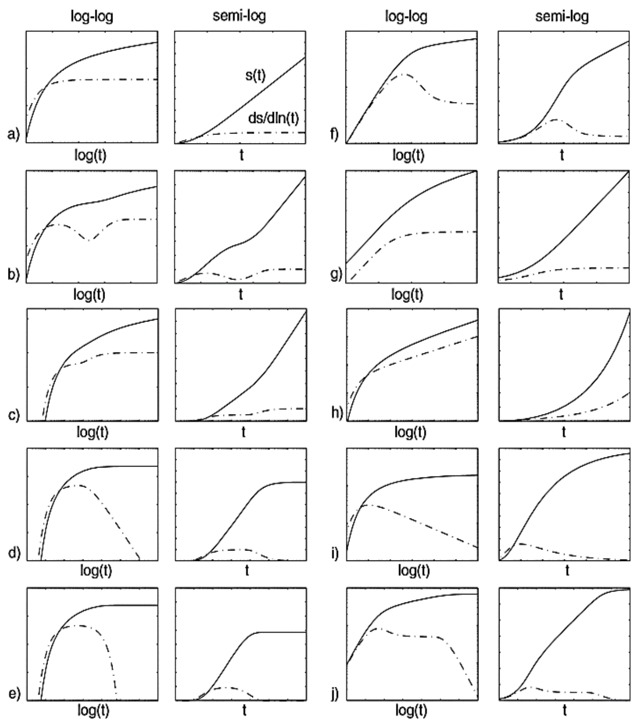


Figure 1. General diagnostic plots in hydrogeology: (a) Theis model: infinite 2D confined aquifer; (b) double porosity or unconfined aquifer; (c) infinite linear no-flow boundary; (d) infinite linear constant head boundary; (e) leaky aquifer; (f) well-bore storage and skin effect; (g) infinite conductivity vertical fracture; (h) general radial flow of non-integer flow dimension smaller than 2; (i) general radial flow model of non-integer flow dimension larger than 2; (j) combined effect of well bore storage and infinite linear constant head boundary[12].

aquifers' comprise crystalline metamorphic or igneous rocks (basalt, slate, granite, schist, gneiss, etc.) beneath a large area in Johor.

2.0 Geological Settings

Located on the southern end of the Malay Peninsula, Johore Bahru-Kulai is incorporated into Malayan New Series map sheet 130, covering some 470 square miles. From east Burma and west Thailand to west Malaysia and possibly even into Borneo, this area forms an elongate orogenic belt that extends southward into the Riau-Lingga archipelago[13].

A granite batholith occupied 70% of the map area. In the west and southwest, consolidated stratified rocks, the Jurong Formation, are found. Gunung Pulai Volcanic Member, a volcanic rock, consists of mainly tuffs, which make up the lower part of the formation. There are several detrital strata in its upper portion, known as the Bukit Resam Clastic Member, that are mostly composed of

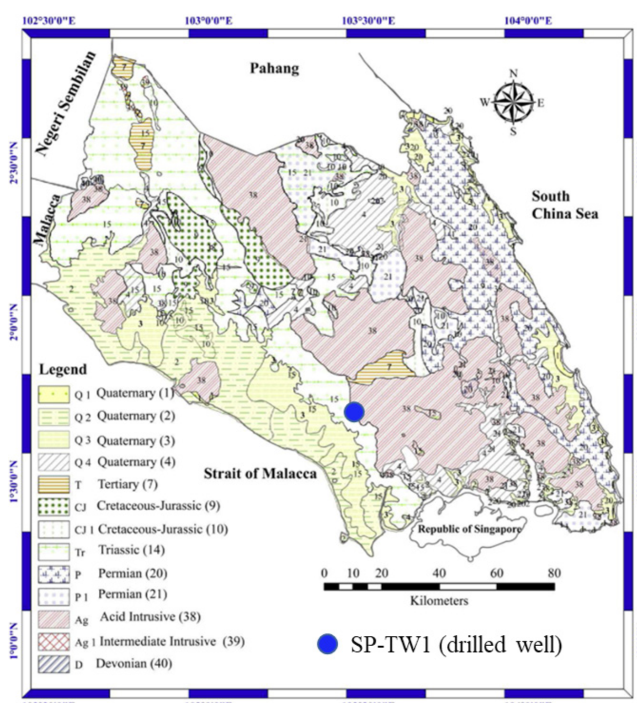


Figure 2. Geological mapping of Johore state[14].

shale and stone. Figure 2 depicts the geological setting of Johore state[13].

A major form of volcanic material in the Gunung Pulai Volcanic Member is tuff or rhyodacitic, although agglomerates, tuffs, and lava of dacitic to andesitic character are also present, as are minor amounts of clastic sediments intercalated with the volcanic strata. Although the Bukit Resam Clastic is poorly exposed, it can be seen to be primarily made up of shale and sandstone changes, with minor layers of siltstone and conglomerate, as well as a few remnants of volcanic tuff[13].

3.0 Methods

3.1 Pumping Tests

Aquifer test or pumping test was carried out mainly to determine the hydraulic characterization of the drilled well. Hydraulic parameters such as transmissivity, storativity and hydraulic conductivity can be determined by running the pumping test of the well. The tests that will be included in this study are the step-drawdown test, the constant discharge test and the recovery test. These tests are vital to obtain the well efficiency as well as the recovery rate of the well.

3.1.1 Calibration Test

A calibration test is performed to determine the pumping flow rate as well as to identify any technical challenges that may develop during the pumping test setup. The pump will start and run momentarily during this time to regulate the flow rate. The water level can fully restore to its usual level once the pump has been switched off before the pump is turned back on. The pumping test will take place the following day.

3.1.2 Step-Drawdown Test

A step-drawdown test is performed while the rate of discharge from a well is increased incrementally. In the step-drawdown test, well loss coefficients B and C are calculated both linearly and non-linearly. Based on these coefficients, it is possible to estimate the actual water level drawdown within a pumping well in response to pumping and also to estimate the efficiency of the well.

The step-drawdown test consists of four to five discharging steps lasting 90 to 120 minutes each, with each stage measuring the well's drawdown. The drawdown is measured at predetermined times. At the start of each stage, drawdown is usually measured at extremely short intervals, progressively increasing the intervals as time progresses. The measurements are recorded on tabulated sheets.

3.1.3 Constant Discharge Test

Following the step-drawdown test, the pumped well is allowed to rest for sufficient time to allow the water level to recover to its pre-pump level. A fixed or constant pumping rate will be used after the step-drawdown test has been recovered. The pumping rate will be based on the results of the step-drawdown test. The constant discharge test is conducted over several days, usually over 72 hours. Typically, however, the exact duration is determined by knowing the type of aquifer, since unconfined aquifers generally require 3 days or longer to stabilize. During the constant discharge test, drawdown measurements are continuously taken in the pumped well and observed by the observation piezometer, and these measurements are recorded on a tabulated sheet.

3.1.4 Recovery Test

Immediately following the constant discharge test, the pump is shut down and the recovery test commences. The recovery test measures the rise of the water level in the pumped tube well at fixed time intervals, which are recorded on another tabulated sheet.

3.2 Data Processing and Analysis

The drawdown data was analyzed using "AquiferTest Pro 6.0 Version 2016", an easy-to-use pumping test and slug test data processing software. AquiferTest Pro offers a user-friendly, customizable environment with automatic type curve fitting to a data collection. Data is manually fitted to the type of curve using parameter controls based on our understanding of the geologic and hydrogeologic setting, where an automatic curve fit is not possible.

AquiferTest Pro uses a theoretical solution, the Theory of Superposition, for its analytical solutions. Starting with a standard solution, the best results are obtained by applying corrections in a sequential manner.

If the aquifer system (i.e. aquifer plus well) were perfectly understood, calculating hydraulic characteristics would be quite simple. In most cases, this isn't the case, therefore evaluating a pumping test boils down to detecting an unknown system. Identification of the aquifer system is based on models, the characteristics of which are assumed to reflect those of the real aquifer system[15].

3.3 Hydrogeochemical Properties

Well sampling of groundwater should be done with caution, and it's best to treat samples as well waters rather than groundwaters when interpreting results. There are many different methods to sample the water, including purging to remove stagnant water. Low-flow sampling could also be used for water sampling (e.g., Puls and Barcelona[16], Lerner and Teutsch[17,] and McMillan, *et al.,*[18].

A water sample taken from the SP-TW1 well is then sent to a laboratory for analysis. The sample is analysed using atomic absorption spectrometry. For the tube well, the Total Dissolve Solid (TDS), pH, turbidity, colour, hardness and conductivity are measured.

4.0 Results and Discussion

4.1 Pumping Tests

The step-drawdown test, the constant discharge test, and the recovery test were all part of the pumping test programmes for the study area. The pumping test was conducted from May 7th to 10th, 2020, using a Grundfos SP17-6 submersible pump with a maximum capacity of 17 m^3/hour and a head of 60 meters.

The submersible pump was installed 73.0 meters below earth, and 50mm diameter riser pipes were subsequently linked to the submersible pump. For measurement, a 50 mm gate valve was attached to the riser pipe in order to regulate flow rate. The riser pipes were then directed to a 90° V-Notch tank. To determine the well capacity and pumping rate for the step-drawdown test, a calibration test was conducted for two hours after the pump installation and other setup had been completed.

4.1.1 Step-Drawdown Test

On May 7, 2020, step-drawdown test has been done consists of five (5) discharging rates which are 2.43m^3/hour, 4.90m^3/hour, 7.43m^3/hour and 12.24m^3/hour and for each steps took around 90 minutes. The initial static water level was recorded at 3.74m below ground level and the final drawdowns for each step were 11.69m, 19.06m, 33.19m, 54.12m and 65.86m respectively. The data for step-drawdown test was plotted in Figure 3.

4.1.2 Constant Discharge Test

On May 8th-10th, 2020, the constant discharge test was carried out for 48 hours after the step-drawdown test was completed. According to the results that have been collected for the step-drawdown test, the pumping rate was set at 8.50m^3/hour for the constant discharge test. Static water level was initially 4.22 meters below ground level during the constant discharge test, and after 48 hours of continuous pumping, water levels reached 55.55 meters, with a total drop of 51.33 meters. The derivative analysis of the constant discharge test is depicted in Figures 4 and 5.

According to the pumping data obtained, the well can be classified as a double-porosity aquifer or a fractured aquifer. This is because Figures 4 and 5 are compared to the previous study by Renard, *et al.,* (2009)[12] as in Figure 1 shows the same plot characteristic. The well also can be considered as fractured aquifer due to high well efficiency and high recovery and discharge rate. This is due to the nature of the aquifer, which has four (4) fractured zones. Each of the fractured zones has high transmissivity and hydraulic properties.

According to the analysis in Figure 6, using the double-porosity equation, the average transmissivity, T is 2.01 m^2/day, the hydraulic conductivity, K is 0.016 m/day and the storage coefficient, S_c is 0.99.

According to the analysis in Figure 7, using the Moench Fracture Flow equation, the average transmissivity, T is 2.05 m^2/day, the hydraulic conductivity, K is 0.0163 m/day and the storage coefficient, S_c is 0.93.

According to the analysis in Figure 8, using the Theis equation, the average transmissivity, T is 2.05 m^2/day, the hydraulic conductivity, K is 0.0163 m/day and the storage coefficient, S_c is 0.93.

4.1.3 Recovery Test

A recovery test was conducted immediately following the Constant Discharge Test. The Recovery Test lasted 330 minutes after the pump was shut off. The data from both wells are plotted, and then Theis (1935)[19] recovery solution is used to calculate transmissivity, as shown in Figure 9. Using Theis Recovery analysis, the average Transmissivity, T recorded is 2.0 m^2/day and the Hydraulic Conductivity, K recorded is 0.0159 m/day. Figure 10 shows the graph of time-drawdown for constant rate and recovery test vs. time for SP-TW1. The initial residual drawdown was 51.33m, and after 330 minutes, the residual drawdown was 8.90m, resulting in an 83.99% recovery.

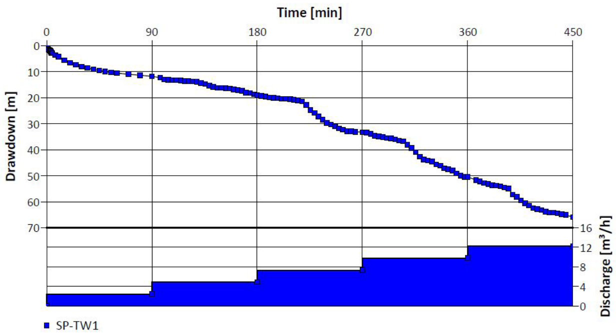


Figure 3. Time-drawdown and discharge rate for step-drawdown test at SP-TW1.

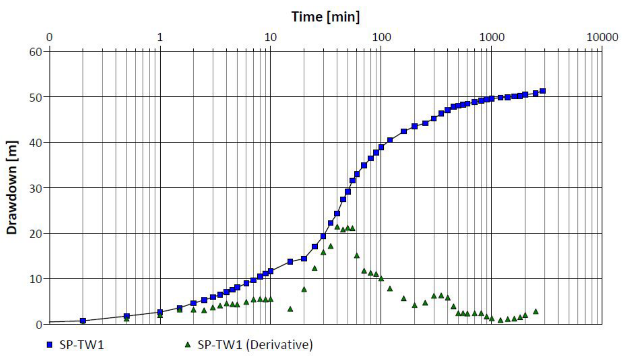


Figure 4. Diagnostic plot (log t vs. s) of the derivative analysis (green) of the pumping test data of SP-TW1.

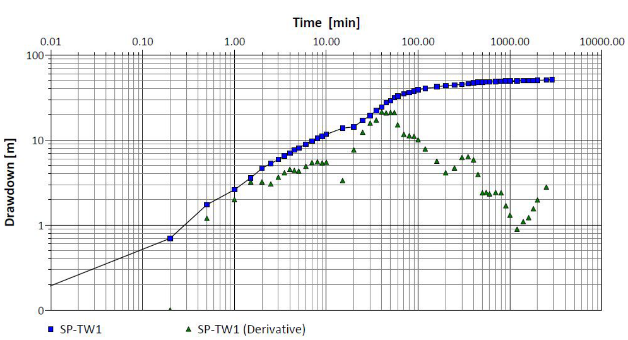


Figure 5. Diagnostic plot (log t vs. log s) of the derivative analysis (green) of the pumping test data at SP-TW1.

4.2 Hydrogeochemistry Properties

In general, no significant changes were detected for the major ion parameters. The results of major ion analysis for the SP-TW1 well as well as the surface water sample (SW1) were plotted in a Piper–Trilinear Hydrogeochemical Diagram for the purpose of water phase classification and hydrogeological interpretation. The diagram shows that the groundwater sample from the SP-TW1 well mainly

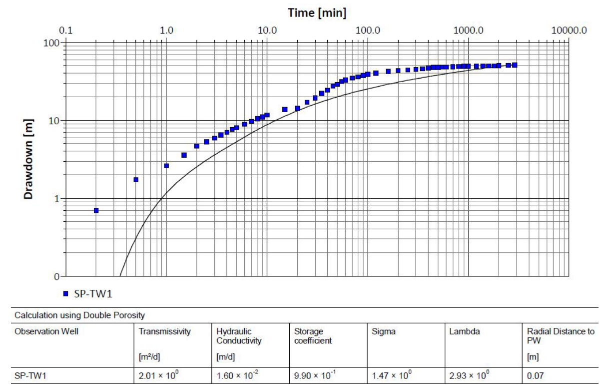


Figure 6. Analysis and evaluation of pumping test data for SP-TW1 using Double Porosity analysis.

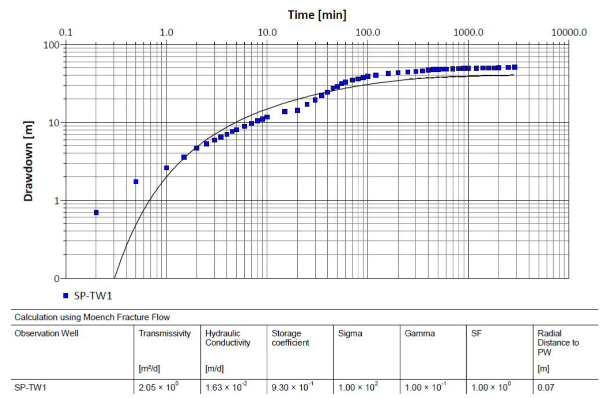


Figure 7. Analysis and evaluation of pumping test data for SP-TW1 using Moench Fracture Flow analysis.

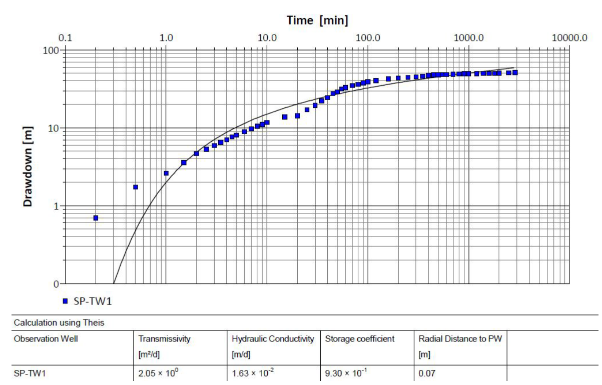
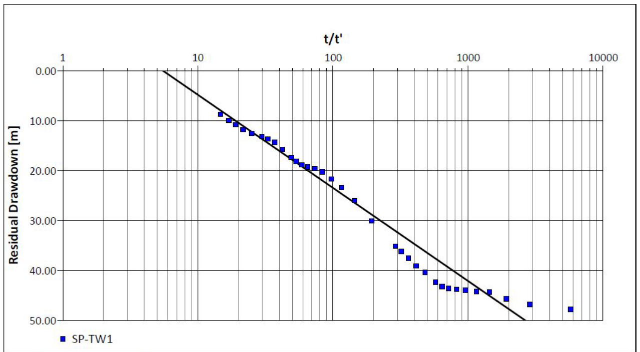


Figure 8. Analysis and evaluation of pumping test data for SP-TW1 using Theis's analysis.

contains calcium-bicarbonate (Ca-HCO_3), while the surface water sample from SW1 from a nearby tributary mainly contains a calcium-sodium-bicarbonate-chloride mixture (Ca-Na-HCO_3-Cl). Based on the classification in the Piper–Trilinear Hydrogeochemical Diagram,



Calculation using THEIS & JACOB

Observation Well	Transmissivity [m²/d]	Hydraulic Conductivity [m/d]	Radial Distance to PW [m]
SP-TW1	2.00×10^{0}	1.59×10^{-2}	0.07

Figure 9. Analysis and evaluation of pumping test data for SP-TW1 using Theis Recovery solution.

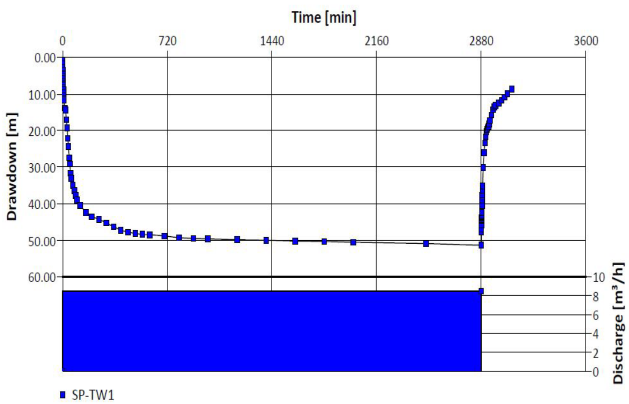


Figure 10. Graph of time-drawdown for constant rate and recovery test vs. time.

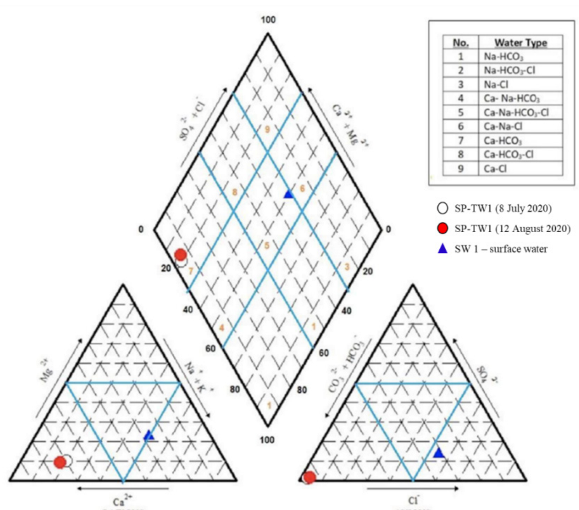


Figure 11. Piper - Trilinear Diagram for SP-TW1 well.

the groundwater source from the SP-TW1 well can be considered fresh groundwater. It is believed that the high topographic area in Gunung Pulai is the groundwater recharge area. In the groundwater recharge area, minerals such as calcite and feldspar will be dissolved by carbonic acid formed as a result of the recharge from rainwater, which in turn produces calcium and bicarbonate ions. Surface water samples are believed to be influenced by the nearby sea due to the location of the site not far from the shoreline. This is indicated by the slightly high chloride content of the well water samples. Generally, the tributaries near the site receive direct recharge from rainfall, including surface water runoff and discharge from shallow groundwater around the area.

The groundwater sample from the SP-TW1 well showed a high Total Dissolve Solid (TDS) value (200mg/l) compared to the TDS value of the surface water value, which was much lower (30mg/l). This shows that the groundwater for well SP-TW1 gets groundwater recharge from rock aquifers in distant areas, causing an increase in the mineral content in them. Significant differences were also found for the pH values, where the surface water is acidic compared to the groundwater from the SP-TW1 well, which is alkaline. The groundwater for SP-TW1 well sample plot in Figure 11 also shows that the plot points are at almost the same position for both of the sampling dates. This indicates that the groundwater sample from the SP-TW1 well did not undergo significant quality changes during that time period.

5.0 Conclusion

In conclusion, the drilled well, SP-TW1 has an average 0.0161 m/d hydraulic conductivity, 3.088 m^2/d transmissivity, and 0.95 storativity value for its hydraulic characteristics. The well is also classified to be in a double porosity aquifer and a fractured aquifer when the results obtained are compared to the previous study. The total dissolve solid for the groundwater of the well is relatively low as the total dissolve solid is 200 mg/L, lower than the drinking water standards set by the Ministry of Health Malaysia. Other than that, the major ions contained in the groundwater sample is calcium carbonate ($Ca\text{-}HCO_3$). This shows that the groundwater is alkaline. Further study would suggest factors affecting the hydraulic parameters of the well and the hydrogeochemistry of the well. Also, an indepth study of the well would also determine whether the well is suitable to be exploited and whether the groundwater produced from the well is suitable to be made as drinking water.

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