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Original Article

Geophysical logging for groundwater investigations in Southern Thailand

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Abstract

In Thailand the Department of Groundwater Resources is drilling to find vital aquifers. Sometimes groundwater formations cannot be identified clearly during drilling; therefore, geophysical logging was applied after drilling and before casing. The tool used here is measuring nine parameters in one run, natural gamma ray, spontaneous potential, single point resistance, normal resistivity (AM 8”, 16”, 32”, and 64”), mud temperature and resistivity. Cutting was used to support the geophysical interpretations. In many cases the groundwater bearing zones could be clearly identified. The combination of and the possibility choosing from nine parameters measured provided the necessary data base to identify groundwater bearing zones in different environments. It has been demonstrated that in different wells different tools are favorable than others. Based on the conclusions of this study geophysical logging in groundwater exploration is recommended as a normal standard technique that should be applied in every new well drilled.

Keywords: geophysical logging, groundwater, aquifer, Songkhla, Phatthalung

1. Introduction

Groundwater is an important natural resource and vital for many people as their only source of daily (drinking) water. However, groundwater resources are unequally distributed in the world due to differences in the geological setting, especially in the shallow part of the subsurface, the first few hundred meters, where often the main groundwater resources are located.

The groundwater occurrence in the subsurface is mainly related to the distribution of permeable layers, e.g. sand, gravel, unconsolidated, fractured or weathered rocks, and impermeable or low-permeable layers, e.g. clay, consolidated sediments or solid rocks. The key physical properties used to describe these permeable and impermeable layers are porosity, permeability or hydraulic conductivity (e.g. Deming, 2002). Porosity (Φ) describes the percentage of pore space between the grains or minerals of a sediment or rock, which can be filled with air or with (ground) water, usually in percent or part of 1. Permeability (k) describes the ability of a rock or sediment to transmit a fluid or gas through its pore space, either in the old unit of darcy or SI unit of m^2. The hydraulic conductivity (kf) has the dimension of a velocity (m/s) and it describes the permeability only for the medium water with its defined viscosity and density. Hoelting (1989) provides a hydrogeological classification based on hydraulic conductivity. High permeable layers have a kf–value of more than 10^{-4} m/s, permeable between 10^{-6} and 10^{-4} m/s, and both are often labeled aquifers. Low permeable layers have a hydraulic conductivity in the range from 10^{-8} to 10^{-6} m/s, and very low permeable ones have a kf–value below 10^{-8} m/s. However, the resulting hydraulic conductivity can be to some extent related to different materials, given here in the order of decreasing kf–value: clean gravel > coarse sand > medium sand > fine sand > silty sand > clayey sand > clay (after Hoelting, 1989). Layers with mainly clay content are often considered impervious in hydrogeological investigations.

For the investigation of groundwater resources surface geophysical methods are the first choice as they can

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delineate areas with higher groundwater potentials and also to some extent can provide depth estimates of the aquifers. To achieve this sufficient contrast in the petrophysical properties between the aquifer and the layers above and below is required (e.g. Ellis and Singer, 2008). The main properties utilized in groundwater exploration are seismic velocities, related to elastic properties and density, electrical conductivity, respectively resistivity, and the dielectric constant. The related geophysical methods are seismic refraction and reflection, a wide range or resistivity methods, among them vertical electrical sounding (VES) and self–potential (SP) measurements, and a variety of electromagnetic (EM) methods. For an overview and also details see Telford *et al.* (1993).

After a site with potential groundwater has been mapped based on the surface geophysical investigations usually drilling is the next step in order to exploit the resources. Not always is the expensive and time consuming drilling process successful, because the subsurface layers encountered with the drilled hole provide no or very low groundwater yields. Low to medium yields can still be a viable source of water for rural communities, but these are often associated to thinner groundwater bearing layers (thickness less than 1–2 m), which hardly can be identified during the drilling process. Higher yield layers will significant produce groundwater outflow into the well and thus can be identified easily during drilling. However, in order to utilize any groundwater layer the borehole has to be stabilized and prevented form collapsing using casing, usually PVC pipes with perforation (also called screens) used at the depth interval of the aquifers and non–perforated ones for the depth sections with no aquifers. By this the groundwater can flow into the well and can be pumped out for further use. A problem here is that unidentified thinner aquifer layers with lower to medium yield might be cased with non–perforated pipes and by this will not be utilized (see Delleur, 2000).

Geophysical logging methods provide an additional toolbox to identify groundwater bearing layers in the subsurface once a borehole is drilled. In general, a tool comprising of several measurements devices is lowered into the borehole and continuous readings of physical values are made and sent via the cable to the surface unit. The interpretation of such data allows a better identification of the subsurface layers regarding groundwater presence and also of thin layers, which often cannot be identified during surface geophysical methods or drilling. With the knowledge of layer type and depth the setting of the casing can be improved and by this the maximum possible yield achieved (see Delleur, 2000).

In Thailand the Department of Groundwater Resources (DGR), is the main government body for the exploration, exploitation and management of groundwater resources. In the southern provinces of Phatthalung and Songkhla the DGR encountered the problem of wells drilled with low to medium yield where the aquifer layers could not be identified during the drilling process. The geophysical logging system from the Geophysics Research Center at the Prince of Songkla University in Hat Yai was used to investigate a number of boreholes. The paper describes the technology, methodology and the results of these investigations and provides conclusions and recommendations for further work.

2. Methodology

2.1 Geophysical logging

The work was in cooperation with the Regional Office of the Department of Groundwater Resources in Songkhla. DGR drilled the wells and usually shortly after drilling the geophysical logging was performed using an MGX II logger from Mount Sopris, U.S.A. The probe, also called tool, comprises nine parameters measured at the same time, with more details given by Rider (2002) and Ellis and Singer (2008):

(1) Natural gamma ray (Gamma)

Three naturally occurring radioisotopes have decay chains and modes involving the emission of gamma rays, specifically ^{40}K, ^{238}U and its daughter products, plus ^{232}Th and its daughter products. The energy spectrum of these decays is concentrated between 0.2 and 3.0 MeV. A natural gamma log records total decay events across the gamma energy spectrum. Results are reported in CPS units (counts per second) (Belknap *et al.*, 1960; Scott Keys, 1990).

(2) Spontaneous potential (SP)

Spontaneous potential logs are a record of the natural potential developed between borehole fluid and the surrounding rock materials. The spontaneous potential log is a graphic plot of small differences in voltage, measured in millivolts (mV) that develop at the contacts between the borehole fluid, the shale or clay and the water in the aquifer. Shale baseline readings against shale/clays formations are relatively constant and are referred as 'shale baseline'. Opposite permeable formations the SP curve typically shows deflections to the left (negative SP) or to the right (positive SP) of shale-base line depending upon the relative salinity of the drilling mud and formation water.

(3) to (6) Normal resistivity (R 8, 16, 32, 64)

Normal resistivity (R) curves are derived from a four electrode system, using two current electrodes, A and B, and two potential electrodes, M and N. As only two electrodes, A and M, are effective in measuring the apparent resistivity the normal devices are sometimes called the two electrode method. Spacing between electrode A and M gives the name of the four normal curves, the 8-inch, 16-inch, 32-inch, 64-inch normal. A and M are relatively close together, whereas B and N are not only far from each other, but are also distant from the electrode group AM. This means that the apparent resistivity is determined primarily by the potential of the measuring electrode M. Resistivity values are shown in ohm–m.

(7) Single point resistance (SPR)

Single point resistance devices measure the resistance of the subsurface layer between a downhole electrode (in the tool) and a surface electrode. The actual measurement is a measurement of voltage between the electrodes using a constant current (e.g. Guyod, 1952).

(8) Fluid temperature (Temp)

The fluid temperature log is a tool for measuring the borehole temperature, where the sensors attached to the tool continuously measures temperature as the tool travels down the well (Ziagos and Blackwell, 1981; Swanberg *et al.*, 1988; Bartolino and Niswonger, 1999).

(9) Fluid resistivity (Fres)

The fluid resistivity tool measures continuously the resistivity of the drilling fluid in an open borehole (Scott Keys, 1990).

Logging was performed when the tool was moving first DOWN the borehole and then again in the UP mode, moving from the bottom to the surface. Usually logging is done in the UP mode due to a stable tool configuration (pull force opposite gravitational force), but the fluid temperature and fluid resistivity tool as well as the SP tool are sensitive to changes created by the downhole movement of the tool, and therefore DOWN measurement was performed also (Scott Keys and MacCary, 1971).

As the logging was done shortly after drilling the cutting samples were available at the drilling site, usually in 1 m intervals. A detailed description of the cutting samples was done before or after the logging. Together with other relevant parameter these information were recorded in a logging sheet for each hole.

The first interpretation of the logging data was done directly after logging with WellCAD program, using all available data and information. The analysis of groundwater bearing layers was used by the drilling crew, which was waiting at the site during logging, to set the screens of the borehole casing, so that the groundwater can flow into the well.

2.2 Data interpretation

The normal resistivity data consist of four single data, with the only difference in the spacing between the current (A) and voltage (M) electrode. With increasing spacing the depth of investigation is increasing twice (2AM). However, if the resistivity of the mud filtrate (Rmf) is equal the formation water resistivity (Rf). If Rmf is smaller than Rf, a typical situation in groundwater logging, then the depth of investigation is getting smaller for all different spacings. With increasing depth of investigation, the normal resistivity tool is measuring first the flushed zone, then the invaded zone, and with the larger AM the un-invaded zone (Figure 1 and 2). The boundaries between these zones are dynamic, as they depend on the initial permeability of the formation. How much mud filtrate can move into the flushed zone with the related resistivity change depends on the initial porosity and permeability. The resistivity values itself depend also on the lithology (e.g. shale or sand) and the quality of the formation water, chemically expresses as the amount of total dissolved solids (TDS).

An important first step in the interpretation of the spontaneous potential data is whether a shale/clay baseline can be established. If this is not possible any further analysis and interpretation is more difficult and uncertain. If a baseline can be established any deflection to the left indicate a permeable groundwater bearing zone, usually a sand or sandstone. Further, the SP deflections are correlated with normal resistivity data. If a deflection corresponds with in increase in resistivity is indicates fresh groundwater with lower TDS, whereas a SP deflection correlates with no changes in R is likely an indicator for salty groundwater or groundwater with higher TDS.

The single-point resistance (SPR) log provides single resistance data along the borehole. As the vertical resolution of the R log is limited depending on the AM-spacing, the SPR log is a better tool for the identification of thin beds with different resistivity. Further, it gives through its absolute value also information about the lithology.

The gamma ray log measures as a passive tool the natural emission of gamma rays by a formation. The emission depends on the mineral content and the amount in the rock or sediment. In particular, shale usually emits more gamma rays than other sedimentary rocks, such as sandstone, gypsum, salt, coal, dolomite, or limestone.

The fluid resistivity log (Fres) is a direct measurement of the resistivity of the borehole fluid (mud resistivity, Rm) with depth. A fluid resistivity log reflects the changes in the dissolved-solid concentration of the well water, possible from

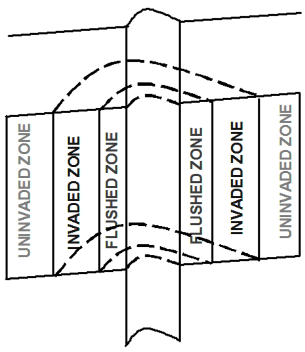

Figure 1. Flushed, invaded, and univaded zone around a borehole.

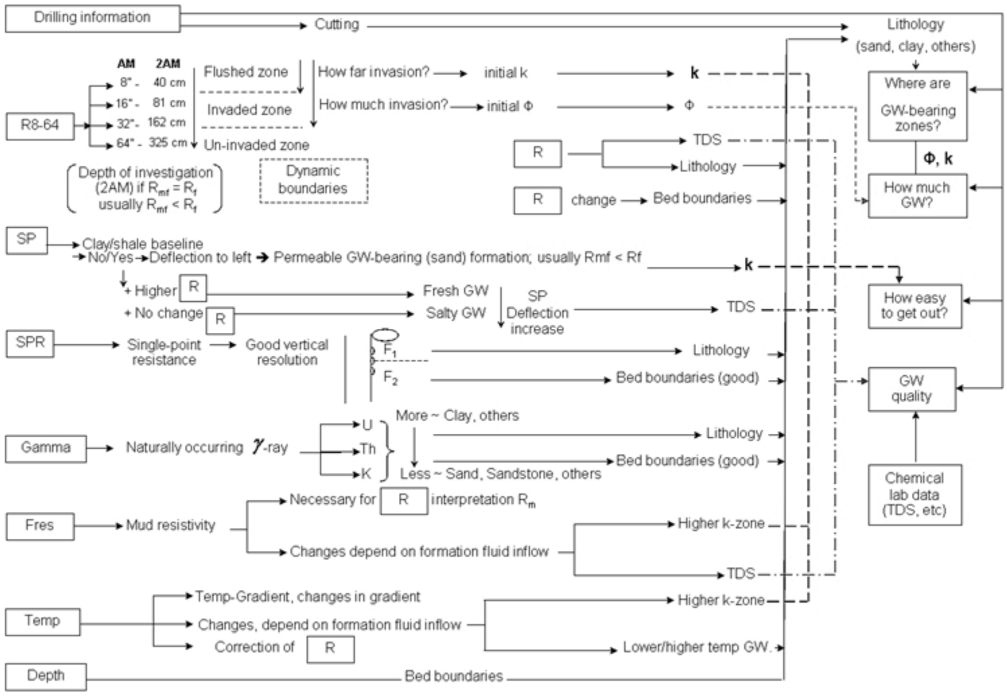

Figure 2. Flowchart of the geophysical logging data analysis and interpretation in respect to groundwater (GW) investigations. The logging data here used are normal resistivity (R) with different spacing between current (A) and voltage (M), 8", 16", 32", and 64", the spontaneous potential (SP), the single-point-resistance (SPR), the natural gamma-ray (Gamma), the fluid resistivity (Fres), the fluid-temperature (Temp), the depth information from the logging equipment, and information obtained during the drilling of the borehole before logging. Rmf = mud filtrate resistivity; Rf = formation water resistivity; Φ = porosity; Sw = water saturation, k = permeability, AM = distance between current and voltage electrode, 2AM = depth of investigation if Rmf = Rf; F1 and F2 = Formation 1 and 2, TDS = total dissolved solid.

groundwater inflow from subsurface formations. The data from the Fres tool are necessary for resistivity log interpretation. Further, they are likely an indicator for higher permeable zones due to the water inflow, and/or changes in the concentration of the total dissolved solid (TDS).

The fluid temperature logging tool (Temp) can give information about temperature changes with depth, including temperature gradient. Any changes in the temperature might indicate groundwater inflow from a subsurface formation and therefore might indicate higher permeability zones.

Further data available are the drilling information and the cutting material. During the drilling process, before logging, the engineers already get important and useful information of the subsurface, for example, at what depth is groundwater inflow and approximately how much. The cuttings are valuable information as they provide a direct access to the subsurface, and mainly used for lithology identification. They are important for the interpretation of the lithology from logging data, as logging data alone still carry some ambiguity (Ellis, 1987).

2.3 Study area

Geophysical logging was carried out in seven boreholes in southern Thailand, selected and accessed in cooperation with the DGR as shown in Figure 3 and 4, with four wells in Songkhla Province, having a final depth between 62 an 106 m. The three other wells are located in Phatthalung Province, which have final depth values between 44 and 102 m.

2.4 Groundwater resources in the study area

Groundwater resources of Southern Thailand are related to a wide spectrum of geological material, from unconsolidated sediments to hard rocks. In the study area following hydrogeologcial regions can be separated (after DMR, 1998; DGR, 2001).

In the northern part of Phattalung the main aquifers consists of sand, gravel, and clay. The average of thickness of the sediments appears to be about 200-400 m. The largest thickness is 500 m. The aquifer is divided into three parts within the depth of 300 m. The first aquifer is found approximately at 80-100 m, and has been tested at about 20-50 m^3/hr. From the ground level the thickness is approximately 10-20 m. The second aquifer is found approximately at 130-150 m, and has been tested at about 10-30 m^3/hr. From the ground level it has a thickness of approximately 15-20 m. The third aquifer is found at approximately 170-200 m, and has been tested at about 15-30 m^3/hr. From the ground level the thick-

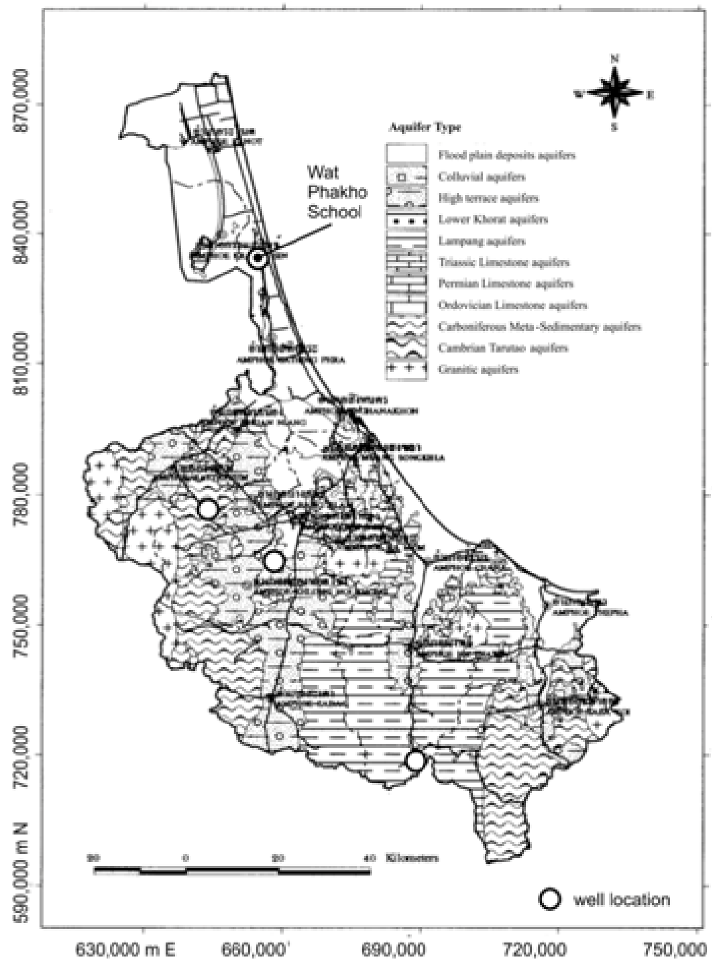

Figure 3. Hydrogeological map of Songkhla Province with major aquifers (after DMR, 1998; DGR, 2001) and locations of the wells. Grid in UTM based on WGS–84.

ness is approximately 10-15 m.

In the northern part of Songkhla Province the aquifers also consisted of sand, gravel, and clay. The average thickness of the sediments here is about 200 m. The aquifer is divided into three parts within the depth of 150 m. The first aquifer is found at approximately 55-80 m, and has been tested at about 15-30 m^3/hr. From the ground level it has a thickness of approximately 10-20 m. The groundwater quality in the first aquifer shows high contents of chloride (300-500 mg/l). The second aquifer is found approximately at 100-120 m, and has been tested at about 15-30 m^3/hr. From the ground level it has a thickness of approximately 10-20 m. The groundwater shows high contents of iron. The third aquifer is found at approximately 130-140 m, and has been tested at about 10-20 m^3/hr. From the ground level the thickness is approximately 5-15 m.

The aquifers in the central and southwestern part of Songkhla Province consisted of gravel and clay. The average thickness of the sediment layers is about 100-200 m. The aquifer is divided into there parts. The first aquifer is found approximately at 20-40 m, and has been tested at about 30-100 m^3/hr. From the ground level it has a thickness of approximately 10-20 m. Groundwater chemistry in the first aquifer shows high contents of iron. The second aquifer is found at approximately 50-60 m, and has been tested at about 20-50 m^3/hr. From the ground level it has a thickness of approximately 10-20 m. Groundwater quality in the second aquifer shows also high iron content. The third aquifer is found at approximately 100 m, and has been tested at about 10-30m^3/hr. From the ground level the thickness is approximately 20-30 m.

3. Results and Discussions

From the seven wells investigated during this study two wells are described in detail below with respect to the groundwater layers identified through the geophysical data interpretation (see Figure 3 and 4).

3.1 Wat Phakho School, Sathingpra, Songkhla

The well at Wat Phakho has a drilling depth of 62 m,

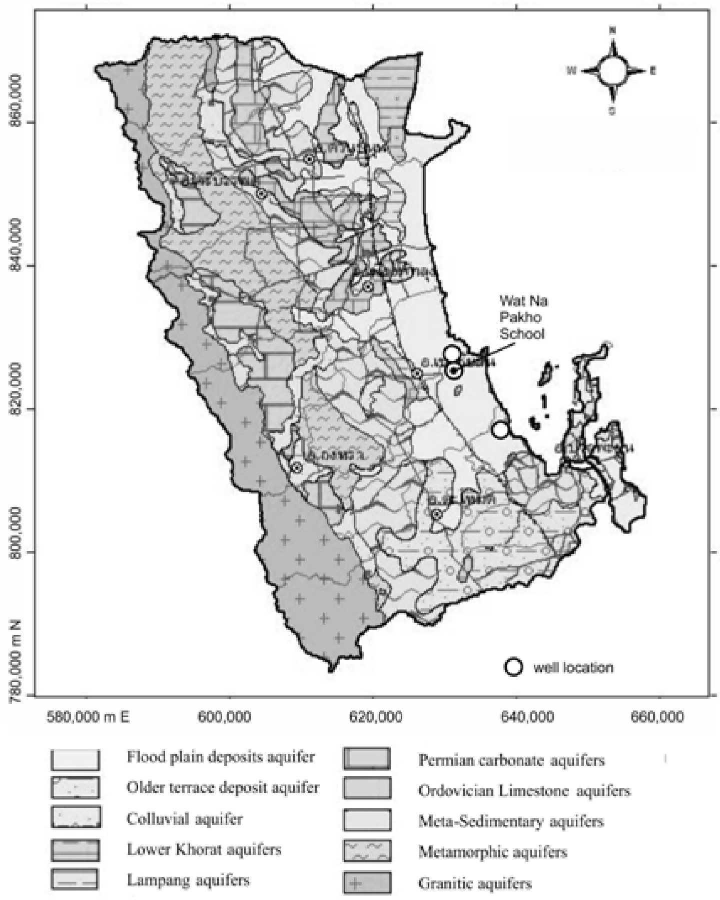

Figure 4. Hydrogeological map of Phatthalung Province with major aquifers (after DMR, 1998) and locations of the wells. Grid in UTM based on WGS–84.

with a change in the borehole diameter from 10" to 6" at 55 m depth. A photo of the cutting is shown in Figure 5 and a description in given in Table 1. First logging data were measured at around 9 m due to the tool length and a girdle needed for the electrical measurements.

In general, the Gamma log shows values between 20.16 to 149.72 cps with changes related to different layers. The SP curve shows deflections to the left from the shale baseline, which could be established from mainly clay containing layers at the bottom of the well, with some correlation to layers in the upper part (see Figure 6). At about 55 m depth some drastic changes in some of the tool readings can be seen, which can be related to the change in borehole diameter (see above) as the tool hit the borehole wall. The occurrence of harder rock at this depth required the change to a smaller drilling bit (see Table 1). In the following an interpretation of the main groundwater layers and their geophysical response is given from the top to the bottom using the downward measurements (see Figure 6):

Depth: 22.34-25.64 m, thickness: 3.30 m:

The Gamma log shows relatively lower values (40.02 cps) indicating a lower clay content. This corresponds with the cutting, which states clay and sand with some shells. The SPR and R logs (8", 16", 32", and 64") show an increase from 58.49 to 73.26 ohm, from 6.07 to 25.26 ohm-m, from 5.06 to 24.82, and from 5.76 to 16.33 ohm-m, respectively. The increase in the resistivity values can be explained with an

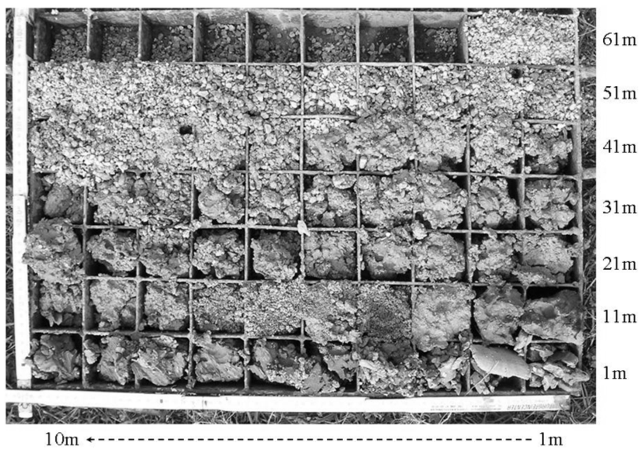

Figure 5. Cutting samples in 1 m intervals from the well at Wat Phakho School, Songkhla Province.

Table 1. Cutting description from the well at Wat Phakho School, Songkla Province.

Depth (m)	Cutting description
1	Clay (hard, light brown and grey)+shell
2-3	Clay (hard, light brown, grey and white)+shell (many)
4	Clay (hard, brown and red)+shell (many)
5-10	Shell+clay (soft)+Sand (less, dark, grey or black)
11-12	Shell+Clay (hard)+ Sand (beach, less, light grey and light brown)
13	Sand (beach)+Clay (soft, light brown and grey less)
14-15	Sand (beach, grain size more than at 13 m)+Clay (light brown)
16	Sand+Shell (light brown and white)
17	Sand+Clay (some)+Shell (light brown and yellow)
18	Sand+Clay (more than at 17 m)+shell (light brown and yellow)
19-23	Sand+Clay (more than at 18 m)+shell (light brown)
24-33	Sand (medium grain size) +Clay (softer than at 23 m, grey and brown)
34-35	Sand (more than at 24-33 m), Clay (grey and brown)
36-37	Sand+Clay (more than at 34-35 m, red and brown)
38-39	Sand (large grain size)+Clay (soft, red and brown)+Sandstone (fragment)
40-41	Clay (softer than at 38-39 m)+Sand (medium to large grain size, red and light brown)
42	Sand (larger grain size)+Clay (some, red color)
43-45	Clay soft+Sand (small to large grain size, red and yellow and brown)
46-48	Sand (medium to large grain size)+Clay (some, red)
49-55	Rock (small grain size, several mm and large grain size, fragments, sharp edges, white, brown, red and yellow)
56-57	Rock (several mm to more than half cm and large, fragments, sharp edges some rounder)
58-62	Rock (less than half a cm, similar grain size, different color mainly white, sharp and rounder edges)

increase in the sand content. The R 64 does not show minor changes, which might indicate that the effective bed thickness is smaller than the R 64 tool length (163 cm), although the layer thickness here is larger. The SP log shows a clear bur small deflection from base line (780.98 mV) to the left (776.50 mV), indicating a relative higher fresh water content and therefore making it an aquifer with probably lower yields.

Depth: 28.80-30.24 m, thickness: 1.44 m:

The Gamma log shows relatively low values (50.63 cps) indicating a lower clay content. This corresponds with the cutting, which states clay and sand. The SPR and R logs (8" and 16") show an increase from 53.88 to 64.88 ohm, from 6.57 to 13.25 ohm-m and from 6.47 to 11.46 ohm-m, respectively. The SP log shows a deflection from the base line (780.98 mV) to the left (774.75 mV).

Depth: 32.46-34.34.32 m, thickness: 1.86 m:

The Gamma log shows relatively low values (40.63 cps) indicating a lower clay content. This corresponds with the cutting, which states clay and beach sand. The SPR and the R logs (8", 16" and 32") show a clear increase from 63.06 to 79.70 ohm, from 9.92 to 40.77 ohm-m, from 9.70 to 44.62 ohm-m and from 10.87 to 36.08, respectively. The increase in the resistivity values can be explained with an increase in the sand content. The SP log shows a larger deflection from base line (780.98 mV) to the left (769.13 mV) indicating that the layer contains likely a larger amount of fresh groundwater.

Depth: 35.00-37.86 m, thickness: 2.86 m:

The Gamma log shows relatively low values (36.21 cps) indicating a lower clay content. This corresponds with the cutting, stating clay and sand. The SPR and the R logs (8", 16" 32", 64") show a clear increase from 69.89 to 99.45 ohm, from 27.09 to 81.24 ohm-m, from 34.72 to 101.60 ohm-m, and from 42.46 to 87.36 ohm-m, respectively. The increase in the resistivity values can be explained with an increase in the sand content. The SP log shows the largest deflection from base line (780.98 mV) to the left (767.00 mV), which indicates a larger amount of freshwater and correlates with the sand lithology. However, the effective layer is relatively thin in comparison to the R 64 length (163 cm), which is the reason why the R 64 log does not show a significant increase here.

Depth: 39.54-44.22 m, thickness: 4.68 m:

The Gamma log shows relatively low values (37.01 cps) indicating a lower clay content. This corresponds with the cutting, which states clay and sand. The SPR show a clear increase from 73.46 to 105.72 ohm, as well as the R logs (8", 16", 32" and 64"), here from 28.38 to 71.19 ohm-m, from 32.41 to 93.61 ohm-m, from 35.81 to 97.75 ohm-m, and from 40.36 to 80.48 ohm-m, respectively. The increase in the resistivity values can be explained with an increase in the sand content. The SP log shows a slight deflection from base line (780.98 mV) to the left (772.75 mV).

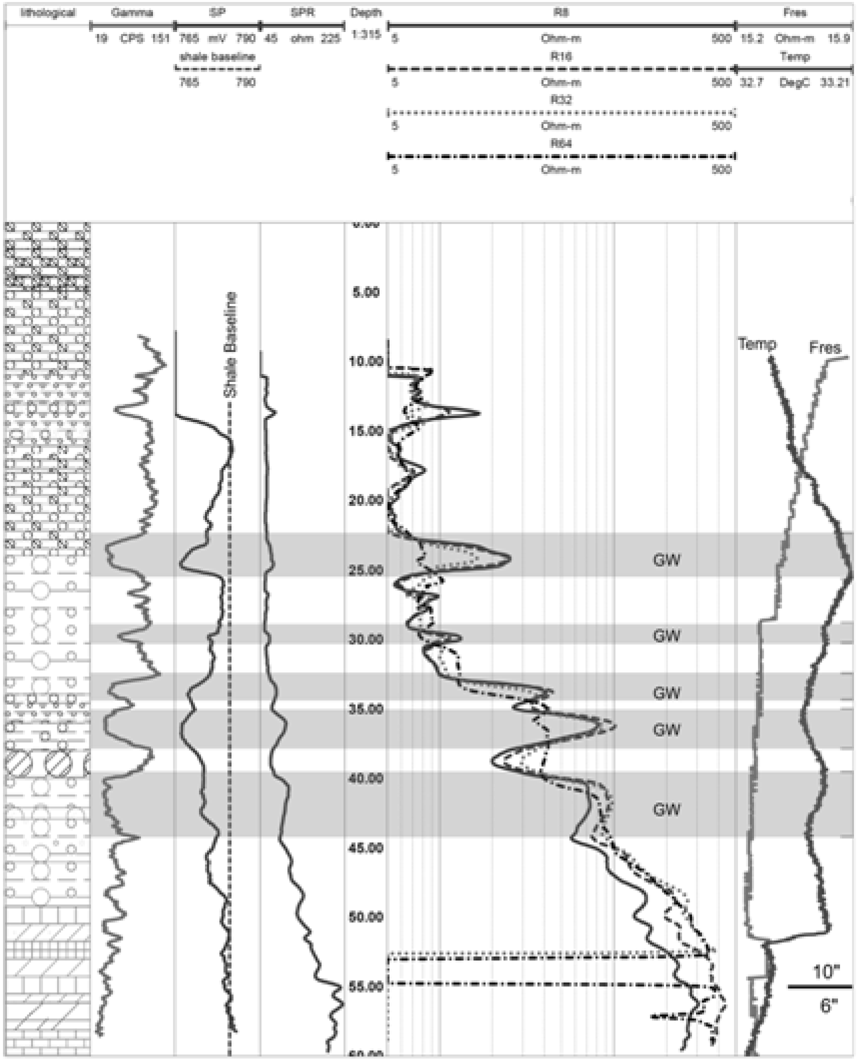

Figure 6. Logging data (downwards) of the well at Wat Phakho School, Songkhla, with the interpretation of groundwater bearing layers (GW). Further explanation in the text. At 55 m depth is a change of the borehole diameter from 10" to 6".

The Temp log shows an increase in the depth interval from 9.65 m to 20.62 m and then decreases. At around 37 m the Temp log shows a minimum. This coincides with the groundwater bearing layer at this depth range, indicating an inflow of cooler groundwater into the well. The Fres log shows a decrease in the depth range from 9.65 m to 51.53 m. Further, from 51.72 m to 52.09 m the Temp log shows a curve deflection and decreases from 33.10°C to 32.81°C. In depth range 51.72 m to 52.09 m the Fres log show an increase from 15.27 ohm-m to 15.41 ohm-m, respectively. The decrease in the Temp and the increase in Fres values can be explained with the change in borehole diameter below as the mud above the smaller diameter is not well mixed as above. The R logs (32" and 64") show sudden change in values at 52.64 m to bottom depth and at 53.03 to 54.73 m that can be also explained by the change in borehole diameter from 10 to 6 inches.

3.2 Wat Na Pakho School, Kaochaison, Phatthalung

The diameter of the drilling at Wat Na Pakho well is 9 inches. The depth from ground surface is 85 m. Cutting data is shown in Table 2 and Figure 7. The cutting lithology shows sand with clay layers towards the bottom. Sand with quartz and clay-rich sand layers continue from 7 m downwards to 81 m. Six intervals show clay layers, 1-2 m, 4-6 m, 16-21 m, 51-52 m, 61-63 m, and 82-85 m. However, the establishment of a shale baseline was difficult. In the following an interpretation of the main groundwater layers and their geophysical response is given from the top to the bottom using the downward measurements (see Figure 8):

Depth: 21.34-24.70 m, thickness: 3.18 m

The Gamma log shows relatively low values (117.44 cps) indicating a lower clay content. This corresponds with the cutting, which states clay (red) and sand (medium to fine

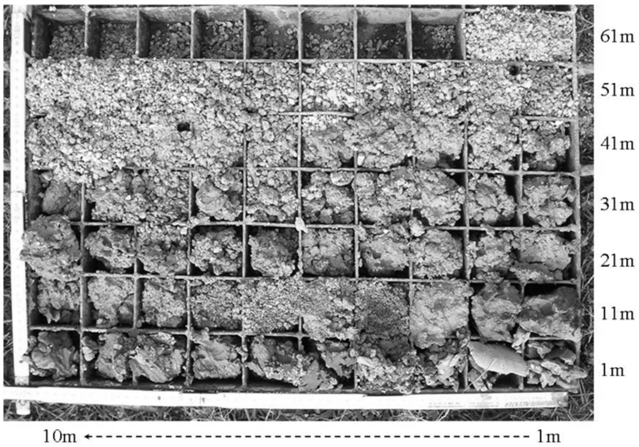

Figure 7. Cutting samples 1 m intervals from the well at Wat Na Pakho School, Phatthalung Province.

to very fine grain size). The single-point-resistance and normal-resistivity logs (R 8 and R 16) show an increase from 166.68 to 193.00 ohm, from 60.13 to 72.03 ohm-m, and from 90.21-95.99 ohm-m, respectively. Here the R 8 and R 16 show an increase, but not the longer spacing normal tools (R 32 and R 64). The increase in the resistivity values can be explained with an increase in the sand content. This layer might contain either relatively more freshwater, likely low absolute amount, or water with a lower TDS value than the layers above and below. The R 32 and R 64 do not show any changes, which indicate and support a relatively low absolute amount of fresh water. The spontaneous potential log shows a small deflection to the left, however the so called shale baseline is not defined until further below. At shallow depth the SP readings are in general difficult to interpret. From the overall data, it is also possible that the formation contains more sand (lower Gamma) and therefore has slightly higher porosity and permeability so that the fresh mud water penetrates deeper into the invaded zone resulting the higher R 8 and R 16 values but has not effect on larger spacing (R 32 and R 64).

Depth: 27.00-30.00 m, thickness: 3.00 m

The Gamma log shows relatively low values (50.87 cps) indicating a lower clay content. This corresponds with the cutting, which states clay and sand (medium grain size) and quartz. The single-point-resistance and especially the normal-resistivity logs (R 8, 16, 32, and 64) show a clear increase from 157.14 to 210.45 ohm, from 50.80 to 111.42 ohm-m, from 74.41 to 145.52 ohm-m, from 124.60 to 167.88 ohm-m, and from 202.15 to 205.56 ohm-m, respectively. The increase in the resistivity values can be explained with an increase in the sand content and the occurrence of more freshwater or water with a lower TDS value than the layers above and below. The spontaneous potential log shows a deflection from base line (818.22 mV) to the left (806.63 mV), but the inter-

Table 2. Cutting description from the well at Wat Na Pakho School, Phattalung Province.

Depth (m)	Cutting description
1-2	clay (white)
3	clayey (red) sand (medium grain size)
4-6	clay (yellow, white and red)
7-10	clayey sand (medium grain size)
11-13	sand (medium grain size) and quartz (white and rounded)
14-15	sandy (white and rounded shape) clay (red)
16-21	clayey (red) sand
22-23	sandy (medium grain size) clay (brown)
24	sand (medium very fine grain size and white)
25-27	sandy (medium grain size) clay (red)
28	sandy (medium grain size) quartz (rounded)
29-30	sandy (medium grain size) clay
31-36	red clay, quartz (larger pieces)
37-39	sand (fine grain size, red and grey)
40-50	clayey (red) sand
51-52	clay (grey and brown)
53-57	sand (large grain size and grey)
58-60	sandy (large grain size) clay (red)
61-63	clay (red and brown)
64-78	clayey (red)+gravel (medium grain size)
79-81	sand (large grain size)+quartz (rounded)
82-85	clay (grey)

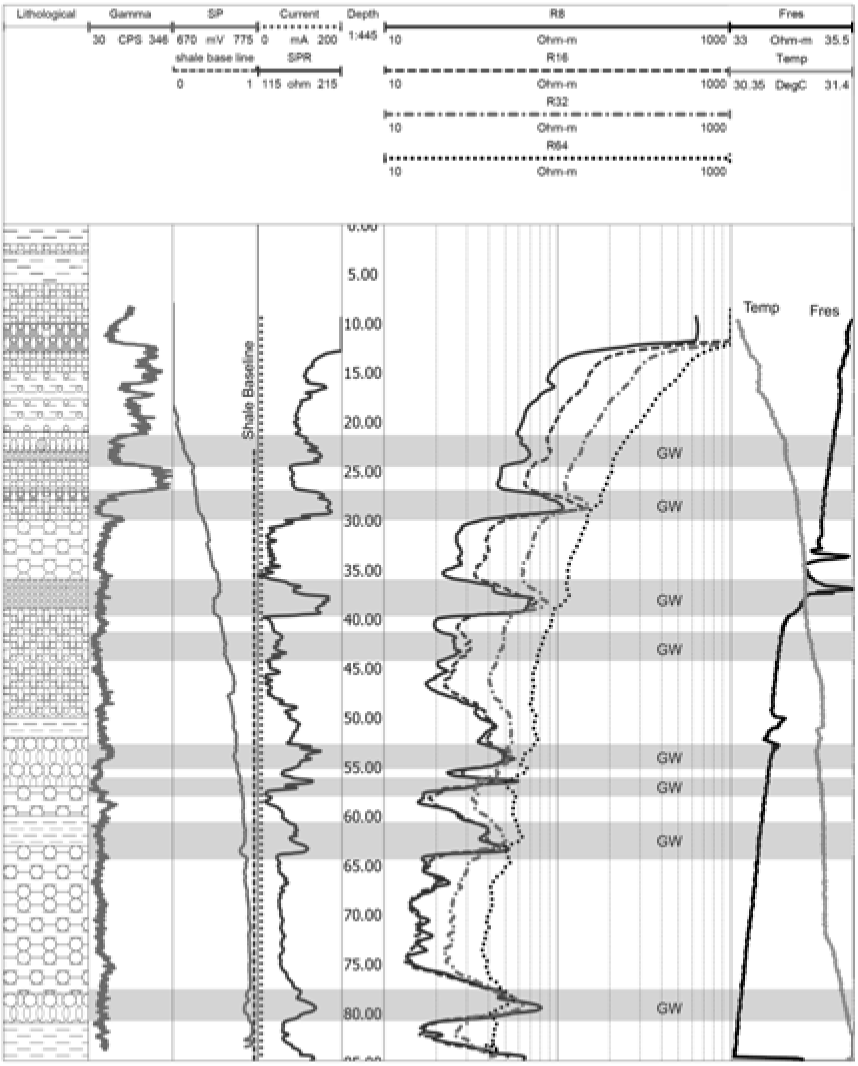

Figure 8. Logging data (downwards) of the well at Wat Na Pakho School, Phatthalung, with the interpretation of groundwater bearing layers (GW). Further explanation in the text.

pretation here is still difficult and ambiguous.

Depth: 36.00-39.76 m, thickness: 4.07 m

The Gamma log shows a decrease from 97.30 to 52.16 cps indicating lower clay content. This corresponds with the cutting, which states clay and sand (medium to fine to very fine grain size) and quartz. The single-point-resistance and normal-resistivity logs (R 8, R 16, R 32, R 64) show an increase from 165.77 to 195.95 ohm, from 45.16 to 73.36 ohm-m, from 37.74 to 79.48 ohm-m, from 70.75 to 86.82 ohm-m, and from 129.92 to 130.92 ohm-m, respectively. The increase in the resistivity values for this layer and the one above can be explained with an increase in the sand content. This layer might contain either relatively more freshwater or water with a lower TDS value than the layers above and below. The spontaneous potential log shows a clear deflection from base line (818.22 mV) to the left (797.13 mV), especially in the lower part of this layer, which correspond to the highest R and SPR values. This indicates that the layer is likely to be separated in two parts with the lower part containing likely more groundwater than the upper part.

Depth: 41.47-44.70 m, thickness: 3.23 m

The Gamma log shows a decrease from 79.27 to 48.84 cps indicating lower clay content. This corresponds with the cutting, clay and sand (medium grain size) and quartz. The single-point-resistance shows only a slight increase from 142.67 to 149.77 ohm, whereas the normal-resistivity logs (R 8, R 16) show an increase from 143.40 to 152.28 ohm, from 22.43 to 29.38 ohm-m, and from 30.51 to 34.38 ohm-m, respectively. Although there is an increase in the resistivity values and SPR the overall pattern might be better explained with an increase in the sand content rather than an increase in groundwater content. The spontaneous potential log shows a deflection from base line (818.22 mV) to the left (797.88 mV) which is quite ambiguous.

Depth: 52.95-55.29 m, thickness: 2.95 m

The Gamma log shows a decrease from 117.21 to 62.80 cps indicating lower clay content. This corresponds with the cutting, which states clay (grey and brown) and sand (medium grain size) and quartz. The single-point-resistance show an increase from 151.90 to 188.20 ohm and the normal-resistivity logs (R 8, R 16) show an increase from 37.78 to 51.72 ohm-m and from 42.74 to 51.80 ohm-m, respectively. R 32 and R 64 show a decrease from 56.20 to 46.78 and from 80.66 to 69.86 ohm-m, respectively. The increase in the resistivity values (R 8, R 16) can be explained with an increase in the sand content. The R 32 and R 64 do not show any changes, which indicate and support a relatively low absolute amount of fresh water. This layer might contain either relatively more freshwater or water with a lower TDS value than the layers above and below. The spontaneous potential log shows a quite small deflection from base line (818.22 mV) to the left (789.13 mV).

Depth: 56.06-58.08 m, thickness: 2.02 m

The Gamma log shows a curve deflection decrease from 70.11 to 46.96 cps indicating lower clay content. This corresponds with the cutting, clay (red) and sand (large grain size) and quartz. The single-point-resistance show a clear increase, whereas the normal-resistivity logs (R 8, R 16) also show an increase from 142.55 to 192.38 ohm, from 147.39 to 165.67 ohm, from 24.55 to 63.60 ohm-m and from 29.86 to 44.62 ohm-m, respectively. R 32 and R 64 show a decrease from 48.12 to 37.08 ohm-m and from 65.83 to 61.43 ohm-m, respectively. The increase in the resistivity (R 8, R 16) values can be explained with an increase in the sand content. The R 32 and R 64 logs do not show any changes, which indicate and support a relatively low absolute amount of fresh water. This layer might contain either relatively more freshwater or water with a lower TDS value than the layers above and below. The spontaneous potential log shows a small deflection from base line (818.22 mV) to the left (790.88 mV).

Depth: 60.47-64.32 m, thickness: 3.85 m

The Gamma log shows a decrease from 83.44 to 51.85 cps indicating lower clay content. This corresponds with the cutting description, showing clay (red, brown and grey) and sand (large grain size). The single-point-resistance show an increase from 143.05 to 173.85 ohm and the normal-resistivity logs (R 8, R 16) show an increase from 27.83 to 53.60 ohm-m and from 30.04 to 47.86 ohm-m, respectively. The increase in the resistivity values can be explained with an increase in the sand content. This layer might contain either relatively more freshwater or water with a lower TDS value than the layers above and below. A lower TDS value can be explained that water chemically interacting with sand will not increase the TDS as sand is relatively chemically inert. The spontaneous potential log shows a deflection from base line (818.22 mV) to the left (790.13 mV), especially clear in the lower part. Here the overall layer might also be separated into different smaller layers, with the lower one likely to contain more water than above indicated by the SP deflection and the peaks in SPR and R values.

Depth: 77.20-80.85 m, thickness: 3.65 m

The Gamma log shows almost no change at absolute lower cps values indicating lower clay content. This corresponds with the cutting, giving clay (red, brown and grey) and sand (large grain size) and quartz. The single-point-resistance show an increase from 140.43 to 184.72 ohm and the normal-resistivity logs (R 8, R 16 and R 32) show an increase from 14.70 to 80.41 ohm-m, from 14.71 to 79.92 ohm-m, and from 24.54 to 63.88 ohm-m, respectively. The increase in the resistivity values can be explained with an increase in the sand content. This layer might contain relatively more fresh groundwater as the spontaneous potential log shows a clear deflection from base line (818.22 mV) to the left (770.13 mV).

The temperature log shows an increase with depth with changing slopes. The fluid resistivity log shows a decrease from the top to the bottom with some spikes at 33.87 m and 37.15 m with an increase from 34.63 ohm-m to 35.38 ohm-m. The decrease in fluid resistivity values can be in general explained with the increase in the temperature. However, the spikes of the Fres log might indicate freshwater inflow and by this increasing the overall resistivity of the mud above. The down and up (not shown here) measurements show differences in the fluid temperature and also in the fluid resistivity. These differences can be explained that the tool by mowing down is disturbing the mud column and by this also the fluid in the mud and therefore also changing the temperature distribution.

4. Conclusions

In this study a conventional geophysical logging tool for groundwater applications was applied to different groundwater wells and situations in Songkhla and Phatthalung Province. The result of the well log analysis of these groundwater wells identified different layers with mainly clay or sand content and water bearing zones. The aquifer lithologies correspond to the flood plain deposits outlined in the groundwater maps shown in Figure 3 and 4. Among all available logs following tools were useful in identifying or separating water bearing zones, spontaneous potential, the normal resistivity tools, and the single-point resistance log.

This study has shown that with additional logging data, here nine tools, significant more information can be gained about the hydrological system, especially taking into account the time used for logging, which is quite short compared to drilling, hours versus days. Further, the application of the logging tools has shown that more log parameters are preferable in identifying water–bearing zones. It has been demonstrated that some tools deliver in almost all wells the necessary aquifer information, but the study has also shown that in different wells different tools are favorable over others. Finally, it has to be stressed that it is of quite importance to have a high cutting sampling rate like in the wells of this study with 1 m intervals, and based on that a good cutting description, preferable also each meter. This provides the necessary base for a detailed cutting to log data correlation and by this provides an enormous information potential for further analysis and studies.

Recommendations

Based on the conclusions of this study geophysical logging in groundwater exploration is recommended as a normal standard technique that should be applied in every new well drilled. First, the logging operation uses relatively less time compared to the data and information gained through the measurements. Second, onsite data interpretation helps the drilling crew to put the screens for groundwater inflow much more effectively than without, especially in wells with lower yield where the aquifers are not immediately recognized during the drilling process. Third, the data gained will add over time to a larger dataset as a base for groundwater management and decision making. Further, it is recommended to continue the scientific investigations of geophysical logging in the groundwater wells in Southern Thailand. For example, a better constrained permeability and porosity values would be favorable.

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