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# Hydrogeological challenges in drilling fractured hardrock aquifer in Kedah

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**Abstract:** This paper presents and discusses the hydrogeological challenges encountered during the drilling of fractured hardrock aquifers in Kedah, Malaysia. The project aimed at drilling 20 boreholes, each to a target depth of 200 meters, across various geological formations. However, initial drilling efforts faced several challenges, including high downhole pressure, fractured zone collapse, insufficient compressor capacity, and unexpected geological conditions, which initially prevented the boreholes from reaching the target depth. Several improvements were introduced to overcome these challenges, including modifying the borehole diameter, adjusting drilling techniques, and installing temporary casing until fresh bedrock was encountered. The most significant improvement was reducing the borehole diameter. Initially, a 10-inch diameter borehole was required to be drilled to a full depth of 200 meters, but difficulties arose when using the DTH hammer beyond 100 meters, especially in hardrock sandstone formations combined with high downhole pressure. A telescopic approach was used, where the diameter was reduced from 10” to 8” to continue drilling. However, this approach proved ineffective due to the water pressure/flow rate decrease when discharge water transitioned from the 8” to the 10” diameter opening, which prevented effective flushing of the drill cuttings to the surface. Ultimately, it was decided to drill an 8” diameter borehole directly from a 10” temporary casing to a depth of 200 meters with no telescoping. This approach succeeded and allowed the team to reach the target depth in all subsequent boreholes, even in fractured formations. Another factor that aided in achieving the 200 meters target depth was improving drilling speed, particularly in poorly consolidated lithologies such as interbedded mudstone formations, to prevent borehole wall collapse. Effective drilling in these fractured formations requires skillful drillers, well-maintained equipment, and experienced hydrogeologists on site. This paper highlights the importance of proper well design and development, emphasizing the need for appropriate techniques before PVC installation to optimise and sustain yield during pumping. Additionally, the use of downhole geophysical tools to capture subsurface conditions including the location of major fractures contributed to a more efficient well design process. With these adaptations and proper well development, the subsequent 10 boreholes were successfully drilled to the target depth of 200 meters, providing valuable insight into groundwater dynamics in Kedah’s fractured hardrock hydrogeology.

**Keywords:** Groundwater drilling, hardrock aquifer, drilling techniques, well development, hydrogeology, Kedah

## INTRODUCTION

Kedah, a state in Malaysia, is constantly faced with severe water supply issues, especially during the typically prolonged annual dry season. These dry periods lead to significant depletion of surface water sources, including reservoirs, potentially resulting in critical water shortages and seawater intrusion along rivers and coastal areas. Such conditions exacerbate water supply disruptions, particularly in areas with inadequate water distribution infrastructure, such as Pendang, Sik, and Baling, where low water pressure in the supply system often results in insufficient water supply, especially during peak demand periods like holidays and festivals (Figure 1).

Malaysia relies heavily on surface water sources, including rivers, lakes, wetlands, and reservoirs, which contribute approximately 98% of the nation’s total water supply for domestic, industrial, and agricultural use. Groundwater accounts for the remaining 2% (Water Environment Partnership in Asia, 2021). Groundwater serves as a crucial alternative during dry spells, particularly in regions like Kedah. However, despite its importance, groundwater usage in Kedah remains low, contributing just one percent of the state’s total water supply resources (Suraya Yaacob, as cited by Zulkifli, 2022). Studies by the Department of Minerals and Geoscience Malaysia (JMG) indicate that Kedah possesses substantial untapped groundwater potential, presenting opportunities for future development.

In response to these pressing challenges, the Groundwater Resources Mapping and Development Project

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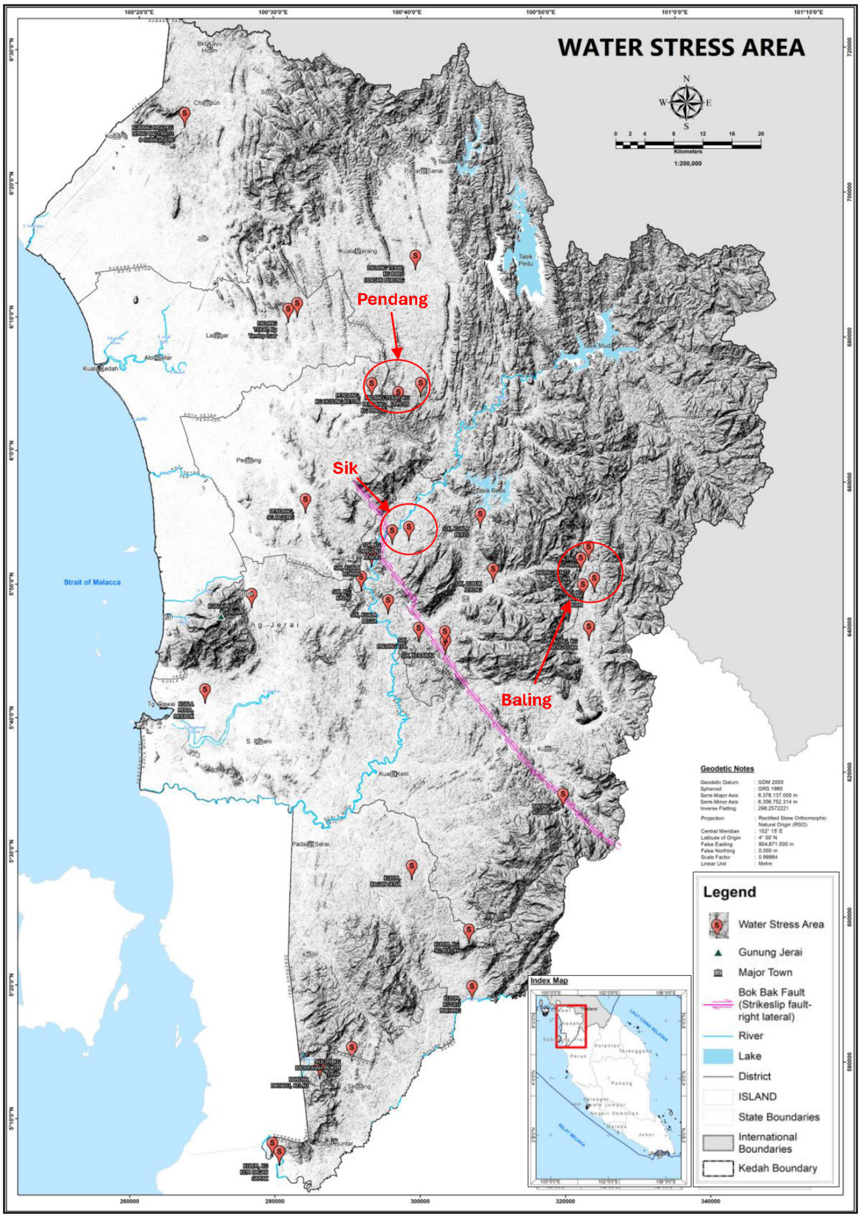

**Figure 1:** Water stress areas in Kedah.

(PABT Kedah) was initiated to effectively identify and develop groundwater resources, aiming to enhance water availability and sustainability for the region. As part of this initiative, VGX Sdn Bhd was tasked with drilling 18 boreholes across mainland Kedah, following comprehensive geophysical surveys.

This paper examines the specific challenges encountered during the drilling process, particularly the difficulty of reaching the target depth of 200 meters within the hardrock aquifers. It discusses the technical solutions implemented to overcome these obstacles and shares valuable lessons learned throughout the project. By documenting these experiences, this paper aims to provide insights that will improve future groundwater development efforts in similar geological environments.

## PREVIOUS RESEARCH

Groundwater exploration in Kedah started in the late 1970s. Initially, most drilling targets were selected based on regional-scale geological information or wildcat drilling in water-stressed areas, often with limited success. Between 1981 and 2007, a total of 339 boreholes were drilled in hardrock formations (JMG Kedah database); however, both drilling depths and yields obtained were generally inconsistent and not cost-effective (Figure 2). Out of the 339 boreholes drilled in Kedah, approximately 47% of these wells were dry, and only 8% yielded more than 1 million litres per day (Figure 3). The use of geophysical methods in groundwater exploration was limited in the early years but gained wider application in the 1990s, leading to greater success in identifying viable groundwater sources. Similarly,

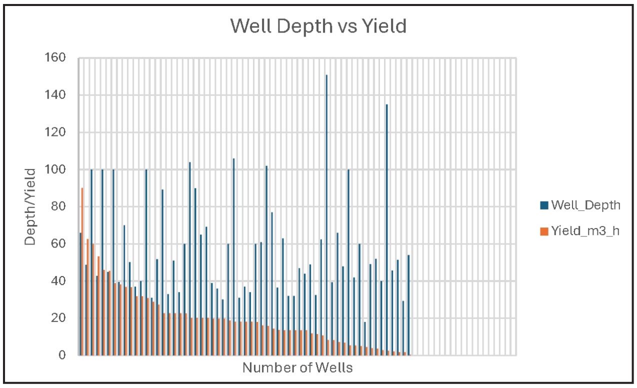

**Figure 2:** Yield versus Depth for the 61 wells drilled in the Semanggol Formation. The maximum depth drilled was 151 m, while the maximum yield obtained was 90 $m^3$/hr. The plot shows no specific correlation between the well depth and drilling yield.

new studies highlighted the effectiveness of geophysical methods in groundwater exploration, particularly 2D electrical resistivity imaging (ERI), which has been later successfully applied in various regions to assess groundwater potential (Kumar *et al*., 2022).

A study of the Kubang Pasu and Padang Terap water supply schemes highlighted the severity of water shortages caused by increasing agricultural and industrial demands, irregular water distribution, and climate change (Ahmad & Tan, 2021). This underscores the need to identify sustainable groundwater sources to prevent over-extraction and ensure a reliable water supply.

Additionally, a geophysical study identified resistivity-chargeability relationships for subsurface characterization in tropical hardrock environments, which are crucial for detecting fractured zones and clay-rich areas. This knowledge helps refine drilling strategies by avoiding unstable clay layers and targeting fractured formations that improve groundwater potential (Chen & Abdullah, 2022). Tailored strategies are essential to address site-specific geological conditions that may not be effectively managed using standard drilling practices. The importance of tailored drilling strategies has also been highlighted in studies from overseas, where site-specific drilling approaches were found to significantly reduce the risk of well failure in hardrock aquifers (Silva *et al*., 2020).

Moreover, insights into recharge mechanisms can enhance drilling success by identifying areas with higher recharge potential. This improves the overall efficiency of groundwater exploration (Adelana *et al*., 2006). Recognising natural recharge processes, such as infiltration and percolation, enables the identification of zones with enhanced groundwater replenishment, further optimising development strategies (Lloyd, 1969).

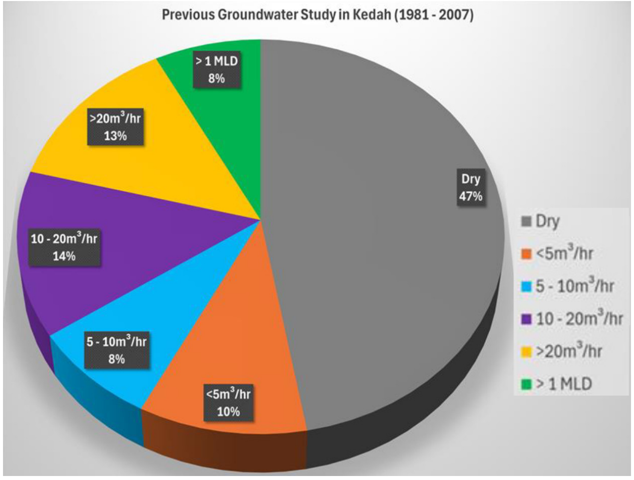

**Figure 3:** Statistics of yield in previous wells (Based on 339 wells that were drilled from 1981 – 2007, (JMG Kedah database)).

In summary, existing literature highlights the diverse challenges associated with drilling in fractured hardrock aquifers and underscores the need for customised strategies that consider geological conditions. The integration of geophysical methods, tailored drilling approaches, and an understanding of seasonal recharge dynamics is essential for overcoming the inherent difficulties of groundwater extraction in complex geological environments. These strategies not only improve drilling success rates but also support the long-term reliability of water supply in regions like Kedah.

## METHODOLOGY

The Groundwater Resources Mapping and Development Project (PABT Kedah) employed a systematic approach to explore and assess groundwater potential across mainland Kedah, covering an area of approximately 9,500 $km^2$. The project methodology was divided into several key phases.

### Geophysical survey

The initial phase involved conducting a Transient Electromagnetic (TEM) survey to identify potential wellfields. This survey provided crucial data on subsurface conditions, particularly highlighting high-potential groundwater zones (Figure 4). A total of 1,465 ground

**Figure 4:** TEM survey conducted to identify the potential wellfields. The layout of the cables during the survey is shown on the left, while the right shows the TEM equipment, ABEM WalkTEM-2, used during the survey.

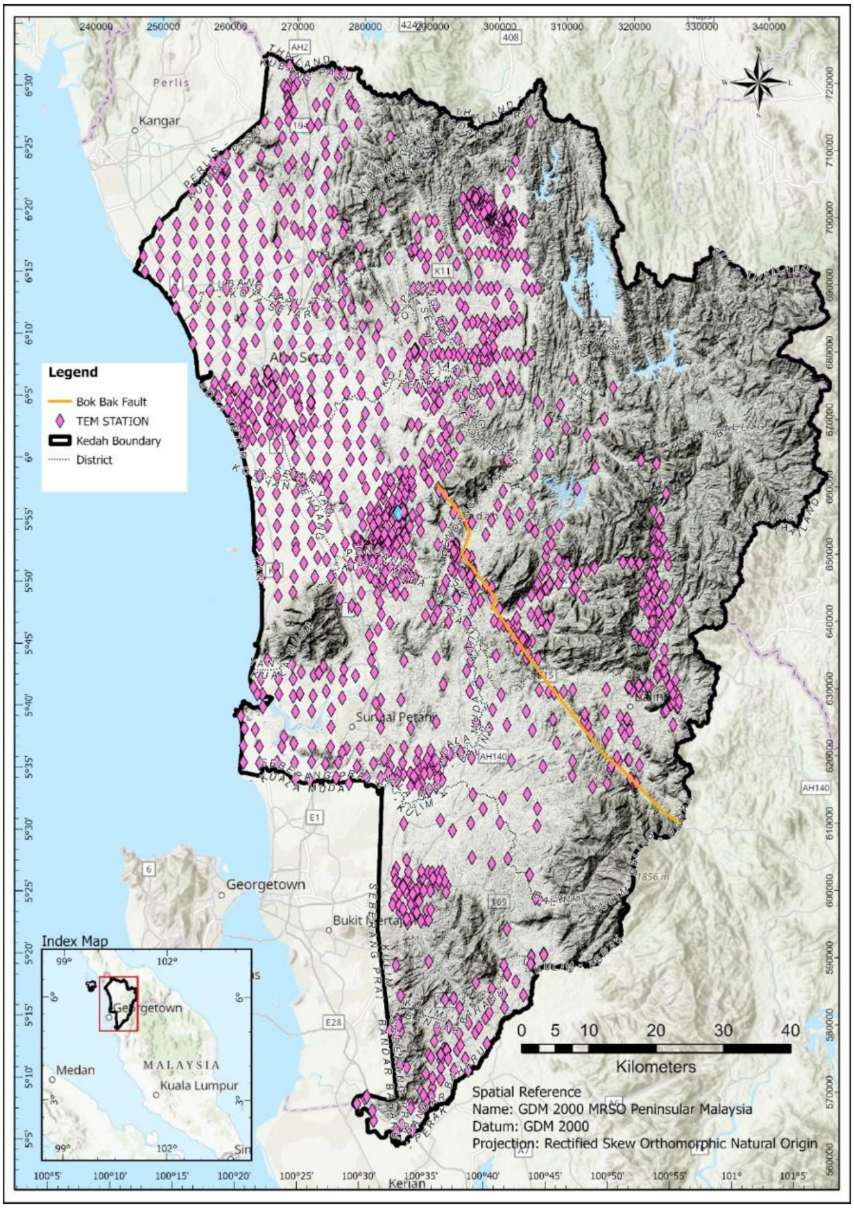

**Figure 5:** Distribution of the 1,465 TEM survey point conducted at Kedah mainland.

station points were surveyed (Figure 5), leading to the identification of 15 potential wellfields across mainland Kedah (Figure 6).

Following the TEM survey, a resistivity survey was conducted within each identified potential wellfield. This additional survey assessed the electrical properties of subsurface materials, allowing for the precise selection of optimal drilling locations. The resistivity data ensured that each drilling site was suitable for groundwater extraction. This coupled geophysical approach allowed the identification of suitable targets for groundwater exploration drilling in each wellfield.

## Drilling techniques

Once the drilling locations were finalised, the project advanced to the drilling phase. Initially, a site survey was weathered layers to prevent collapse and maintain borehole stability as drilling progressed.

Once the temporary casing was in place, drilling continued using a Down-the-Hole (DTH) hammer bit, which is designed to efficiently break through hardrock. Using compressed air, the hammer drives a piston to fracture the rock, while simultaneously rotating to pulverize the broken material. The compressed air also flushes cuttings and groundwater from the borehole. Throughout drilling, the site hydrogeologist carries out a geological logging by analysing the flushed-out drill cuttings. The hydrogeologist records the rock formations, types, depths, and the presence of water-bearing zones. Water yield during drilling was measured using a V-notch weir placed at the site, with measurements taken at each rod change and whenever an increase in yield was observed.

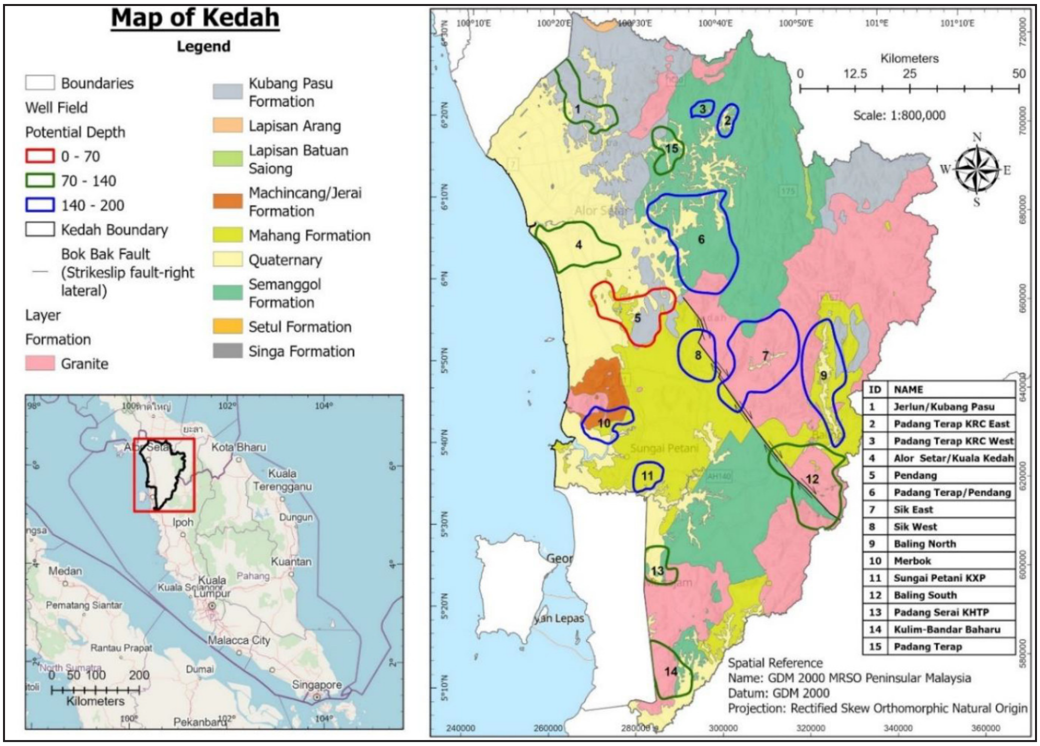

**Figure 6:** The 15 potential wellfields were delineated based on 1,465 TEM survey points conducted across mainland Kedah. A total of 18 boreholes were subsequently drilled within these wellfields (refer to Figure 11).

## Downhole geophysical survey and PVC casing installation

After drilling was completed, downhole geophysical logging was conducted to identify the exact locations of the fractured zones, lithological/formation boundaries, and assess the condition of the borehole wall (Figure 7). This downhole geophysical logging is then correlated with geological logging to refine the well design. The coupled geological and geophysical data guides the well design (Figure 8), including the placement of screens and blank casings to optimise water extraction from the most productive zones.

Downhole geophysical logging also assessed borehole wall conditions. When uneven walls or protruding rocks were detected, reaming with a roller or tricone bit was performed before PVC casing installation. This step ensures that the borehole walls are smooth and even, facilitating proper casing installation and achieving the desired well design.

The PVC casing installation followed, using Class D uPVC blank and 2 mm screen casings (Figure 7). The PVC casing diameter was selected based on the borehole diameter to ensure a secure fit and optimal performance. The casings and screens were installed based on the well design. After PVC installation, the annular space between the borehole wall and casing was filled up in stages according to the well design. A gravel pack was placed around the screen to aid filtration and prevent fine particles from entering the well. Above the gravel pack, a layer of bentonite pellets was added to seal the borehole and prevent vertical water movement. The remaining annulus space was either backfilled with clayey soil and/or sealed with cement grouting to stabilise the casing and protect the well from surface contamination. Stainless steel connectors were used to secure the PVC casings, ensuring a durable and sealed well structure.

**Figure 7:** Image on the left shows the downhole geophysical logging conducted before the PVC installation, as shown on the right.

## Well development and pumping tests

After reaching the desired depth, well flushing (development) was carried out to remove residual drill cuttings and debris to improve the hydraulic connection between the borehole and the aquifer. This was done to improved water quality as well as long-term well efficiency

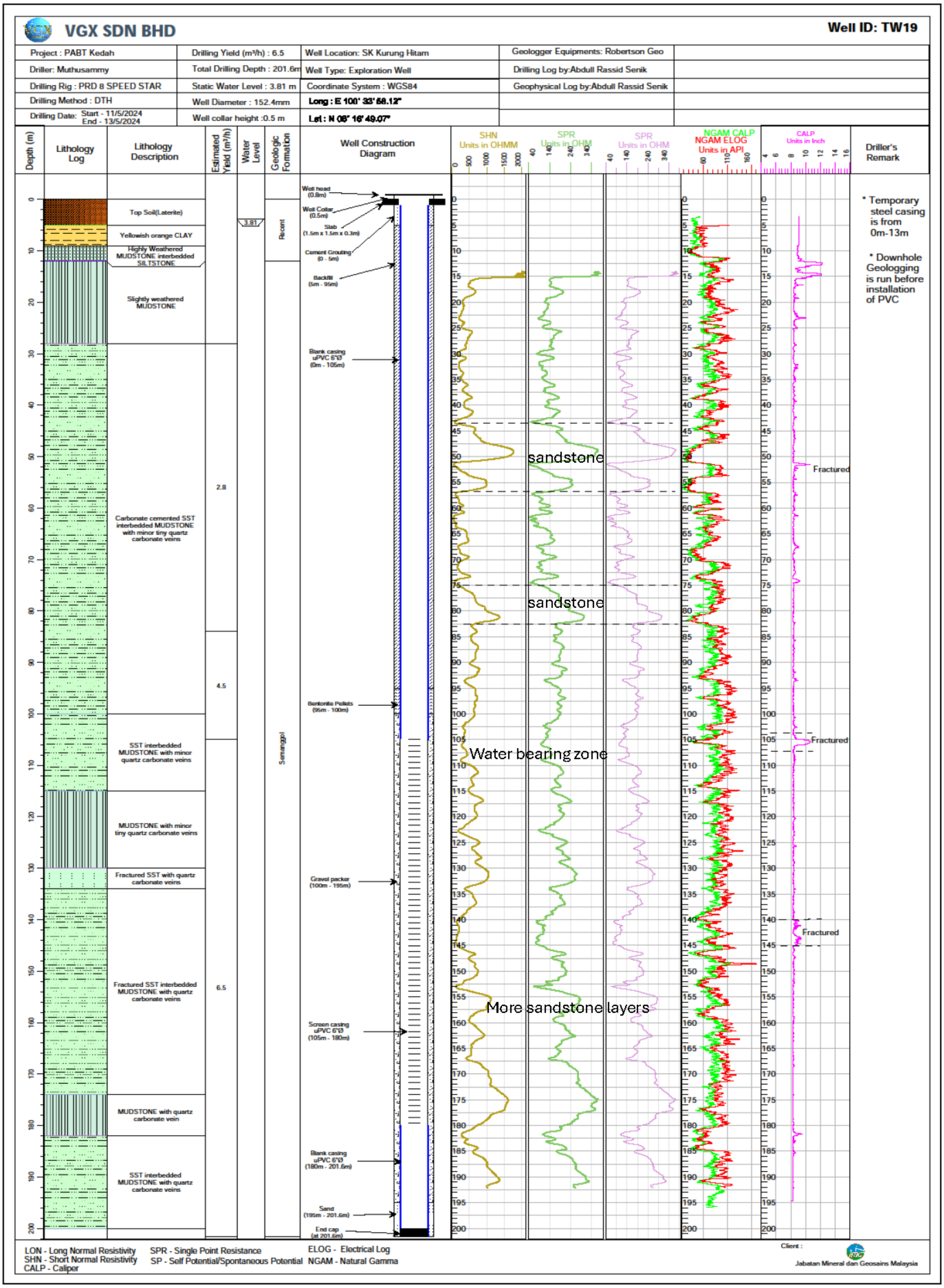

**Figure 8:** An example of a well log of borehole TW19, drilled in Semanggol Formation. The figure illustrates the correlation between geological and geophysical data collected before PVC installation to refine the well design. This log provides critical insights into fractured zones, lithological boundaries, and borehole conditions, guiding the optimal placement of well screens and casing to enhance groundwater extraction efficiency.

and productivity. Well flushing is conducted for a minimum of three hours to ensure thorough cleaning. Following the well development, aquifer pumping tests are conducted to evaluate each well's performance, determine aquifer hydraulic parameters, and assess hydraulic characteristics (efficiency) of each well. These tests measured discharge rates and monitored drawdown levels, providing insights into groundwater extraction potential at each well.

After pump installation, step and constant rate pumping tests were performed to assess aquifer productivity, hydraulic characteristics, and pump capacity. The step pumping rates for each well were estimated based on drilling data and designed to obtain hydraulic parameters from the subsequent constant rate pumping and recovery test data. Before the step pumping test, a maximum pumping rate test was conducted to evaluate maximum drawdown and pump capacity. During this test, the pump operated at its maximum capacity, and the time taken for the water level to reach the pump depth was recorded. Based on these results, the pumping rate for each step was determined and the drawdown curves were plotted to determine the aquifer loss and well loss coefficients.

The aquifer and well loss coefficients were calculated using the Hantush-Bierschenk method (Bierschenk, 1963; Hantush, 1964). The well loss coefficient can be used to assess well design efficiency, as it indicates the extent of additional energy loss during pumping. A lower well loss coefficient (< 0.05 $h^2/m^5$) reflects a well designed and developed borehole with minimal energy loss (Walton, 1962). In the PABT Kedah project, most of the calculated well loss coefficient values were low (refer to Table 1), suggesting that the wells were effectively designed and adequately developed, resulting in reduced additional well losses during pumping.

Following the step test, a 72-hour constant rate pumping test was conducted using 70% of the well's maximum efficiency discharge rate to fully stress the aquifer. Since the step pumping test was conducted effectively, the selected constant pumping rate was precise, allowing the water level to reach steady-state flow within 72 hours of pumping. A recovery test was carried out immediately after the pump was switched off to observe how quickly the water level returned to pre-pumping conditions. Transmissivity values were determined from the constant pumping and recovery tests. The Cooper-Jacob straight-line method (Cooper & Jacob, 1946) was used to calculate the parameter from the constant rate drawdown portion of the test, while the Theis

**Table 1:** Table below shows the well loss coefficient calculated for each borehole based on the step pumping test. Refer to Figure 11 for well location.

| Borehole | Location | Lithology | Well loss coefficient ($h^2/m^5$) |
|---|---|---|---|
| TW01 | Ladang Bukit Ketapang | Interbedded shale and sandstone | 0.015 |
| TW02 | SK Kubang Palas | Interbedded shale and sandstone | 0.0011 |
| TW03 | SMA Daril Iktisam | Interbedded sandstone and shale | 0.0143 |
| TW04 | SMPVK, Merbok | Metasandstone | 14.3 |
| TW05 | Playground MPSP | Interbedded mudstone and shale | 0.0438 |
| TW06 | SK Bukit Choras | Shale | 13.8 |
| TW07 | KEDA Resort & Training | Metasandstone | 1.62 |
| TW08 | SMK Taman Hi-Tech | Granite | 4.30 |
| TW09 | Masjid Raudhatul Falah | Granite | 2.63 |
| TW10 | Madrasah Minhajul Qawim | Interbedded shale and mudstone | 0.0018 |
| TW12 | SK Kodiang | Limestone | 0.0497 |
| TW14 | SK Tanjung Pari | Interbedded limestone and shale | 0.0749 |
| TW15 | SK Kampung Kota Bukit | Interbedded mudstone and shale | 1.26 |
| TW16 | Tabika Kemas Kg Tupai | Granite | 0.58 |
| TW17 | SK Kampung Bukit | Interbedded sandstone and shale | 0.213 |
| TW18 | SMK Tajar | Interbedded Sandstone and shale | 0.0107 |
| TW19 | SK Kurung Hitam | Interbedded Sandstone and shale | 0.289 |
| TW20 | SMK Serdang Baru | Interbedded Sandstone and shale | 0.021 |

recovery method (Theis, 1935) was applied to the recovery data. Hydraulic conductivity was then calculated by dividing the transmissivity value by the aquifer thickness. For this project, the Agarwal solution method (Agarwal, 1980) is also used to determine storativity from the recovery data from single pumping well as no observation wells were available near the pumping wells. We note that these storativity values are of limited accuracy due to a lack of monitoring boreholes nearby but at least an approximate estimate is determined.

## Water quality

Water sampling was carried out during the constant rate pumping test. Both on-site and in-situ water quality analyses were carried out in the field to obtain preliminary field water quality data (Figure 9). The in-situ water quality analysis measured the physical parameters such as pH, salinity, Total Dissolved Solids (TDS), conductivity, and dissolved oxygen in the water using the H198194 Hanna multiparameter probe. The on-site analysis measured the chemical parameters such as iron, manganese, nitrate, and nitrite using the HI-83399 photometer.

Water samples were collected at the 71st hour of the 72-hour constant pumping test. These samples were preserved and transported under controlled temperature conditions within 48 hours from the site to the ALS Laboratory in Shah Alam. A duplicate sample was also sent to the JMG laboratory in Ipoh for detailed analysis. The samples were analysed for 42 parameters in total. Selected laboratory results were compared with field data to validate consistency and reliability. Table 2 presents the in-situ water quality, while Table 3 compares the on-site and laboratory results for TW-02 at SK Kubang Palas. This serves as a form of data validation and verification.

Overall, the water quality was found to be within acceptable limits for most parameters, although there was a

**Figure 9:** In-situ and on-site water quality analysis conducted during constant pumping tests, measuring the physical and chemical parameters.

**Table 2:** The in-situ water quality measurements were taken during the constant pumping test using the Hanna multiparameter probes at 30 minutes, 24 hours, 48 hours, and 71 hours of pumping.

| Duration: Pumping test started on 5.30 pm, 27th October 2022 | 30 min after pumping started | 24 hours after pumping started | 48 hours after pumping started | 71 hours after pumping started |
|---|---|---|---|---|
| Date | 27/10/2022 | 28/10/2022 | 29/10/2022 | 30/10/2022 |
| Time | 6.00 PM | 5.30 PM | 5.30 PM | 4.30 PM |
| Temperature (°C) | 28.02 | 26.88 | 28.37 | 28.41 |
| pH | 6.79 | 6.28 | 6.59 | 6.61 |
| Conductivity (µs/cm) | 224 | 235 | 248 | 257 |
| Total Dissolve Solid (ppm) | 117 | 121 | 124 | 129 |
| Dissolve Oxygen (%) | 64.2 | 65.9 | 0.6 | 0.7 |
| Salinity (PSU) | 0.12 | 0.12 | 0.12 | 0.12 |

**Table 3:** The on-site water quality results, compared with laboratory analysis, show a close correlation and are compared to the raw water quality standards set by the Ministry of Health (KKM, 2004).

| Parameters | On-site analysis results | Laboratory analysis results | R.W.Q (KKM) |
|---|---|---|---|
| Chemical Oxygen Demand (COD) | 32 mg/L | 3 mg/L | 10 mg/L |
| Total Dissolved Solids (TDS) | 129 mg/L | 136 mg/L | 1500 mg/L |
| Manganese | 1.4 mg/L | 0.68 mg/L | 0.2 mg/L |
| Iron | 2.96 mg/L | 4.8 mg/L | 1.0 mg/L |
| Nitrite ($NO_2$) | 0 | 0.05 mg/L | - |
| Nitrate ($NO_3$) | 0.416 mg/L | <0.01 mg/L | 10 mg/L |

slight elevation in iron and manganese levels in some wells, which are typical in groundwater from sandstone formations.

To further interpret groundwater chemistry, Piper and Stiff diagrams were used to classify hydrochemical facies. Most wells exhibited a Calcium–Bicarbonate facies, indicating fresh groundwater influenced by carbonate dissolution and recharge processes. However, three wells (TW06, TW12, and TW18, refer to Figure 10) displayed Sodium–Chloride or Sodium–Magnesium–Chloride–Sulphate facies, which correlated with higher salinity and ion concentrations. These signatures were likely influenced by seawater intrusion, paleo-saltwater remnants, or agricultural runoff. These findings help explain groundwater quality variations across inland and coastal formations in Kedah.

## RESULTS

A total of 18 boreholes were drilled as part of the Groundwater Resources Mapping and Development Project (PABT Kedah) at mainland Kedah. The specific locations of the boreholes in the wellfields are shown in Figure 11.

This paper will focus on the 18 boreholes that were undertaken by VGX Sdn Bhd. The drilling process commenced in September 2022, following the completion of the initial ground conditions assessments and geophysical surveys to determine suitable drilling sites. During the initial phase of drilling, which lasted from September 2022 to December 2022, eight boreholes were completed. However, several difficulties prevented the team from reaching the targeted depth of 200 meters.

After evaluating these challenges and modifying drilling techniques, the remaining 10 boreholes, drilled between March 2023 and June 2024, successfully reached the 200-meter target depth. The following sections discuss the key challenges encountered during drilling and the specific solutions implemented to achieve success across various geological formations.

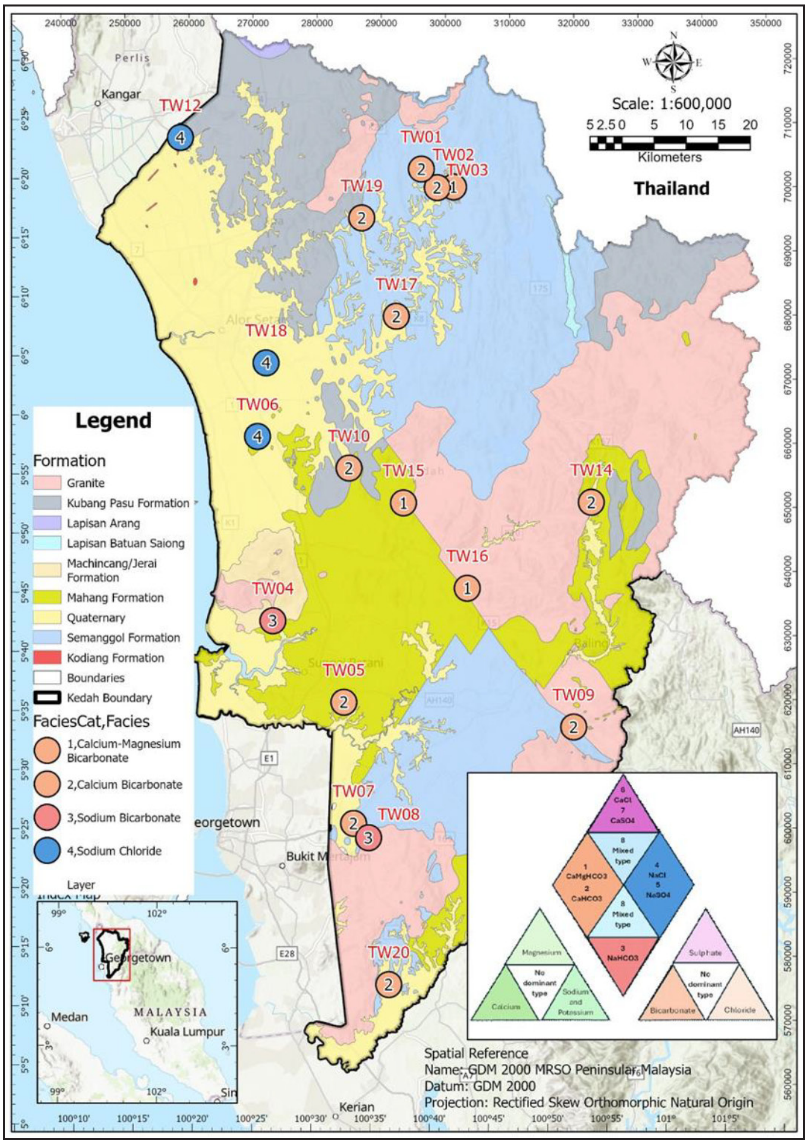

**Figure 10:** Distribution of groundwater hydrochemical facies in mainland Kedah.

## Drilling challenges

During the initial drilling stages in Kedah, various technical and geological challenges prevented the boreholes from reaching the targeted depth of 200 meters. High downhole pressure emerged as one of the significant obstacles, particularly in boreholes with substantial water yields, such as TW02 (Figure 12). High downhole pressure refers to the elevated pressure conditions encountered at depth in the borehole. In the case of TW02, this was caused by the high drilling yield (142 $m^3$/h). The water pressure prevented good contact of the hammer bit with the rock, which caused inefficient percussion, hindering progress. It was found that compressor power was inadequate to counteract the high downhole pressure.

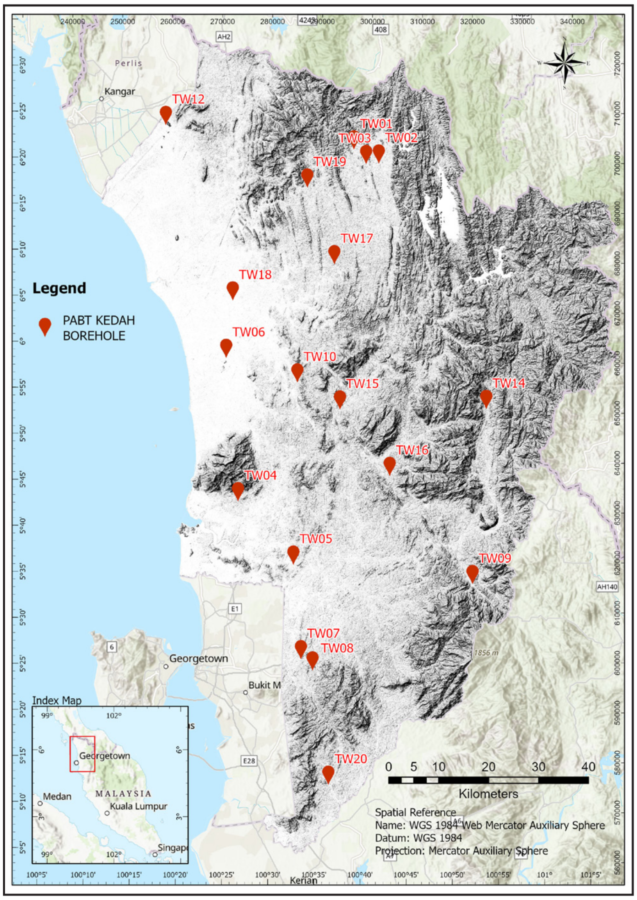

**Figure 11:** Location of the 18 wells drilled under the PABT Kedah Project.

Compressor performance proved to be a significant challenge throughout the drilling campaign. The initial compressor (1070 cfm @ 350 psi) struggled to counteract the high downhole pressure in the 10” diameter borehole, leading to equipment malfunctions, such as burst hoses. In addition, inadequate maintenance compromised compressor performance, leading to ineffective flushing of drill cuttings and accumulation of cutting in the borehole. For example, at TW05, the compressor rated at 300 PSI, experienced reduced efficiency due to insufficient maintenance.

TW05 (Figure 12) drilled into the Mahang Formation, which is composed predominantly of argillaceous shale and mudstone. These rocks are highly susceptible to weakening when exposed to water, which increases instability and the risk of wall collapse. Prolonged drilling at TW05 due to a number of reasons exacerbated these issues (refer to Table 4), leading to significant borehole wall failures and ultimately preventing the borehole from reaching the target depth of 200 meters.

Drilling in highly fractured formations, particularly near fault zones, presented additional challenges. TW07 (Figure 12) was drilled near a fault, probably a contact fault between the Bukit Mertajam-Kulim Granite and the Semanggol Formation. This borehole encountered extensive fracturing, which caused significant borehole instability. Large rock fragments frequently broke off and fell back into the borehole, repeatedly jamming the hammer bit. Although multiple cleanouts were performed, the compressor struggled to flush out the larger fragments effectively, further hindering the drilling progress at TW07. Figure 13 shows the large rock fragments removed during cleanouts.

The unpredictable characteristics and poor rock competency of fractured zones further complicated the

**Figure 12:** The figures depict drilling activities at site TW02 in Kuala Nerang, TW07 in Kulim, TW05 in Sungai Petani, and TW10 in Pendang.

**Table 4:** Summary of the drilling.

| Date of drilling | Well ID | Drilling period | Drilling depth | Formation | Lithology |
|---|---|---|---|---|---|
| 11/09/2022 – 04/10/2022 | TW02 | 23 days | 145 m | Semanggol | Interbedded shale and sandstone |
| 08/10/2022 – 22/10/2022 | TW08 | 15 days | 147 m | Granite | Weathered granite |
| 26/10/2022 – 12/11/2022 | TW07 | 17 days | 70 m | Semanggol | Interbedded shale and metasandstone |
| 23/11/2022 – 29/11/2022 | TW03 | 6 days | 120 m | Semanggol | Interbedded shale and sandstone |
| 02/12/2022 – 12/12/2022 | TW04 | 11 days | 61 m | Jerai | Pegmatite and metasandstone |
| 04/12/2022 – 15/12/2022 | TW09 | 12 days | 150 m | Granite | Chloritized granite |
| 15/02/2023 – 09/03/2023 | TW06 | 24 days | 122 m | Mahang | Interbedded shale and mudstone |
| 04/03/2023 – 19/05/2023 | TW05 | 75 days | 103 m | Mahang | Interbedded shale and mudstone |
| 23/06/2023 – 23/07/2023 | TW10 | 30 days | 210 m | Mahang | Interbedded shale and mudstone |
| 28/07/2023 – 31/07/2023 | TW01 | 3 days | 204 m | Semanggol | Interbedded shale and sandstone |
| 23/09/2023 – 24/09/2023 | TW12 | 2 days | 202 m | Kubang Pasu | Limestone |
| 06/10/2023 – 19/10/2023 | TW14 | 14 days | 202 m | Mahang / Baling group | Interbedded limestone and shale |
| 20/032024 – 21/03/2024 | TW15 | 2 days | 224 m | Mahang | Interbedded shale and mudstone |
| 29/03/2024 – 31/03/2024 | TW16 | 3 days | 207 m | Granite | Granite |
| 07/04/2024 – 09/04/2024 | TW17 | 3 days | 202 m | Semanggol | Interbedded shale and sandstone |
| 26/04/2024 – 28/04/2024 | TW18 | 3 days | 202 m | Kubang Pasu | Interbedded shale, mudstone and sandstone |
| 11/05/2024 – 13/05/2024 | TW19 | 3 days | 202 m | Semanggol | Interbedded sandstone and mudstone |
| 27/05/2024 – 1/06/2024 | TW20 | 6 days | 200 m | Semanggol | Interbedded mudstone and sandstone |

**Figure 13:** The large rock fragments flushed out during drilling at TW07.

drilling, increasing the risk of borehole collapse and equipment entrapment. At TW10 in the Mahang Formation (Figure 12), a fractured zone was encountered at a depth of 38 meters, yielding 20 m³/h. The high-yielding fractured zone continuously produced displaced rock fragments, leading to borehole collapse. As a result, the drill bit and rods became stuck in the borehole. Their extraction required several days and the use of specialised tools by a separate team, causing substantial delays (Table 4).

The original borehole design proposed a 12-inch temporary casing until hardrock was encountered, followed by a 10-inch borehole drilled to a depth of 200 meters. This design was initially implemented at SK Kubang Palas using a Foremost DR-24 Dual Rotary Drive Truck-Mounted Drilling Rig, equipped with a 1070 cfm @ 350 psi compressor. However, drilling was only completed to a depth of 145 meters.

## Improvements implemented

To address the drilling challenges encountered during the initial phase, several strategic adjustments were made to the drilling specifications and techniques. The most significant improvement was reducing the diameter of the borehole.

Initially, the borehole design involved using a 12-inch temporary casing, followed by a 10-inch drill bit for the entire depth. However, drilling with the 10-inch bit proved ineffective beyond 70 meters, particularly in hardrock formations with high downhole pressure. The large borehole diameter posed challenges in reaching the target depth of 200 meters. As drilling progressed, the larger diameter resulted in slower penetration rates and increased equipment strain, particularly on the compressor when the downhole pressure increased due to the high discharge yield. The larger bit size required more power to maintain drilling efficiency as the depth increased.

To overcome this issue, a telescopic approach was introduced. When drilling with the 10-inch bit became challenging, the bit size was reduced to 8 inches. This approach allowed drilling to proceed beyond 100 meters but still failed to reach the targeted depth of 200 meters. The transition between the 8-inch and 10-inch borehole sections caused a drop in air–water pressure, reducing efficiency of the flushing of drill cuttings. As a result, cuttings accumulated at the borehole base, hindering further drilling.

The telescopic approach aimed to optimise air-water pressure within the borehole and facilitate better cuttings removal by reducing the borehole diameter. However, the transition between the 8-inch and 10-inch sections resulted in pressure losses that hindered cuttings removal. Therefore, the new approach involved drilling entirely with an 8-inch drill bit after the installation of 10-inch temporary casing. This change allowed for more efficient hammering and drilling through the harder rock formations to achieve the target depth of 200 meters.

This method proved to be highly effective, enabling VGX to consistently reach depths of 200 meters in the remaining 10 boreholes. By reducing the borehole diameter to 8 inches, air pressure within the borehole became more consistent, facilitating more efficient hammering and cuttings removal. This improvement also significantly reduced equipment failures, such as compressor hose bursts and hammer bit jams, which had previously caused significant delays. Compressors with a minimum capacity of 350 PSI and 1100 CFM were adequate to manage high pressure in deeper sections of the boreholes at this diameter, allowing drilling to continue smoothly in high-pressure zones without experiencing delays such as those encountered in earlier boreholes.

### Improved drilling efficiency

Table 4 presents the drilling data, highlighting the substantial improvements in drilling duration following changes in borehole diameter. For instance, TW01 and TW12 reached depths of 204 meters and 202 meters in just 3 days and 2 days respectively, compared to TW02 and TW05, which required 23 days and 75 days to drill only 145 meters and 103 meters respectively. This represents an average 70% reduction in drilling time for the remaining wells, which was achieved through the use of an 8-inch borehole diameter that provided better control over air pressure and allowed for more efficient hammering and flushing of cuttings using a rig equipped with a 350 psi, 1100 cfm compressor. The result was a 100% success rate in achieving the targeted drilling depth of 200 meters across all remaining boreholes, even in challenging geological conditions.

### Reduction in equipment failures

Another key advantage of reducing the borehole diameter was the significant decrease in equipment failures. Prior to this improvement, frequent delays were caused by compressor hose breakdowns and hammer bit jams, for example at TW05, which experienced multiple equipment failures and took 75 days to complete, despite only 17 days of actual drilling. After reducing the borehole diameter to an 8” borehole, equipment failure rates dropped by approximately 80%, leading to fewer mechanical interruptions and resulting in faster, more reliable drilling operations.

### Stability in fractured zones

In addition to improving time efficiency, the reduced borehole diameter also enhanced borehole stability in highly fractured zones. By increasing drilling speed, the borehole walls remained more stable, minimising issues related to collapse in fractured formations.

To further improve stability, temporary casing was installed down to fresh bedrock, which helped prevent the collapse of overlying alluvial layers. For instance, TW10 showed significantly improved borehole stability after the fractured zones were sealed off with temporary casing.

One of the highlights of our drilling operation was avoiding using bentonite or other drilling muds, though it is often used by drillers to prevent the collapse of fractured walls. This decision was made to prevent bentonite from entering and clogging fracture openings, which could reduce well yield unless thoroughly removed during borehole development. The use of bentonite and other drilling muds can necessitate tremendous effort during well development to clean the borehole and formation to obtain maximal possible groundwater water flow into the borehole.

### Overall impact

The cumulative impact of these improvements led to a reduction in average drilling time from 23 days per well to just 3-4 days in later boreholes, while enabling all boreholes to reach the targeted depth of 200 meters. By stabilising air pressure requirements, reducing equipment failures, and improving drilling efficiency, these procedural changes allowed the project to achieve a consistent success rate, even in geologically challenging formations.

### PVC installation and well development

During the initial drilling work, challenges were also encountered during the installation of PVC casings, primarily due to unexpected borehole conditions. Although the initial well design appeared adequate, practical difficulties arose. Sediment accumulation and the uneven borehole walls created significant obstacles, complicating the proper installation of PVC casings to the well design depths.

A significant improvement occurred with the introduction of regular well flushing, conducted not only after reaching the targeted depth but also at each rod change during the drilling process. This regular flushing more effectively removed sediment and fine cuttings that settled in the borehole, reducing obstructions and facilitating the PVC installation process.

Additionally, downhole geophysical logging was carried out immediately after the drilling to obtain accurate data on the borehole’s condition. This logging data was vital for optimising the well design to correlate with the borehole lithology and character to maximise groundwater flow. The exact placement of the screen was determined based on the geological and geophysical logging, ensuring an integrated approach to the well design to optimise the water flow into the borehole.

Where the caliper log from the geophysical survey indicated uneven walls or irregular borehole dimensions, reaming with a roller bit was a necessity to smoothen the borehole walls. This reaming process ensured a more uniform borehole diameter and wall smoothness, enabling the PVC casing to be installed as planned. Figure 14 shows the image of the uneven borehole condition captured by the camera probe during the downhole geophysical logging.

By implementing these measures—prolonged flushing, geophysical logging, well reaming, and with proper well design—the PVC installation process became significantly more efficient. These improvements resulted in a more effective well design and well development that enhanced groundwater abstraction from these wells.

## CONCLUSION

In conclusion, the Groundwater Resources Mapping and Development Project (PABT Kedah) encountered a range of technical and geological challenges during the drilling of the boreholes in fractured hardrock aquifers. Key challenges included high downhole pressure, equipment limitations, and difficulties arising from encountering highly fractured and weathered formations, which initially impeded the boreholes from reaching the target depth of 200 meters.

To address these issues, strategic improvements were implemented, such as optimising the borehole diameter to reduce stress on drilling equipment, ensuring the effective installation of temporary casing until fresh hardrock, and conducting comprehensive pre-drilling assessments of equipment and machinery conditions. These measures not only enhanced drilling efficiency but also contributed to the successful completion of the boreholes to depths of 200 meters.

These findings provide valuable insights into groundwater exploration in fractured hardrock aquifers, particularly in Kedah, where reliance on surface water remains high despite untapped groundwater potential. The results demonstrate how strategic drilling adaptations can improve success rates, reduce drilling time, and enhance well performance in challenging geological settings. By documenting the challenges encountered and the solutions implemented, this study serves as a reference for future groundwater development projects in Malaysia and other regions with similar hydrogeological conditions.

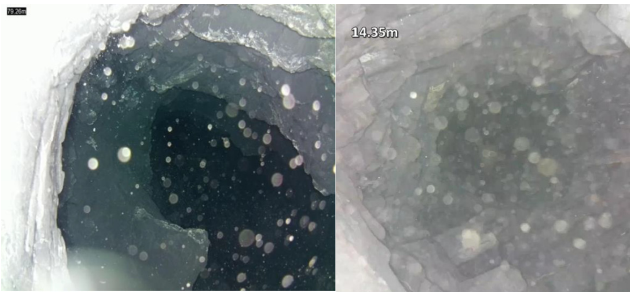

**Figure 14:** Images above shows the borehole condition captured by the camera probe during the downhole geophysical logging at TW01. The drillers were advised to do the reaming using the roller bit to smoothen the borehole wall before the PVC installation.

The lessons learned from this project offer practical guidance for future groundwater initiatives, particularly in complex hardrock environments. Applying these strategies to similar projects can enhance groundwater resource development, ensuring a reliable water supply while mitigating drilling risks. Ultimately, this project contributes to advancing drilling practices and improving our understanding of groundwater extraction in fractured hardrock aquifers.

## AUTHORS CONTRIBUTION

VVR conceived the study and contributed to downhole geophysical interpretations and well development analysis. PSD conducted the geological and hydrogeological analysis and led the writing of the manuscript. VVR and ZAS verified the drilling techniques and hydrogeological assessments. VVR, ZAS, and ACM supervised the project, provided technical guidance, and reviewed the manuscript.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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