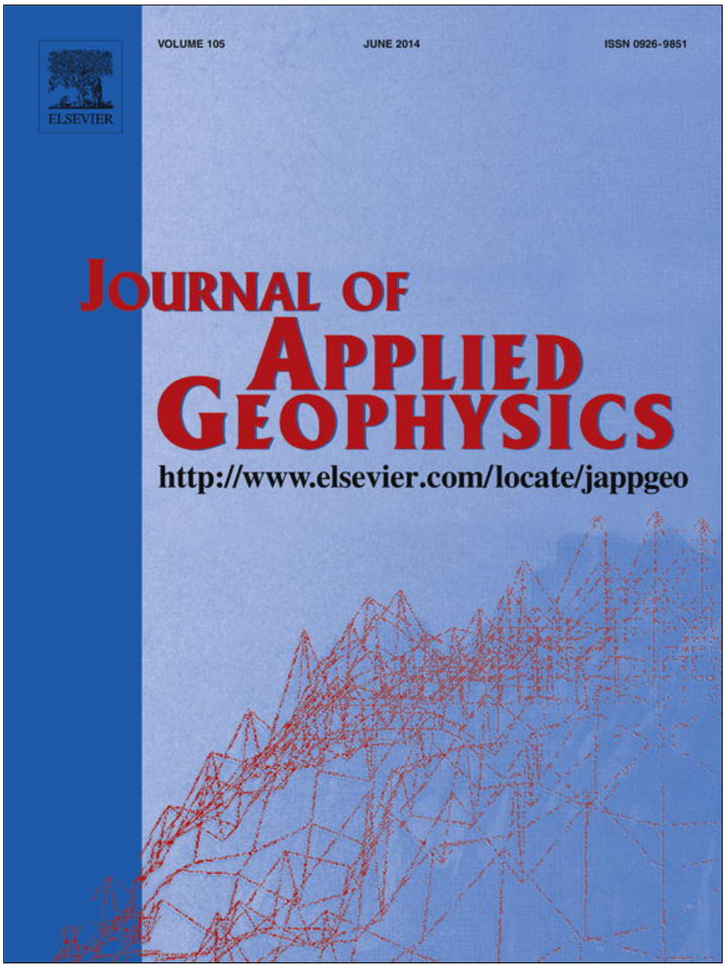
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The combined use of heat-pulse flowmeter logging and packer testing for transmissive fracture recognition

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ABSTRACT

This paper presents an improved borehole prospecting methodology based on a combination of techniques in the hydrogeological characterization of fractured rock aquifers. The approach is demonstrated by on-site tests carried out in the Hoshe Experimental Forest site and the Tailuge National Park, Taiwan. Borehole televiewer logs are used to obtain fracture location and distribution along boreholes. The heat-pulse flow meter log is used to measure vertical velocity flow profiles which can be analyzed to estimate fracture transmissivity and to indicate hydraulic connectivity between fractures. Double-packer hydraulic tests are performed to determine the rock mass transmissivity. The computer program FLASH is used to analyze the data from the flowmeter logs. The FLASH program is confirmed as a useful tool which quantitatively predicts the fracture transmissivity in comparison to the hydraulic properties obtained from packer tests. The location of conductive fractures and their transmissivity is identified, after which the preferential flow paths through the fracture network are precisely delineated from a cross-borehole test. The results provide robust confirmation of the use of combined flowmeter and packer methods in the characterization of fractured-rock aquifers, particularly in reference to the investigation of groundwater resource and contaminant transport dynamics.

1. Introduction

Increasing attention has been paid in recent years to the identification and characterization of transmissive fracture zones in otherwise nearly impermeable crystalline and sedimentary rocks in the mountainous areas of Taiwan. This interest has been prompted by rising environmental concerns surrounding the country's rural development. The major focus in such studies is on assessing the distribution of fracture networks and quantifying permeability at different depths in bedrock formations. However, there is rarely any obvious correlation between lithology and structure and the distribution of hydraulically conductive fracture systems in a heterogeneous mountainous environment (Gustafson and Krásný, 1994). One can probably assume the direction of groundwater flow to be topographically dependent on a catchment scale but one cannot simply describe the flow regime as a subdued replica of the landscape on a local scale. Large uncertainties unavoidably remain in determining the presence and location of preferential flow paths attributed to past tectonic activity (Chia et al., 1986).

In general, the internal hydrogeologic structure of bedrock serving as the primary control of base flow production but does not always coincide with local topography (Asano and Uchida, 2012). Many of the hydrogeological investigations reported in the literature are therefore concerned with the heterogeneous and anisotropic nature of the fractured bedrock aquifer. For example, the borehole testing results of Gustafson et al. (1991) indicated that 44% to 61% of fractures in granite are non-conductive. Tanaka and Miyakawa (1992) reported that highly conductive intervals within a borehole are correlated with the presence of densely fractured zones. In similar investigations, Hamm et al. (2007) demonstrated that hydraulic transmissivity is more closely related to fracture aperture than to fracture frequency. Ku et al. (2009) and Lo et al. (2012) have proposed different empirical models for transmissivity prediction based on televiewer logging and hydraulic test data. Their results show that by considering rock quality designation (RQD), gouge content designation (GCD), fracture width and lithology permeability index, a rational prediction of rock mass transmissivity can be made on a catchment scale comparison. Chou et al. (2012) also proposed an empirical criterion for identifying hydraulically conductive fractures applicable to both sedimentary and metamorphic rocks. Their study showed that by considering the fracture geometries as the necessary premise, a priori accurate prediction of the highly transmissive fractures can be obtained. Furthermore, applications of the cross-borehole investigation techniques in defining a hydraulic connection between discrete fractures and preferential flow have been adopted by many researchers (Hess, 1986; Le Borgne et al., 2006; Paillet et al., 1987; Williams and Paillet, 2002). Their studies prove that such an approach is simple and efficient for a larger-scale fractured bedrock investigation. This approach is particularly suitable for the investigation of groundwater

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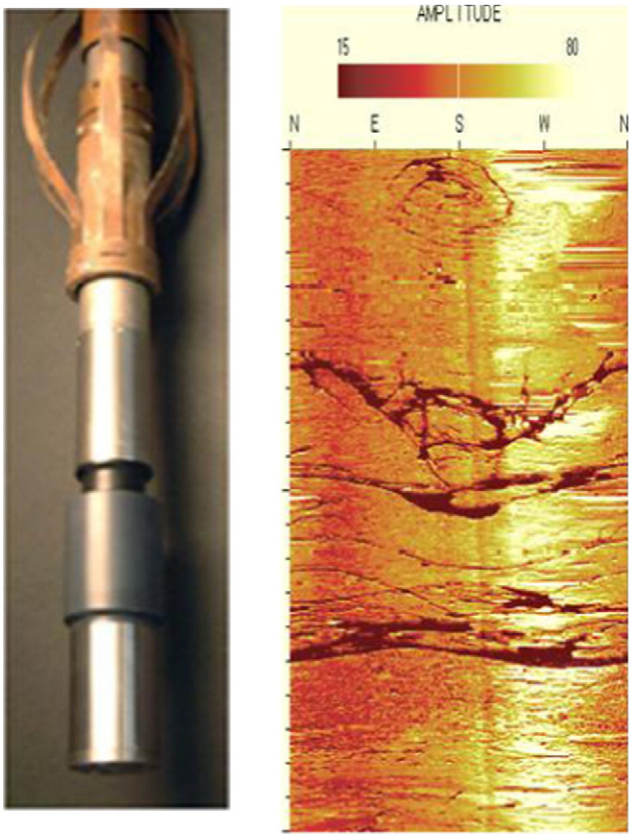

Fig. 1. Acoustic televiewer and scanned borehole image.

resource management, contaminant migration analysis, and mine-drainage system design (Paillet et al., 2012).

2. Investigation technologies

The demand for alternative water resources in mountainous areas is expected to continue to rise in Taiwan over the next decade. In order to contribute to a better understanding of the localized groundwater flow regime in a fractured-bedrock aquifer, the overall goal of this study is to present a rational approach for integrating the results and from different borehole investigation methods having various levels of resolution and depths of investigation. Borehole televiewer logging, flowmeter logging, and packer testing are performed at two different sites in this study according to the environmental conditions and financial resources of the study site. These techniques are described as follows.

2.1. Borehole televiewer logging

In situ fracture imaging using the acoustic borehole televiewer to characterize the distribution of fractures along the borehole axis has long been used in various field investigations (Williams and Johnson, 2004). This technique offers 360-degree borehole-wall imaging as the probe is moved along a water or mud-filled borehole. Relevant geologic features and structural discontinuities can be assessed in terms of the location, orientation, angle, width, and infilling material of fractures and other planar features such as bedding planes and foliation. In addition, borehole imaging can reduce uncertainties associated with conventional rock core drilling techniques, such as the representation of missing intervals (lost core) and the dislocations that can arise from damage during handling or inadequate recording (Kierstein, 1990; Williams and Johnson, 2004). The high resolution acoustic televiewer (HiRAT) was used in this study, which uses a fixed acoustic transducer and a rotating acoustic mirror system to acquire the acoustic signal reflected from the borehole wall. The amplitude of the reflected acoustic signal is simultaneously recorded and converted to a photograph-like image (Fig. 1).

2.2. Heat-pulse flowmeter logging

The heat-pulse flowmeter (HPFM) used in this study consists of a wire-grid heating element and two sensitive thermistors (heat sensors) that are positioned above and below the wire grid. The annulus between the measurement section of the probe and the borehole wall is sealed with a flexible rubber disk in order to force all of the borehole flow through the instrument's measurement tube. A pulse of heat is generated by capacitor discharge through the wire grid and migrates toward one of the thermistors, depending on the direction and rate of groundwater flow. The vertical flow velocity can be computed from the time required for the thermal pulse to pass the thermistors using a flow calibration derived in the laboratory (Fig. 2). Under steady flow conditions with a stable borehole water level, the vertical distribution of the groundwater flow can be obtained by making consecutive measurements of water flux at different depths along the borehole. Borehole flowmeter logging not only provides useful information to characterize an aquifer's permeability, but also aids in identifying the location of the water-producing/receiving zones and fracture connectivity (Gellasch et al., 2012; Le Borgne et al., 2004; Lee et al., 2012; Muldoon et al., 2001; Paillet et al., 1987, 2012; Williams and Paillet, 2002). In addition, Miyakawa et al. (2000) pointed out that HPFM logging often has to be carried out by either pumping water into or extracting water out from the borehole because it is difficult to detect hydraulic pathways under ambient conditions with low groundwater velocities or no vertical gradient to drive flow between fractures intersecting the borehole.

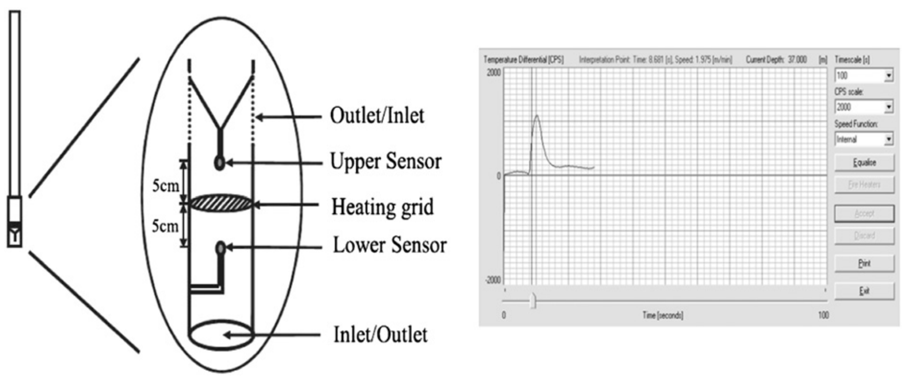

Fig. 2. Schematic drawing of flowmeter (left); and heat-pulse curve (right: the elapsed time in X-axis and the temperature difference measured by the thermistor in Y-axis) (revised after Lee et al., 2012).

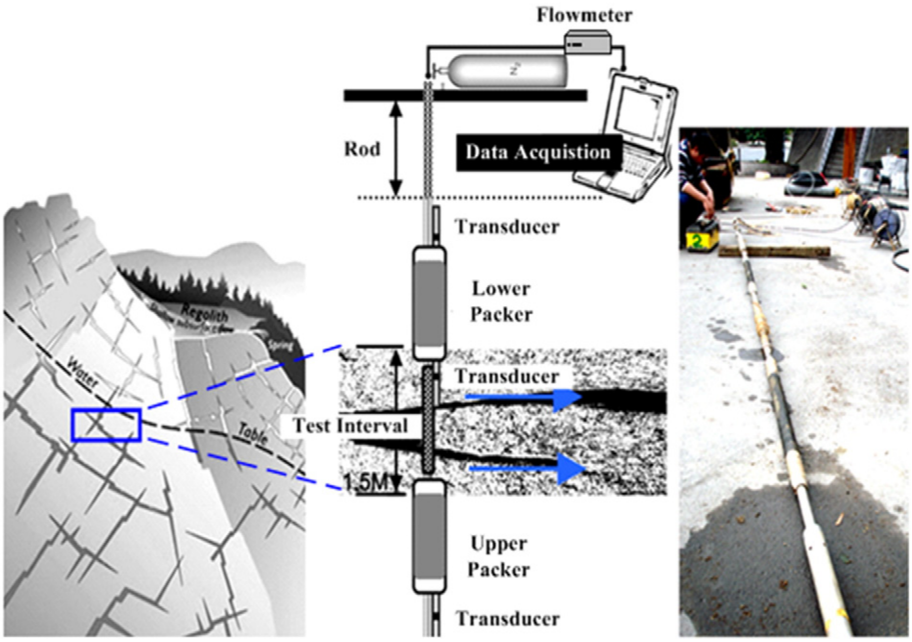

Fig. 3. Schematic drawing of double packer system.

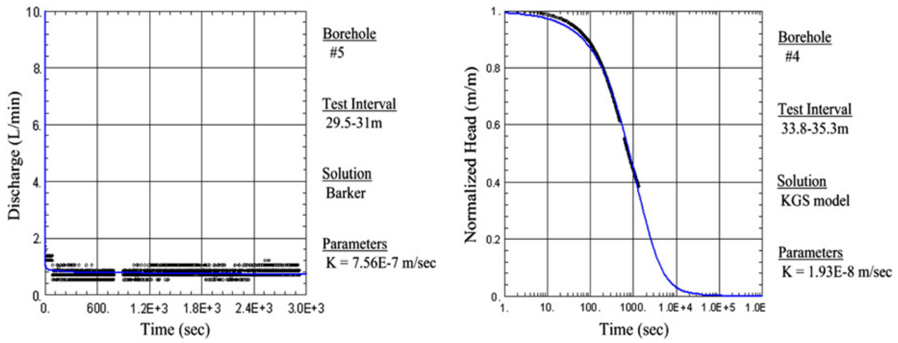

Fig. 4. The hydraulic parameters computed using AQTESOLVE: constant flow test data (left); and pressure pulse test data (right).

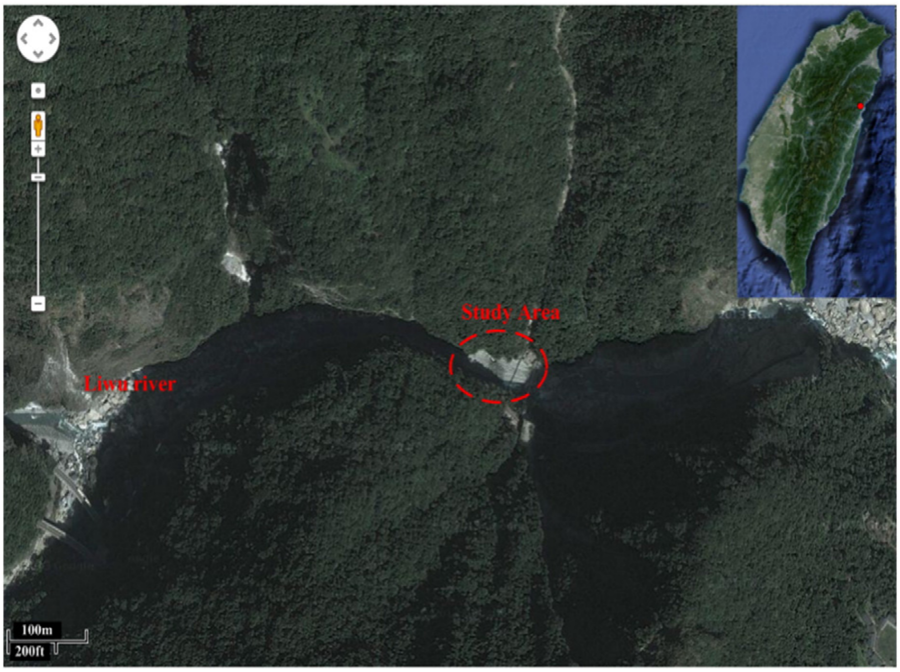

Fig. 5. Aerial photo of the Tailuge test site.

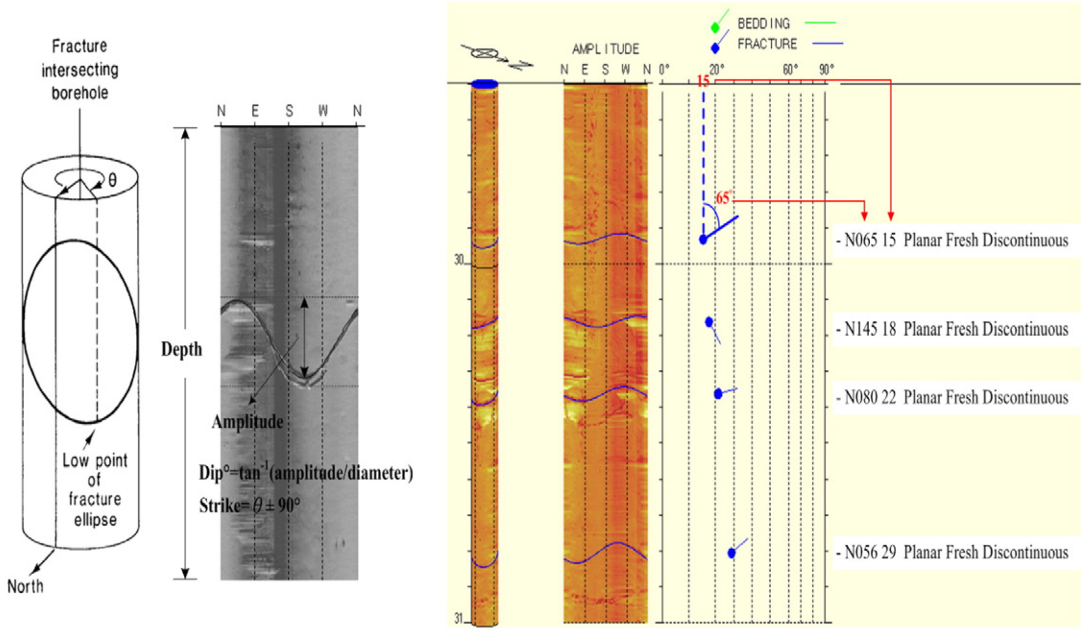

Fig. 6. Fracture strike and dip determination from televiewer logging (revised after Paillet et al., 1987) (left); and fracture orientation calculated by Rgldip 6.0 (right).

2.3. Double packer hydraulic test

The double-packer hydraulic test is one of the most common approaches applied when determining the transmissivity and storage coefficient along discrete sections of a borehole. This approach allows the investigation of the spatial variability of permeability and flow in a borehole that is intersected by various hydrogeological units (Chou et al., 2012; Ku et al., 2009; Lo et al., 2012; Miyakawa et al., 2000). In this study, the test was conducted by isolating a 1.5 m long section within the borehole and observing the variation of injected flow rate and pressure over a period of time. The system consisted of two inflatable rubber packers, a shut-in valve, flowmeters to measure the rate of injection, a submersible pump, and three transducers for measuring the piezometric pressure in the isolated interval and in the areas above and below the packers (Fig. 3). The rubber packers were inflated with nitrogen delivered from a gas cylinder. The shut-in valve was used to open and close the hydraulic connection between the pipe string and the test section. The injection rate was measured by a flowmeter at the land surface. The relevant hydraulic data (piezometric pressure, time, flow rate, etc.) were analyzed using the software AQTESOLV (HydroSOLVE Inc., Reston, VA), which allows both virtual and automatic curve matching (Duffield, 2004) (Fig. 4). The quantitative evaluation of hydraulic parameters was carried out as an iterative process of the best fit theoretical response curves based on the measured test data.

3. Prediction fracture transmissivity using FLASH program

The first investigation was performed at a test site in Tailuge National Park, Hualien, Taiwan. The site is located in the Liwu River basin of eastern Taiwan, with the elevation of 237 m above sea level and a topographic slope of 6.0° (Fig. 5). A borehole was drilled to a depth of 100 m at the test site using a combination of mechanical and pneumatic drilling rigs with HQ bits (borehole diameter of 10 cm). Rock samples were collected and allowed for an initial lithostratigraphic classification. According to data obtained during drilling, the formation can be divided into three units: regolith (0 to 15.7 m), weathered marble bedrock (15.7–20.1 m), and fresh marble bedrock (20.1 to 100 m). The groundwater level was about 19 m below the land surface.

The locations of fractures and the density of fracturing were first determined using the borehole televiewer logs. The orientation (dip direction, dip, and azimuth) and distribution of fractures or fracture zones on the continuous and oriented 360° view of the borehole wall were calculated using the post-processing software Rgldip 6.0 (Robertson Geologging, Ltd. UK) (Fig. 6). Stereographic projection analysis of the determined fracture orientations identified the primary orientation (dip direction/dip) of fractures as N302/66 (Fig. 7). Heat-pulse flowmeter logging was then conducted under both ambient (non-pumping) and pumping conditions. The measurements were made at one-meter intervals and the vertical flow profile along the borehole was obtained. In this study, the calibration of measured flowmeter response is based on the work of Lee et al. (2012), who conducted laboratory tests to relate known flow velocities

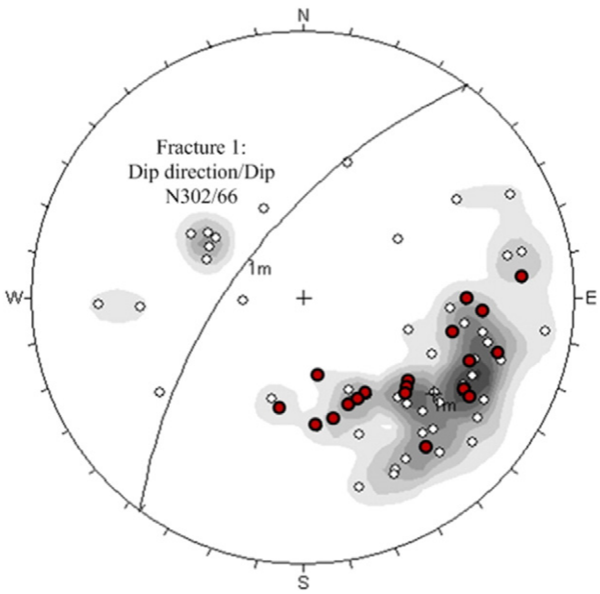

Fig. 7. Stereographic plot (equal area, lower hemisphere) of the Tailuge test site.

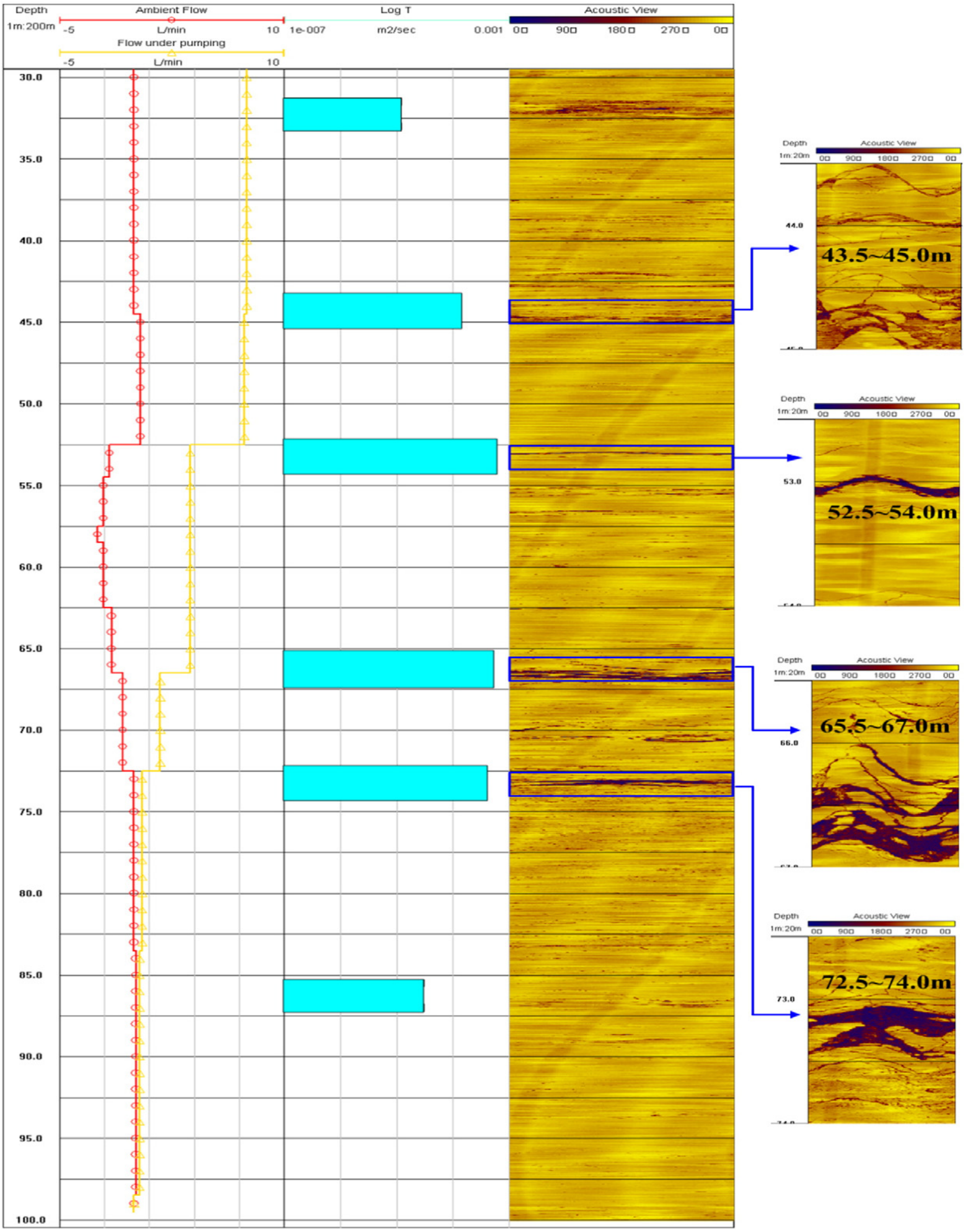

Fig. 8. Ambient and injection flow profile measured by the flowmeter; transmissivity obtained by the packer test; and borehole televiewer log of borehole EH-03.

Table 1
Prospecting data of different test intervals in borehole EH-03.

Borehole	Test interval	Average fracture dips	Amount of fractures/fracture zone	Transmissivity (m^2/s)	Groundwater recharge or discharge
EH-03	31.5–33.0	60.6	3/0	1.22×10^{-5}	
	43.5–45.0	56.3	6/1	1.41×10^{-4}	Discharge
	52.5–54.0	50.3	3/1	5.66×10^{-4}	Recharge
	65.5–67.0	69.0	4/1	4.95×10^{-4}	Discharge
	72.5–74.0	49.5	2/1	4.14×10^{-4}	Discharge
	85.5–87.0	73.4	3/0	3.15×10^{-5}	

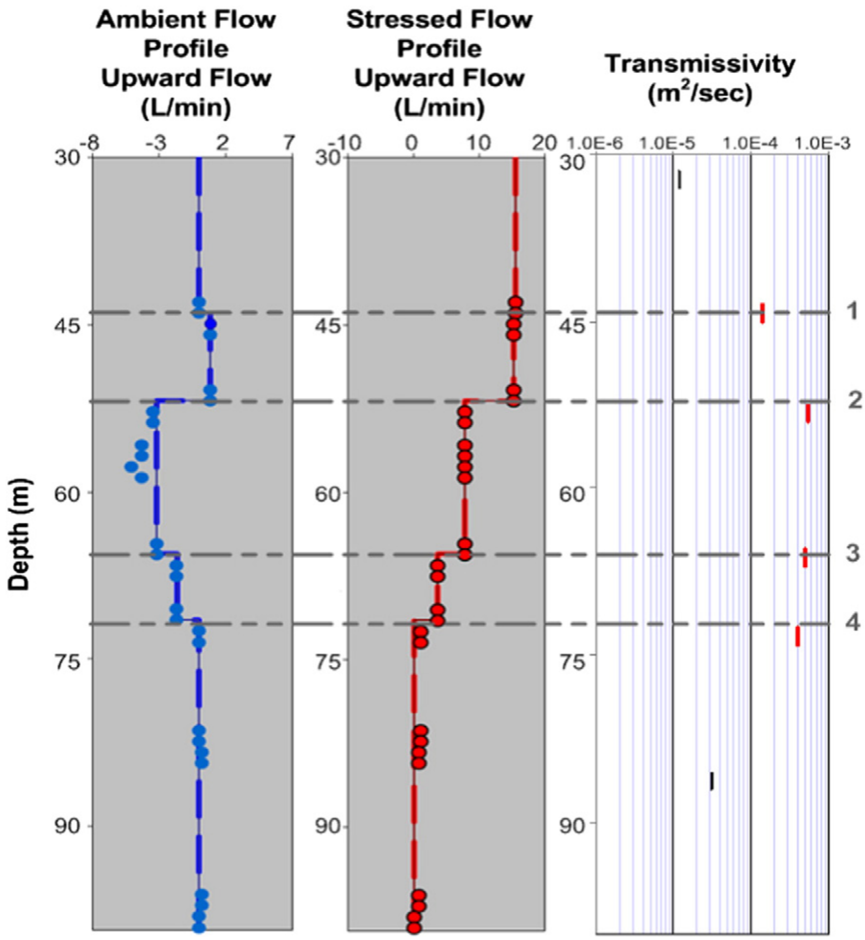

Fig. 9. Cross-comparison of flow profile required from the FLASH program (circles: measured data; line: simulated results) and transmissivity of borehole EH-03.

in calibration tubes to the corresponding heat-pulse flowmeter response given units of pulse travel time. In the pumping stage of the tests, a submersible pump and piezometer were inserted in the well at the depth of 23 m and 27 m, respectively. The pump was connected to the flow meter and controller and was thus able to control the pumping rate at the land surface. Water was extracted from the well with a constant rate of 8 L/min and maintained for 2 h. The drawdown was measured every 30 s by the piezometer. The flowmeter log was run once the drawdown was stabilized at about 0.5 m below the initial groundwater level. The composite of flow logs shown in Fig. 8 indicates that the flow rates at depths of 44–45 m, 52–53 m, 66–67 m, and 72–73 m show sharp changes under both ambient and pumped conditions. The upward flow increased at depths of 66–67 m and 72–73 m under the ambient condition, indicating permeable fractures that may connect to hydraulic head with strong recharge potential. In contrast, the upward flow was significantly reduced at the depth of 52–53 m, where the fractures have a strong discharge potential. When additional groundwater flow was induced in the well by pumping, we measured significant increases of upward flow in the above mentioned fracture sections.

Six intervals were selected for packer testing and the transmissivity was determined through the data of piezometric pressure, time, flow rate, etc. As the results show in Fig. 8 and Table 1, there was a reasonable agreement between the flowmeter log and packer test data. The transmissivity in each of the intervals associated with inflow during pumping on the flow logs is high (geometric mean T: 3.59×10^{-4} m^2/s). Clearly, the most permeable fractures are present in these sections. In contrast, the transmissivity outside of those intervals is relatively low (geometric mean T: 1.95×10^{-5} m^2/s). The fractures in the conductive intervals described above are indicated by the red dots in the stereographic plot (Fig. 7). Most conductive fractures are located within the major fracture clusters showing that the fracture permeability at the Tailuge National Park site is related to local geological structure.

A computer program FLASH (Flow-Log Analysis of Single Holes; Day-Lewis et al., 2011) was used to estimate fracture transmissivity based on flowmeter logging data acquired under the ambient and

Table 2
Transmissivity computed from the FLASH program and the packer test for 4 conductive fracture sections of borehole EH-03.

Fracture	FLASH			Packer test	
	Depth (m)	Fraction of total transmissivity (%)	Transmissivity (m^2/min)	Test interval (m)	Transmissivity (m^2/min)
1	44.0	7.6	8.61×10^{-5}	43.5–45.0	1.41×10^{-4}
2	52.0	22.1	1.47×10^{-4}	52.5–54.0	5.66×10^{-4}
3	66.0	36.4	2.43×10^{-4}	65.5–67.0	4.95×10^{-4}
4	72.0	33.9	2.26×10^{-4}	72.5–74.0	4.14×10^{-4}

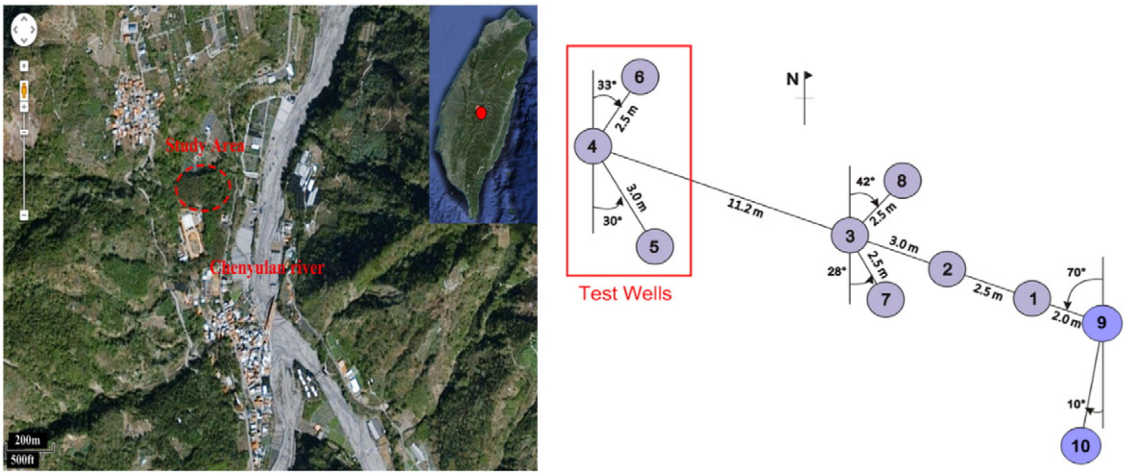

Fig. 10. Aerial photo and borehole distribution of the Hoshe test site.

pumped (injected) flow conditions in the same well. The program is based on the multi-layer Theim equation of confined radial flow in a fractured or porous aquifer (Thiem, 1906). When under ambient or stressed (pumping or injection) conditions, the equations are written as (Day-Lewis et al., 2011):

$$Q_i^a = -\frac{2\pi T_i^{factor} T^{total}\left(h_w^a - h_i^0\right)}{ln(r_0/r_w)} \tag{1}$$

$$Q_i^s = -\frac{2\pi T_i^{factor} T^{total}\left(h_w^s - h_i^0\right)}{ln(r_0/r_w)} \tag{2}$$

where: Q_i^a and Q_i^s are the volumetric flow in the well under ambient and stressed conditions, respectively; T^{total} is the total transmissivity of aquifer; T_i^{factor} is the transmissivity of each individual fracture; h_w^a is the groundwater level in ambient condition; h_w^s is the groundwater level in stressed condition; h_i^0 is the far-field hydraulic head of each individual layer; r_w is the radius of the well; and r_0 is the radius of the influence such that that there is no change in groundwater level outside r_0 during pumping or injection. In this study, T^{total} was obtained by performing a single packer test in EH-03. The test interval is set from 30 to 100 m, which is consistent with the flowmeter logging. Q_i^a and Q_i^s were obtained from flowmeter logging. r_w, h_w^a and h_w^s were directly measured in the experiment. The radius of influence, r_0, is assumed based on the topography of groundwater recharge distance. As indicated by Day-Lewis et al. (2011), the estimated transmissivity is not sensitive to assumed r_0 as it appears inside the logarithm in Eqs. (1) and (2).

The flow profile and transmissivity estimates from the FLASH program are shown in Fig. 9. It is apparent that 4 permeable fracture sections were delineated at depths of 44 m, 52 m, 66 m, and 72 m, where the last three fracture sections have a higher capacity to transmit water (comprising more than 93% of total borehole permeability). The transmissivity values that are derived from the FLASH program and the packer test are shown in Table 2. The computed values from the FLASH program closely match the results of the packer test, thereby confirming that the FLASH program provides a quick and reasonable estimate of fracture transmissivity.

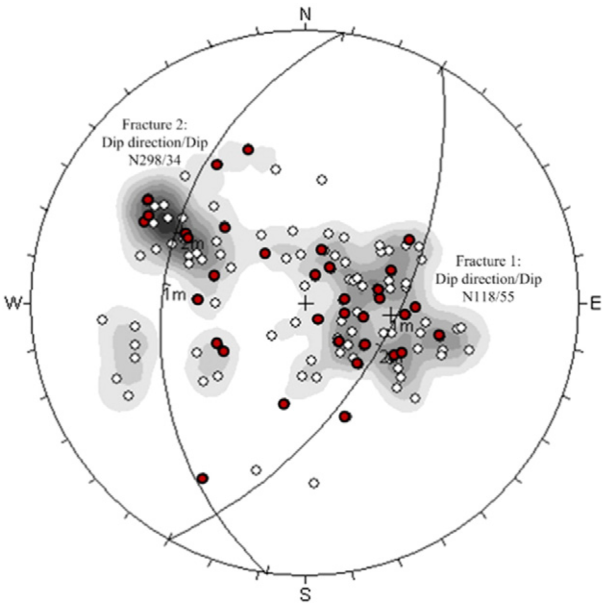

Fig. 11. Stereographic plot (equal area, lower hemisphere) of the Hoshe test site.

4. Cross-hole test to characterize fracture connectivity

The second test was conducted in the Hoshe Experimental Forest in Nantou. The site is located in the Chenyulan River basin of central Taiwan, with an elevation of 749 m above sea level and a topographic slope of 26.2° (Fig. 10). The site is covered with a Quaternary terrace deposit of unconsolidated material (gravel, sand, and silt). Ten boreholes were drilled to depths ranging from 35 m to 45 m, with a diameter of 10 cm. According to data obtained during drilling, the rocks encountered by the borehole can be divided into two major geologic units: regolith (0 to 20 m) and fresh fine-grained sandstone with minor amounts of quartz vein (20 to 40 m). Groundwater level was about 8 m below the land surface. In order to prevent the collapse of the loose soil in the shallow layer, PVC surface casing (9.6 cm diameter) was installed above the bedrock part of the borehole. In this study the preliminary investigation is focused on boreholes #4, #5, and #6, with depths of 45 m, 35 m, and 35 m, respectively and separations of 2.5 m to 3 m.

Televiewer logs were first obtained to identify the location of fractures and degree of fracturing in the three boreholes. According to stereographic projection analysis, the major fracture orientations can be divided into two sets: N118/55 and N298/34 (Fig. 11). Ambient flow measurements were then made at one-meter intervals in borehole #4 and borehole #5. As the results show in Figs. 12 and 13, obvious changes in flow rate were found at depths of 23–24 m, 29–30 m, and 42–43 m in borehole #4. Similar flow zones were found at the depths

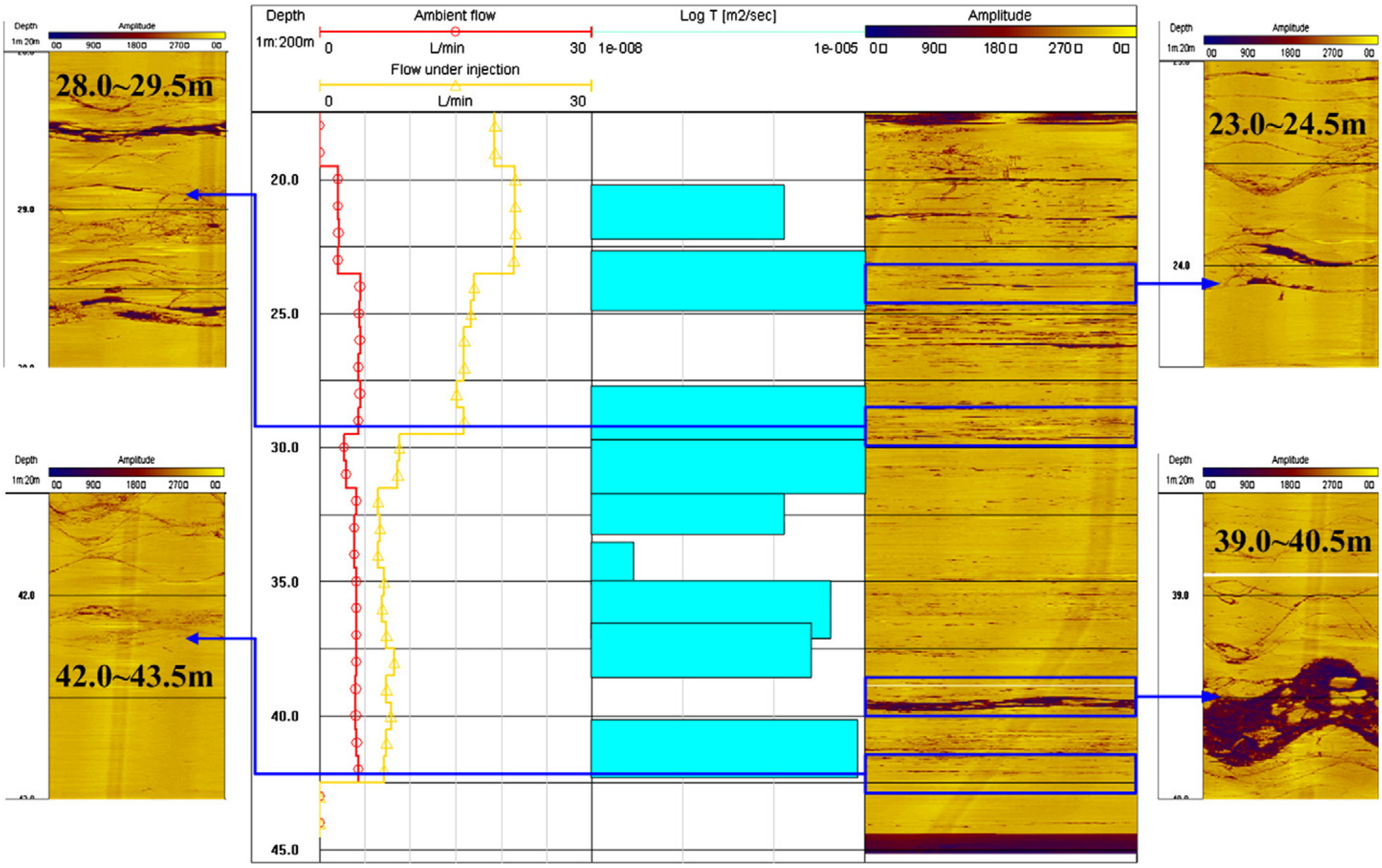

Fig. 12. Ambient and injection flow profile measured by the flowmeter; transmissivity obtained by the packer test; and borehole televiewer log of borehole #4.

of 22–23 m and 29–30 m in borehole #5. These changes in flow rate were attributed to transverse flow in these highly permeable intervals either augmenting or depleting the rate of vertical flow along the borehole, thus inducing a sharp change in vertical flow measured by the flow meter. The fractures located in those sections have higher transmissivity and are connected to surrounding recharge or discharge sources. Significant increased upward flow was found at the depth of 42–43 m in borehole #4 and at the depth of 29–30 m in borehole #5. Fractures in these depth intervals may connect to high hydraulic head associated with groundwater recharge potential. In comparison, the fractures at the depth of 23–24 m in borehole #4 and 22–23 m in borehole #5 may be associated with groundwater discharge potential. Furthermore, no flow was measured above the bedrock layer (20 m), demonstrating that an outflow zone exists at the bedrock–regolith transition.

Double-packer hydraulic tests were then conducted in borehole #4 and borehole #5 to determine the transmissivity of fractures. A total of 16 intervals were selected for testing (nine for borehole #4 and seven for borehole #5) and the transmissivity was determined for each. A cross-comparison of the transmissivity and flowmeter logging is shown in Figs. 12 and 13. A good correspondence was found between the two, which indicates that those intervals exhibiting strong groundwater inflow or outflow may be associated with higher transmissivity (geometric mean T: 9.75×10^{-6} m^2/s). In contrast, the transmissivity of other intervals is relatively low (geometric mean T: 9.06 $\times 10^{-7}$ m^2/s). The ambient flowmeter log can be considered a useful method for identifying fractures that have higher transmissivity and are connected to the local flow system. The data for each test interval, including the number of fractures (or fracture zones), dip of fractures, and transmissivity are summarized in Table 3. A stereographic plot (Fig. 11) shows that the orientations of the conductive fractures (red dots) fall within the major fracture clusters. This reveals that the fracture permeability at the Hoshe site is also related to the local geological structure. However, when compared to the Tailuge National Park site, fracture orientation at the Hoshe site is distributed more randomly and represents more than one fracture set. The fracture network at this site is perhaps more complex and it is more difficult to delineate hydraulic pathways based on the fracture orientation data.

In order to efficiently determine the fracture hydraulic connections in the bedrock, the cross-borehole investigation was performed by combining a single packer test and flowmeter logging in nearby boreholes. In conducting the cross-borehole test, the packer was lowered to a depth of 20 m in borehole #6 to isolate a test interval extending from 20 m to 44 m in depth. A pressure of 0.4 kg/cm^2 was applied to the test interval in order to induce additional flow through the fracture network. The injected flow rate and pressure were simultaneously measured during the test, which allows for the calculation of hydraulic parameters. Once the injected flow had stabilized at about 40 L/min, flow measurements were made at one-meter intervals in boreholes #4 and #5. According to flow log measurements in Figs. 12 and 13, the flow measured during injection in the adjacent boreholes differs from that previously measured under ambient conditions. A reversed flow direction (inflow instead of outflow) was observed at the depth of 23–24 m in borehole #4 under injection in borehole #6. Significant flow differences under the injected condition were found at depths of 23–24 m, 28.5–30 m, and 41.5–43 m in borehole #4 and 28–29.5 m in borehole #5. The results are attributed to the strong recharge flow produced through the fracture network by artificially increased hydraulic head in the adjacent well. Consequently, these fractures are confirmed as the primary flow path between the boreholes (Fig. 14). Most of the high transmissivity sections indicated by the packer test data are associated with obvious flow differences when flow logs obtained during injection are compared to the ambient flow logs. However, the packer test also shows that even though there is substantial

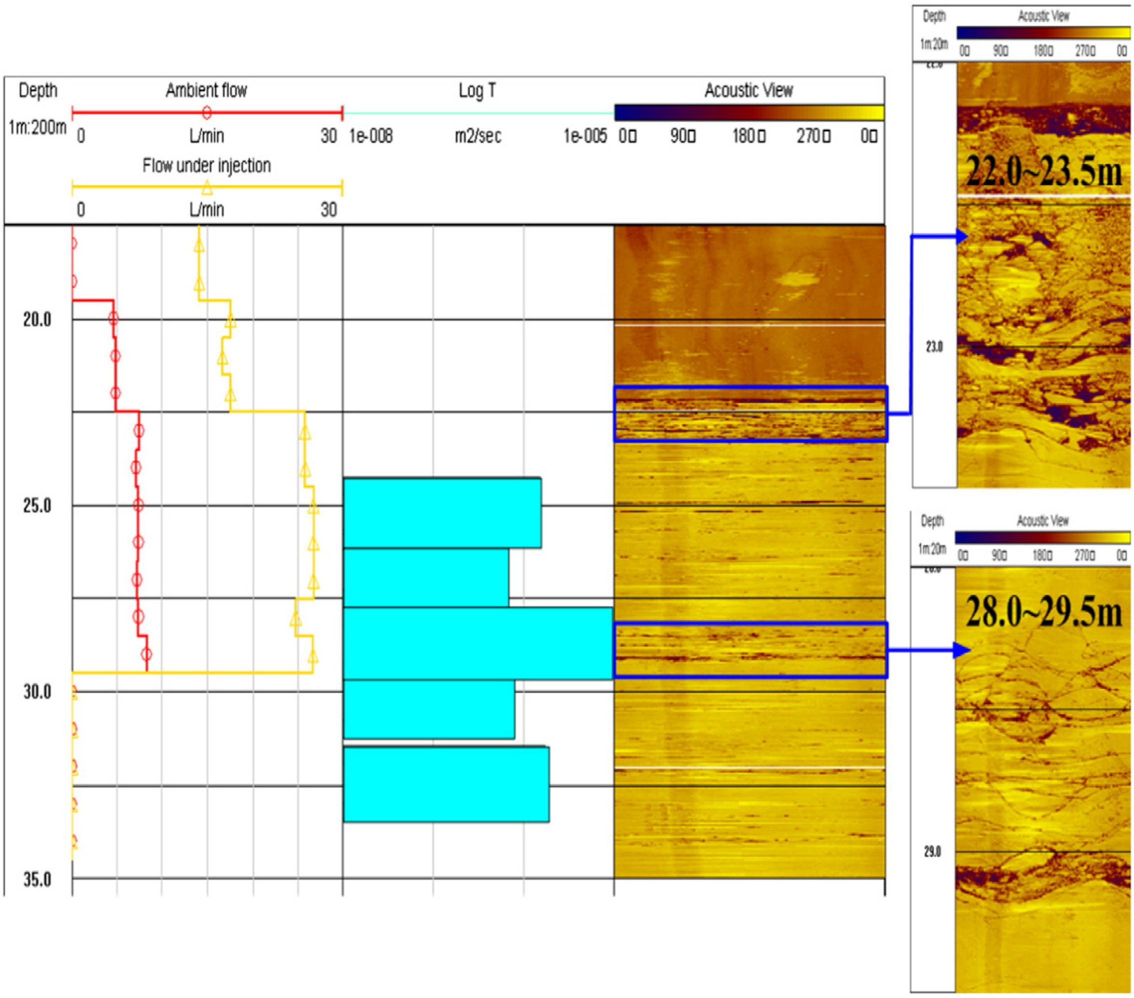

Fig. 13. Ambient and injection flow profile measured by the flowmeter; transmissivity obtained by the packer test; and borehole televiewer log of borehole #5.

transmissivity at the depth of 30–31.5 m in borehole #4, no significant flow difference between injection and ambient flowmeter logs was observed at that depth. This indicates that fracture transmissivity is not the only factor controlling the groundwater movement in that bedrock interval. Hydraulic connections in fractured networks also play an important role in transmitting the groundwater, particularly in complex fractured rock aquifers (Long et al., 1996). Besides, in borehole #4, a clay-filled aperture can be found at 39–40 m in which people were often misled into thinking that it is a highly conductive fracture (Fig. 12). In reality, at that depth, groundwater flow was significantly restricted and therefore no distinct difference in flow velocities can be drawn. This indicates that one should avoid an over-reliance on the

Table 3
Prospecting data of different test intervals in borehole #4 and borehole #5.

Borehole	Test interval	Average fracture dips	Amount of fractures/fracture zone	Transmissivity (m^2/s)	Groundwater recharge or discharge
#4	19.1–20.6	53.1	7/0	1.39×10^{-8}	
	20.5–22.0	48.5	2/1	6.42×10^{-7}	
	23.0–24.5	40.5	7/0	1.07×10^{-5}	Discharge
	28.0–29.5	30.9	6/1	1.04×10^{-5}	Recharge
	30.0–31.5	35.3	3/0	1.09×10^{-5}	Discharge
	31.5–33.0	45.9	5/0	1.31×10^{-6}	
	33.8–35.3	46.5	1/0	2.90×10^{-8}	
	35.3–36.8	37.1	2/0	1.42×10^{-6}	
	36.8–38.3	50.4	4/0	2.40×10^{-6}	
	39.0–40.5	55.6	4/1	3.09×10^{-6}	
	42.0–43.5	38.9	2/0	7.71×10^{-6}	Recharge
#5	24.5–26.0	41.7	3/0	2.33×10^{-6}	
	26.0–27.5	59.4	2/0	9.98×10^{-7}	
	28.0–29.5	37.5	5/1	1.34×10^{-5}	Recharge
	29.5–31.0	20.9	4/0	1.13×10^{-6}	
	30.5–32.0	23.3	2/0	4.89×10^{-6}	
	31.7–33.2	20.9	2/0	2.63×10^{-6}	
	33.2–35.0	67.2	2/0	2.31×10^{-6}	

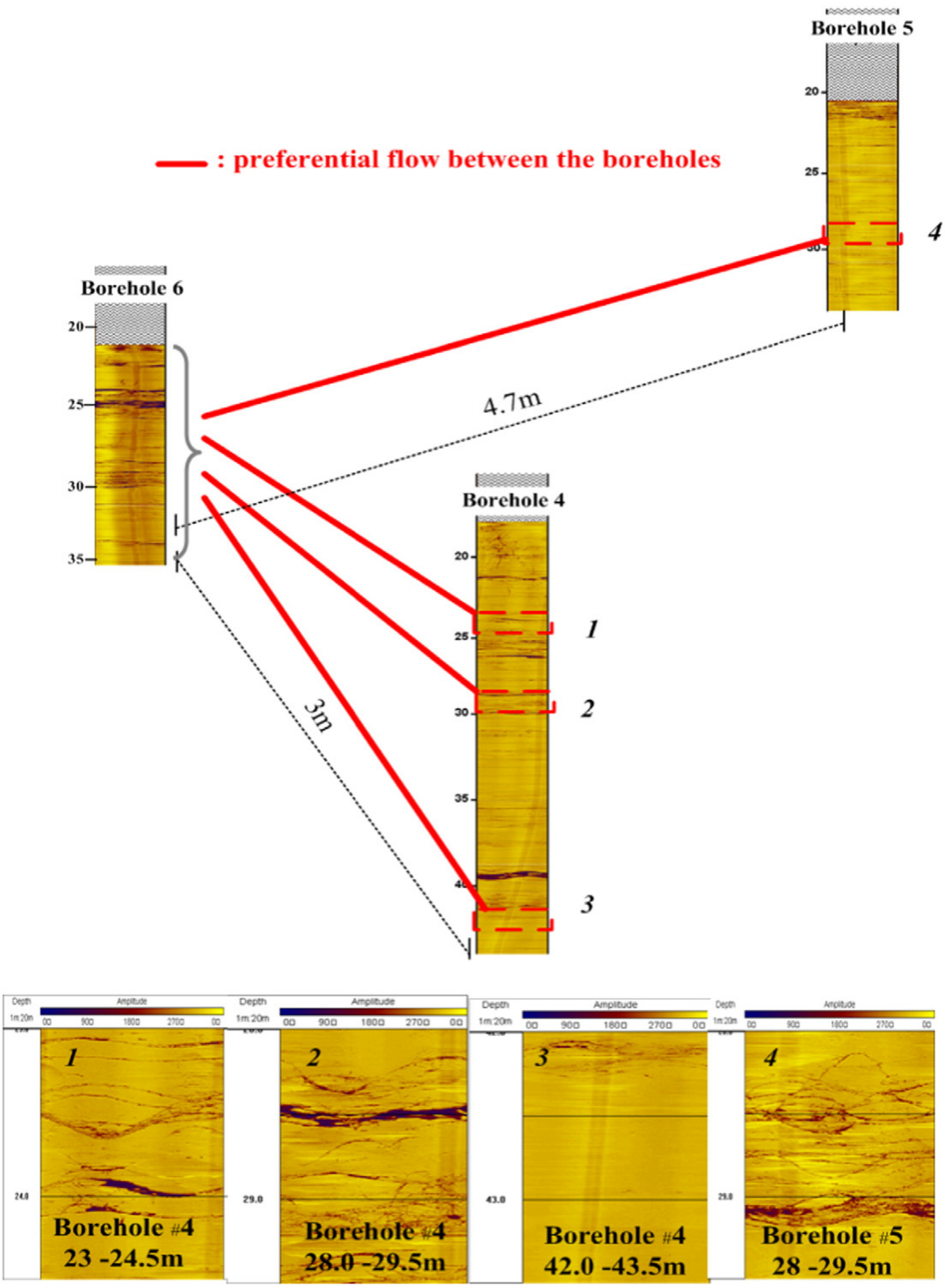

Fig. 14. Schematic drawing of preferential flow between the boreholes in the Hoshe test site.

interpretation of acoustic televiewer images. Rather, the complementary use of flowmeter and packer methods allows for a more thorough and efficient investigation.

5. Conclusions

Large uncertainties remain in determining the preferential flow paths in fractured-bedrock aquifers, which have long been a challenging issue in the groundwater resource management. To contribute to a better understanding of the localized groundwater flow regime in a fractured-bedrock aquifer, this study presents two case studies performed by different borehole techniques to investigate the hydraulic characteristics of a fractured bedrock aquifer. In each site, the location and degree of the fracturing, as well as fracture orientations and density, are identified by borehole televiewer logging. Heat-pulse flowmeter logging provides a continuous flow profile in the borehole, which is capable of locating the permeable fractures which exhibit transmissivity 1–2 orders of magnitude greater than the other fractures. The double-packer hydraulic test is an ideal approach that determines the hydraulic parameters of different fracture features. Although each test has its own advantages and limitations, by integrating different logging data the chosen techniques can be considered very useful in addressing the complexity of the fractured bedrock hydraulic characteristics.

In addition, in the first site, the computer program FLASH was applied to estimate fracture transmissivity from the ambient and pumped flowmeter logging data. In comparison with the results of packer test, the program is shown to be a quick and effective tool capable of estimating fracture transmissivity. In the second site, the packer tests and flowmeter logging were employed in tandem for cross-borehole investigation of fracture connections in the region between boreholes. As the results show, the approach can effectively delineate the hydraulic pathways between the fractures. In addition, we found that fracture transmissivity is not the only factor controlling the groundwater movement in a fractured rock mass aquifer, the effect of fracture connectivity also plays a very essential role in transmitting the groundwater. Finally, the stereographic projection analysis shows that the fracture permeability distributions at two test sites are correlated with local geological structure. These results provide robust evidence promoting the synergistic integration of borehole hydrogeological logging and aquifer testing for fractured rock aquifer characterization, which is particularly suitable for the investigation of groundwater resources and contaminant transport dynamics.

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